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Experimental Optical Techniques for Single Phase Flows in Microchannels: A Study

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Abstract- Miniaturization of electronic devices has led to increases in chip power and denser packaging of components. Micro devices such as micro heat exchangers are required to dissipate high heat flux produced in them. The coolant flows through the microchannel, which is one of the vital components of a microfluidic device. Specifically, fluid flow in micromachined conduits has emerged as an important research area. Thus there is a need for more detailed investigation of the fluid behavior inside microchannel so that flow can be modeled accurately for obtaining better results. This paper outlines the experimental optical techniques particularly, MicroPIV, Confocal microscopy and Florescence microscopy, for visualizing flow in microscale devices .Some references where these techniques have been applied successfully are also listed in the paper.

Index Terms- Microfluidics; MicroPIV; Confocal Microscopy; Fluorescence microscopy.

1. INTRODUCTION

The fluid behaviour at the micro-scale is different from 'macro-fluidic' behavior as the factors which are not so significant in conventional macro-scale flows start to dominate in micro-scale flows such as surface tension, energy dissipation and slip flow. Microfluidics is the science that studies how fluid behaviour changes as the scale is reduced to micro level.

Due to growing demand of devices which are relatively small in size and which can handle high heat flux dissipation problems, the microfluidic devices are becoming more prevalent both in commercial application and in scientific investigation. Microchannel is one of the basic devices in microfluidics system.

The classification of channels based on their smallest dimension, D_s, proposed by Kandlikar and Grande 2003 [1] is listed in Table 1.

Sr No.	Types of Channels	Smallest dimension, D_s
1	Conventional Channels	$D_s > 300$ µm
2	Minichannels	300 µm > D_s > 200 µm
3	Microchannels	200 µm > D_s > 10 µm
4	Transitional Microchannels	10 µm > D_s > 1 µm
5	Transitional Nanochannels	1 µm > D_s > 0.1 µm
6	Molecular Nanochannels	$Ds < 0.1$ µm

Table 1: Channel classification scheme, Kandlikar and Grande [1]

Analysis of fluid flow is crucial for design of various micro devices such as micropump, microchannel heat sink etc. Investigations of flow help in determining the behavioral characteristics of fluid which are essential for safe operation and optimal design of microfluidic devices. Because of minute size of microfluidic devices, direct contact measurement techniques are not viable for measuring flow in MEMS devices, thus necessitate the use of optical techniques. This paper, thus, focus on studying various experimental techniques based on optics for observing flows in microchannels.

2. EXPERIMENTAL TECHNIQUES FOR OBSERVING FLOWS IN MICROSCALE DEVICES:

2.1. *Micro Particle image velocimetry*

Particle Image Velocimetry is a quantitative flow visualization technique which uses discrete particle distributions to visualize the flow. This well established optical method has become a standard tool in the last decade for fluid velocity measurements in a microchannel. One of the main advantages of this method is that the output data is the vector plot of the velocity field where each vector tells about both the direction and magnitude of the velocity at the local position. This data obtained in the vector format can be directly compared with CFD data.

This technique determines two dimensional velocity fields in a two dimensional measurement plane using conventional microscopy and digital imaging methods. The velocity is determined by measuring the particle displacement over a precisely selected time using a double-pulsed laser technique. The flow is seeded with the tracer particles whose density

matches with the density of the fluid so that tracer particle is able to follow the flow. A laser light sheet illuminates a volume of fluid which is observed with the help of a microscope .The light emitted by the tracer particles focused by microscope objective lens is collected by the objective lens and are recorded using a CCD camera at an instant of time t_0. After a short interval of time Δt, of the order of micro or milliseconds, a second pulse illuminates the tracer particles again, and their position is recorded at the time $t = t_0 + \Delta t$, creating a second set of particle image pattern. So during the flow the tracer particles moving with a velocity u slightly shift by a displacement ΔL in these two consecutive recordings. The particle displacement ΔL is evaluated from the two digital images, so that $u= \Delta L/ \Delta t$ (Figure 1).

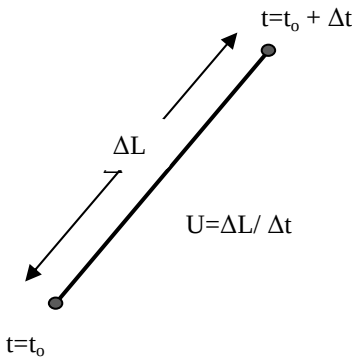


Fig. 1. Velocity Determination in fluid flow

Micro-PIV is a modification of PIV so as to access the microscale fluidic devices. Some of the factors that differentiate microPIV from its conventional counterpart as pointed out by Wereley et al. [2] are listed below:

(i) The seeding particles are small in comparison to the wavelength of illuminating light.
(ii) Particle size being small, Brownian motion may become a significant source of random error in measurement of the particle displacement between successive images, especially for slow moving flow fields.
(iii) There is considerable difference in flow illumination. In contrast to PIV, where a thin sheet of laser light is generated to illuminate a single plane of interest in the fluid flow, in microPIV, however, entire volume of the flow is illuminated.

The typical optical configuration of a microPIV system include a CCD camera, a microscope (upright or inverted) equipped with fluorescence filters, a light source (usually a double-pulse laser), and suitable optical accessories such as optical fibers, beam expanders, etc. The fluid inside the microfluidic device such as a microchannel is seeded with tracer particles which got illuminated by the double pulse laser and imaged through the microscope objective onto the CCD array of the camera.

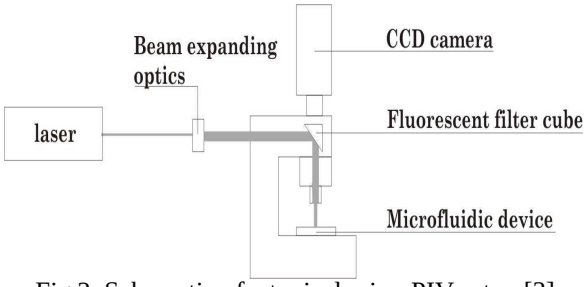


Fig.2. Schematic of a typical microPIV setup [3]

The laser beam is directed to the microscope directly or by means of an optical fiber. The fluorescent filter cube consists of a dichromatic mirror and an emission filter. The correct filtering scheme ensures the collection of appropriate light signals, while rejecting unwanted wavelengths, in order to obtain data of the highest possible quality and thus the highest measurement accuracy.

Depending on the size of the flow field and illumination conditions, a range of objectives with different magnification levels are applied for microPIV. The fluorescent signal from the small seeding particles in microPIV is weak, thus requiring high numerical aperture objectives due to their high light-gathering power.

This technique has gained popularity and being applied by a number of researchers for flow studies in microscale devices during the past few years. Santiago et al. [4] was first to apply this technique to a rectangular microchannel and he observed that microPIV can yield a spatial resolution of the flow field of approximately one micron. Sharp and Adrian [5] performed microPIV experiments on glass tubes, and they identified transition through the presence of unsteady changes in centerline velocity. Their findings more closely relate to conventional theory, with critical Reynolds numbers ranging from 1800 to 2200. Li et al. [6] performed similar studies on microchannels with transition criteria defined also with deviations in centerline velocity, and they found the transition Reynolds number to be 1535. They also found that the fully turbulent region began at Reynolds numbers of 2630 to 2853. Li and Olsen [7, 8] performed microPIV visualizations on microchannels and determined that no early transition to turbulence was present in their studies. Recently, simultaneous velocity measurements of two liquid phases in a Y-junction microchannel were reported by Kim et al. [9] and two-phase transient flow has been studied by Shinohara et al. [10].

2.2. *Confocal MicroPIV*

It is a well-developed technique and has significant advantage as compared to the traditional wide-field fluorescence microscopes. In a wide-field fluorescence microscope, light from a light source is thrown on the entire specimen and at the same moment of time all parts of the specimen that fall in the optical path, are excited and the resulting fluorescence is detected by the microscope's photo detector or camera including a large unfocused background part. Whereas in contrast, a confocal microscope uses point illumination and a pinhole in an optically conjugate plane to eliminate out-of-focus signal. As only light produced by fluorescence very close to the focal plane can be detected, the image's optical resolution, particularly in the sample depth direction, is much better than that of wide-field microscopes [11].

Due to its excellent spatial filtering technique alongside multiple point light illumination system, this kind of microscope has the capability to take infocus images with optical thickness less than 1 mm. As a result, it is possible to achieve a PIV system with not only extremely high spatial resolution but also with capability to generate 3D velocity data.

High-speed spinning disk confocal microscopy was first used in 2004 for micro-scale flow field measurements but at that time it suffered low temporal resolution (up to 120 frames per second). Since then, technological advancement in camera and spinning disk field lead to the development of confocal systems capable of up to 1,000 frames per second.

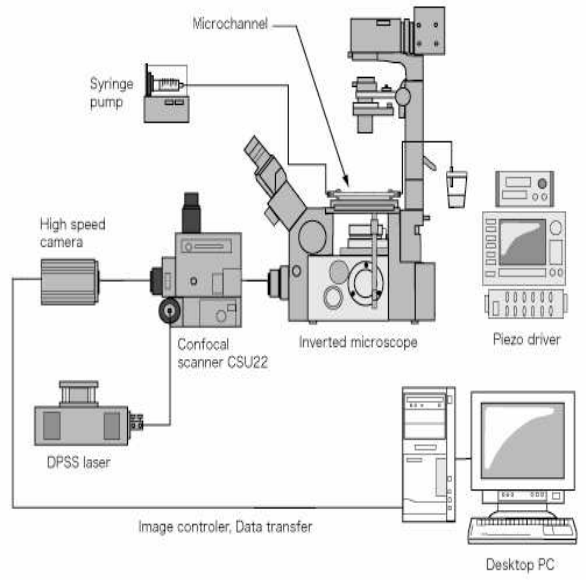


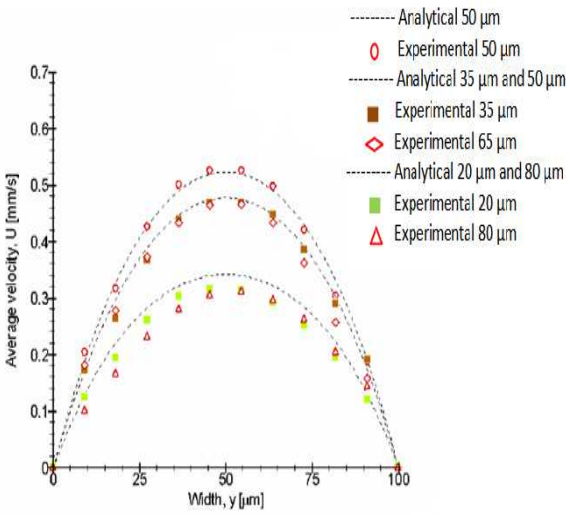
Fig. 3 Confocal microPIV set up [12]

The confocal micro-PIV system shown in Fig. 3 consists of three main units as an inverted microscope, a confocal scanning unit and a diode-pumped solid state laser. A high-speed camera is coupled into the outlet port of confocal scanner and microchannels are placed on the platform of the inverted microscope. Rate of supply of working fluids can be kept constant by using a syringe pump.

RUI et.al[12] examined the ability of the confocal micro-PIV system to measure velocity fields of both homogeneous and non-homogeneous fluids in two different kinds of microchannels, i. e., 100 µm glass square and rectangular (300µm wide, 45µm deep) PDMS microchannel.

The good agreement obtained by them (as shown in Fig.4) between measured and estimated results suggested that this system is a very promising to obtain detail information about micro-scale effects in microchannels.

Fig.4. Comparison between experimental data and



analytical solutions [13] at several optical sectioned images in 100 µm square microchannel using pure water as working fluid.

Orin Hemminger et. al [14] make use of high speed confocal imaging system to create 3D velocity profiles of working fluid flowing in trapezoidal microchannels at speeds of 1000 frames per second. Additionally, the ability to track a separate solid particle phase was demonstrated successfully using this technique.

2.3. *Fluorescence Microscopy*

This technique uses a light microscope for studying properties of organic/inorganic substances using the phenomenon of fluorescence instead of, or in addition to, reflection and absorption. It consist of a dichoric mirror to direct the light on to the specimen for illumination and two filters, namely emission and excitation filter and a detector as shown in Fig. 5. In many cases, a segment, to be tested in the specimen is tagged with a fluorescent molecule called a fluorophore.

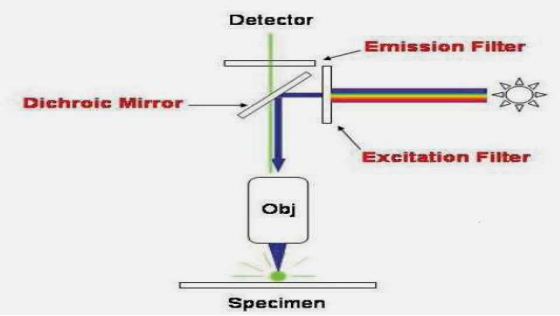


Fig.5. Fluorescence Image Principle (Wikipedia: Fluorescence_microscopy)

This method is widely accepted for studying the dynamic behavior exhibited in live cell imaging as it can differentiate individual proteins with a high degree of specificity from nonfluorescing material. The sensitivity of the microscope is high enough to identify as little as 50 molecules per cubic micrometer.

The major factor that provides fluorescence microscopy an edge over other optical imaging techniques, for both in vitro and in vivo imaging is that different molecules can be marked with different colors, in this way it allows multiple molecules to be tracked at the same time; hence the movement of individual cellular components can be analyzed.

Guoging et. al [15] measure and analyze the mobility of fluorescent species in specially designed microfluidic channels at micron and sub-micron scales; fabricated on fused silica wafers using fluorescence correlation spectroscopy.

Jinpian Diao et. al [16] developed a prototype three-channel microfluidic chip which has the capacity to generate a linear concentration gradient within a microfluidic channel and is helpful in the study of bacterial chemotaxis in conjunction with fluorescence imaging techniques.

3. CONCLUSION

This study reviews the experimental techniques on single phase microchannels for observing flow in microscale fluidic devices. Different techniques such as microPIV, Confocal microPIV and Fluorescence microscope are presented in this paper along with highlighting some of the areas where microscale fluid behavior has been studied successfully using these techniques. Though these techniques can access fluid behavior in micro devices, but a lot of research need to be done to develop some more rigorous methods/techniques especially suited for microfluidic devices so that flow behavior can be observed more accurately, thus will enhance the design of microfluidic devices and accurately predict flow characteristics of microscale flows.

REFERENCES

[1] Satish Kandlikar ve William Grande, “Evolution of microchannel flow passages – Thermohydraulic performance and fabrication technology,” Proceedings,https://ritdml.rit.edu/handle/1850/7459.

[2] 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.

[3] Michal M. MIELNIK, Lars R. SAETRAN, “Micro Particle Image Velocimetry – an overview”.

[4] Santiago JG, Wereley ST, Meinhart CD, Beebe DJ, Adrian RJ(1998): A particle image velocimetry system for microfluidics. Exp. Fluids., Vol.25, pp 316-319.

[5] Sharp, K.V., and Adrian, R.J.(2004): Transition from laminar to turbulent flow in liquid filled microtubes, Experiments in Fluids, Vol. 36, p. 741–747.

[6] Li, H., Ewoldt, R., and Olsen, M.G.(2005): Turbulent and transitional velocity measurements in a rectangular microchannel using microscopic particle image velocimetry, Experimental Thermal and Fluid Science, Vol. 29, p. 435–446.

[7] Li, H., and Olsen, M.G.(2006): Aspect ratio effects on turbulent and transitional flow in rectangular microchannels as measured with microPIV, Journal of Fluids Engineering, Vol.128, p. 305-315.

[8] Li, H., and Olsen, M.(2006): MicroPIV measurements of turbulent flow in square microchannels with hydraulic diameters from 200 m to 640 m, International Journal of Heat and Fluid Flow, Vol. 27, p. 123–134.

[9] Kim, B.J., Liu, Y.Z., Sung, H.J.,(2004): MicroPIV measurement of two-fluid flow with different refractive indices, Meas. Sci. Technol., Vol. 15, pp. 1097-1103.

[10] 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.

[11]http://en.wikipedia.org/wiki/Confocal_microscopy.

[12] Lima, R.; Ishikawa, T.; Tanaka, S.; Takeda, M.; Tsubota, K.; Wada, S.; Yamaguchi, T.(2007): “Velocity fields of blood flow in microchannels using a Confocal microPIV system, 9th International Symposium on Future Medical Engineering Based on Bionanotechnology. Future medical engineering based on Bionanotechnology, pp. 311-316.

[13] H. Bruus (2004): Theoretical microfluidics Lecture notes MIC Department of Micro and Nanotechnology Technical University of Denmark Denmark.

[14] Orin Hemminger, Zhao Yu, Chunhe Zhang, L. James Lee, Liang-Shih Fan (2007): “Microfluidic velocity measurements using three dimensional confocal microparticle tracking velocimetry (CM-PTV)”, Engineering Conferences International.

[15] Guoqing Shen ; Baohe Chang ; Bryan D. Dickerson ; Xiaoxuan Li and Lloyd M. Davis (2009): "Coupling confocal fluorescence microscopy and microfluidic device for single molecule detection", Proc. SPIE 7207, Microfluidics, BioMEMS, and Medical Microsystems VII, 72070H.

[16] Jinpian Diao, Lincoln Young, Sue Kim, Elizabeth A. Fogarty, Steven M. Heilman, Peng Zhou, Michael L. Shuler, Mingming Wu and Matthew P. DeLisa, “ A three-channel microfluidic device for generating static linear gradients and its application to the quantitative analysis of bacterial chemotaxis”, www.rsc.org/loc | Lab on a Chip.