33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Spatio-temporal image analysis of particle streaks in micro-channels for low-cost electro-hydrodynamic flow characterization

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Abstract— **Flow characterization is a primary analytical method for performance evaluation of microfluidic devices. With the increasing prevalence of microfluidic devices in recent years, there is a growing need for simple methods of automated flow estimation. In this work, a novel flow diagnostic technique based on image analysis of particle streaks is introduced, to characterize local flow velocities. While 1D velocimetry using particle tracks has occasionally been discussed for macro-scale environments, the use of particle streaks for 2-D flow characterization in micro-channels has not been explored. The proposed technique is qualitatively validated against electrokinetic experiment and numerically validated with simulated flows.**

I. INTRODUCTION

With the advancement of microfluidics and lab-on-a-chip devices in the last decade [1], there has been an increasing requirement for understanding fluid and particle-fluid velocity fields at small scales. In addition to providing insight into the physics of particle flow phenomena, micro-channel velocimetry has been instrumental in evaluating the performance of microfluidic lab-on-a-chip devices. Non-intrusive velocimetry methods based on particle flow imaging have been particularly popular and, of these, micro particle image velocimetry (μPIV) has often been used for micro-channel velocity estimation [2]. In this method the flow is seeded with tracer particles and cross-correlation between consecutive images of particle constellations at identical spatial locations is used for flow diagnosis. Laser-based illumination, an inverted microscope and a high speed camera are typically used in μPIV to capture sharp particles images [3].

While studies on μPIV have shown it to be effective, the image acquisition requirements are stringent, costly and entail difficult set up. In addition to their high cost, laser-based μPIV illumination systems need cautious handling and suffer from interference problems [3]. Also, high-speed flows require costlier and more complex image acquisition hardware. As an alternative method that is cheap, quick and yet effective, the use of particle streaks is proposed. In contrast to PIV based methods which impose quality requirements on the camera to prevent signal decorrelation due to particle motion blurs (streaks), the information conveyed by the streaks is utilized, thus implicitly relaxing our hardware requirements. Prior work involving the use of particle streaks for macro scale velocity fields is found in the works of Bergthorson et al. [4], Herring et al. [5] and Muller et al. [6]. However, with the exception of sporadic uses to calculate spatially constant or average channel velocities [7], streaks are generally considered undesirable imaging artefacts in microfluidic flow-imaging. Accordingly, the prospect of using streaks for characterizing 2-D velocity fields in micro-channels is of interest.

In addition to a much cheaper hardware requirement, the image analysis in our proposed method is completely different from μPIV. Our method involves exposure-controlled imaging of fluorescent particle streaks distributed over the spatial extent of the micro-channel. Since particle tracks represent the local displacement during the time of exposure, short streaks can effectively represent local velocity vectors. Hence for a smooth, time-invariant flow, a spatially continuous collection of such velocity vectors directly characterizes the spatial velocity field $[V(x,y)]$. Thus, our method is not based on cross-correlation unlike μPIV. It is also different from particle tracking velocimetry (PTV) as particles are not tracked across image sequences. Instead, the spatio-temporal distribution of the particle track length "seen" at a point is analysed for obtaining the velocity field.

The goal of this paper is to introduce a simplified and cheap flow measurement solution capable of quick, high-quality velocity field characterization that may be effectively used for determination of electrokinetic parameters [8] and investigation of microfluidic phenomena.

II. DATA ACQUISITION

A. Experimental set up

The electrokinetic experiment used a PDMS micro-channel in which particles flow due to a spatially variable electrophoretic force achieved by using a tapered channel geometry. The taper width was inversely (hyperbolic) related to the distance and this could be shown to give rise to a linear velocity gradient arising from a combination of electrokinetic forces. The main objective was to create streaks in a region of velocity gradient and then quantify the electrodynamic forces from the velocity measurements [9].

The microfluidic channel (depth 10 microns) was fabricated via standard soft lithography using PDMS. Plasma treatment was used to render the channels hydrophilic and a glass slide was used to cover the channel (Fig. 1). Fluorescently-labelled polystyrene particles (1 μm, sulfated) diluted to a concentration of approximately 5×10^6 particles/mL in buffer were used as tracers. At the start of an experiment, the pressure was equilibrated to stop hydrodynamic flow and then a voltage ($\sim$500 V) was applied using

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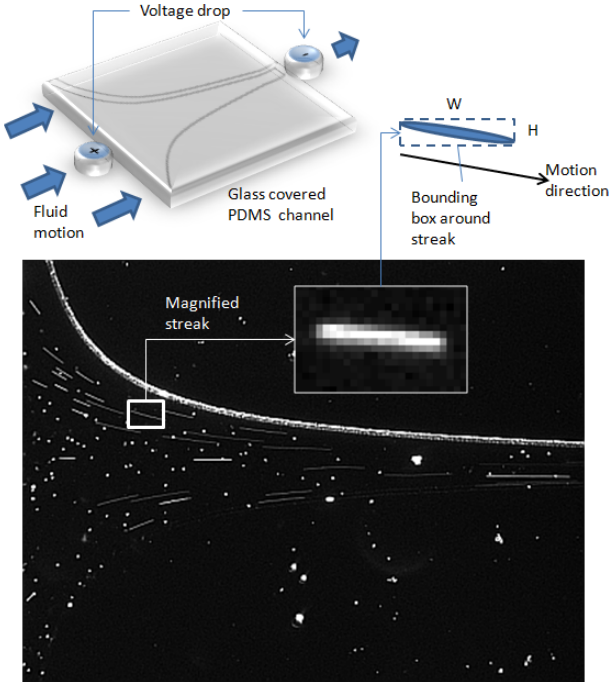

Fig. 1. Schematic for the electrokinetic experiment is shown in the top figure. An acquired image is shown in the bottom. The streak lengths progressively increase across the channel in the image. A magnified streak (inset) and the bounding box used during processing are also shown. Particles stuck to the PDMS channel floor appear as 'dots'.

two platinum electrodes dipped into the external reservoirs. Volume illumination from a mercury short-arc light source (OSRAM, H30 103 w/2) was used and the particles were imaged by a standard, simple and affordable combination of inverted microscope (IX70, Olympus), CCD camera (Q Imaging Inc.) and Streampix III software (Norpix).The exposure time was adjusted depending on the experiment (30 ms - 90 ms). The frame rate was approximately 17 frames per second.

B. Simulation

Quantitative analysis of the streak velocimetry method is provided by two sets of simulations. Firstly, simulated data is obtained for a 1-dimensional velocity field, as would be observed at the channel center-line in Fig. 1. This is useful because very often, for quick device diagnostics, center-line velocity is measured. Moreover, the concept is easily extended to 2-D. The second set simulates the Hagen-Poissueles flow.

1) Simulation of Center-line particle flow under linear velocity gradient: Particle streaks form due to the prolonged imaging of the particle over a period of (exposure) time. For computation, this time is divided into small steps Δt

$$\Delta t = \frac{T_{\text{exposure}}}{M}; M\text{large}$$

The local velocity expressed as incremental change in distance over time at an arbitrary ith instant is given by,

$$V_E(x_i) = \frac{x_{i+1} - x_i}{\Delta t}$$

The change in particle position for a known velocity field and the particle streak length is then given by

$$x_{i+1} = x_i + V_E(x_i)\left[\frac{T_{\text{exposure}}}{M}\right] \quad (1)$$

$$L = \sum_{i=1}^{M-1} V_E(x_i) \cdot \Delta t \quad (2)$$

The initial starting positions are randomly selected. The result of the simulation is a set of streaks in 1-dimensional space which are used as input to our processing algorithm.

2) Simulation of Hagen-Poissueles flow: Simulated data of particle streaks was obtained for Hagen-Poissueles flow for quantitative performance analysis. In Cartesian coordinates, the velocity distribution for a diametric cross section for such a flow is of the form

$$V(x, y) = K(R^2 - y^2) \quad (3)$$

where K and R are constants. To simulate measurement noise, zero mean additive white Gaussian noise n, with standard deviation proportional to particle image diameter was added to the estimated length. For a particle with initial position at (x_0, y_0), the final position after T time of exposure is then given by

$$(x_1, y_0); x_1 = x_0 + T \cdot K \cdot (R^2 - {y_0}^2) + n \quad (4)$$

Initial particle positions were generated at random and then the streaks (assumed at focal plane) were generated based on the final positions. A typical simulated image can be seen in Fig. 2 (bottom) and a stack of such images are used as input to our processing algorithm.

III. DISCUSSIONS AND RESULTS

The steps of our processing algorithm are described next.The entire image processing algorithm was implemented using Matlab (Mathworks Inc.) and the processing time for a 1000 frame (480 × 640) sequence is about a 2-3 minutes.

A. Streak image analysis and velocity estimation

A stack of frames with particle streaks covering the region of interest (ROI) is the input. The images are firstly processed to minimize the noise and imaging artefacts. Blurred and non-ellipsoidal objects are removed by morphological image processing. Streaks are then segmented by local adaptive thresholding and fitted in a bounding box. The width W and the height H of the box (Fig. 1) represent the exposure time-weighted local horizontal and vertical velocity components respectively. The component values are then stacked separately, for each spatial location. The histogram of the temporal data at a spatial position is analysed and outlier data points are eliminated based on the local mean, median and standard deviations from the spatio-temporal stack. In our processing, streaks with lengths more than 2 standard deviations were eliminated. Local averaging then yields the resultant local velocity component. This procedure is repeated for the entire ROI thus generating the 2-D horizontal and vertical velocity field components.

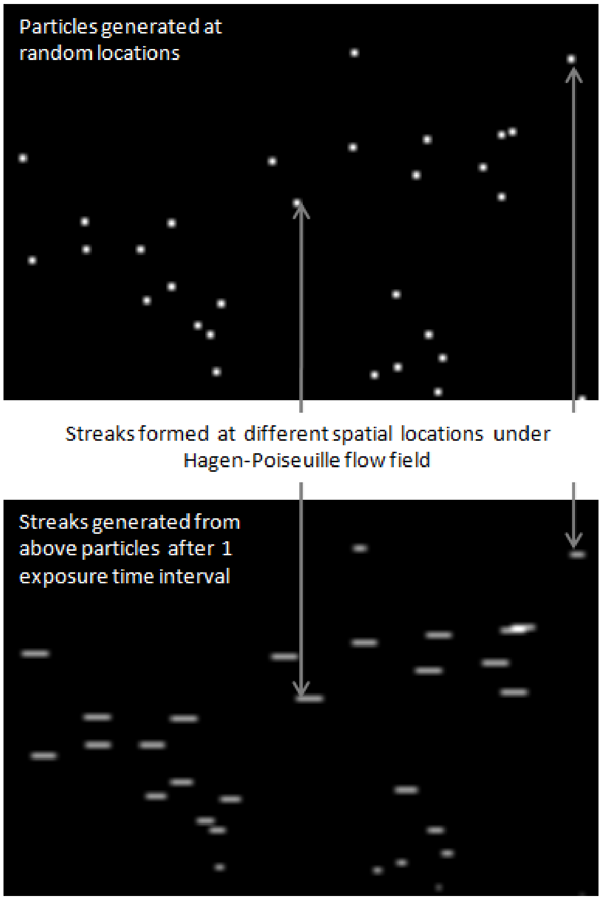

Fig. 2. Simulated image frame with streaks formed in a Hagen-Poiseuille flow (bottom). The top frame shows the randomly selected initial positions. During the exposure time the particle travels forming the streak. The streak lengths vary in the vertical direction.

B. Errors due to channel depth

Unlike μPIV, our method is based on shape and not cluster pattern and intensity. Accordingly, the defocusing problems are different than the known depth-of-correlation problem encountered in μPIV [10]. For deeper channels, defocussed streaks over and below the focal plane often get imaged. These are eliminated during morphological processing which is based on the image diameter of a static tracer particle (recorded separately) in focus. Streaks which are much “thicker” get eliminated. This is only possible since streaks have a shape and a thickness determined by the particle image diameter. Moreover, the intensity loss due to defocusing is effectively used in the local adaptive thresholding (selecting the highest intensity streak). Streaks in different layers can also get sharply imaged together, particularly when the channel depth is small. In this case, erroneous lengths (longer) can bias the local length distribution (due to the mixing of lengths at different depths). But with a large dataset, the mean, median and standard deviation can be used to eliminate such outliers considerably. It may also be noted that unless there is a considerable velocity gradient among immediately adjacent layers, the streak-length-error introduced at a particular focal plane would be small. This is typically true if the functional properties of the microfluidic channel are somewhat uniform across the depth.

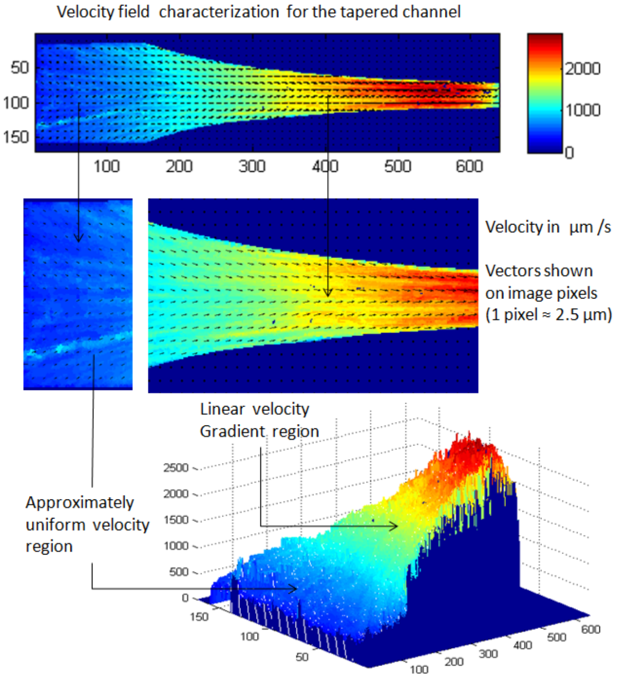

Fig. 3. Velocity estimation results for the electrokinetic experiment. Two regions from the complete 2-D velocity distribution (top) is enlarged and shown (middle). The bottom figure shows the approximately linear nature of the velocity gradient.

C. Results from experiment and simulations

Fig. 3 shows the 2-D particle velocity field obtained for the electrokinetic experiment. The results indicate two distinct regions, one in which the velocity is small and approximately uniform and the other where there is a velocity gradient that appears to be approximately linear and as expected [9]. The velocity variations are smooth in both X and Y and fairly constant in the Y direction. The observed flow field is not exactly symmetric about the center-line and this is expected in an experimental scenario. The velocity field minima and maxima are clearly distinguished and with a very nominal image capture frame rate (17 fps). The streak image intensity varies with velocity, but since our method does not rely on correlation, there is no error till the streak detection is challenged by the imaging noise. The velocity field is thus efficiently characterized by a simple, affordable image acquisition set up.

The velocity estimation result for the streak length data generated for a center-line with linear velocity gradient is shown in Fig. 4. The true velocity changes by 100 microns per second over a spatial extent of 1000 microns. This is used as an input to the spatio-temporal averaging process. Approximately 1000 streaks with randomly generated starting positions were used in the simulation. The results show excellent tracking of the true velocity, with an absolute error less than 0.5 microns per second for the entire spatial extent.

Simulation results for the Hagen-Poiseuille flow are shown

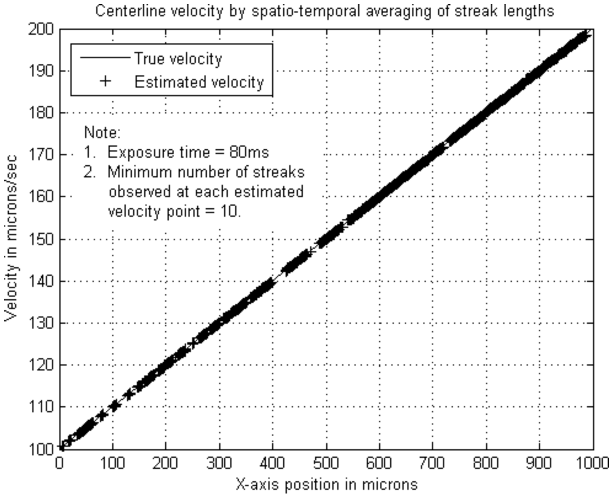

Fig. 4. Velocity estimation results for center-line velocity field.

in Fig. 5. About 200 simulated image frames were used. It is seen that while too few frames(loss in statistical strength) or short exposure times (measurement noise dominates) show small mismatch in tracking, with adequate number of frames and adequate control on the exposure time, the velocity variation can be tracked accurately.

The proposed method is being further developed and improved, in particular with eliminating channel depth issues and directional ambiguity of streaks. However, it may be noted that for most experimental scenarios with steady flows, local flow characters (convergent or divergent) are typically known and can be used for resolving this ambiguity. With the current algorithm, streaks which get occluded by a channel entrance do not contribute effectively to the estimation. Multiplexing different (small and large) exposure times, appears to solve this problem. The proposed method would also be compared to PIV in an extended version of this work.

IV. CONCLUSIONS

A novel technique for 2-D flow characterization in micro-channels is proposed and explored in this preliminary study. While providing efficient flow diagnostics, the proposed method intrinsically does not rely in stringent hardware requirements and is intended to be a powerful yet quick tool for routine micro-channel velocimetry. The method described tracks the local flow and with adequate data would yield consistent results for time-invariant smooth velocity fields. The sampling of the underlying field can be controlled by the size of the fluorescent tracers and exposure time and this adds additional control. Eliminating the current limitations, mathematical modelling of particle tracks for improving the performance and expanding the scope of the proposed method is the focus of our future work.

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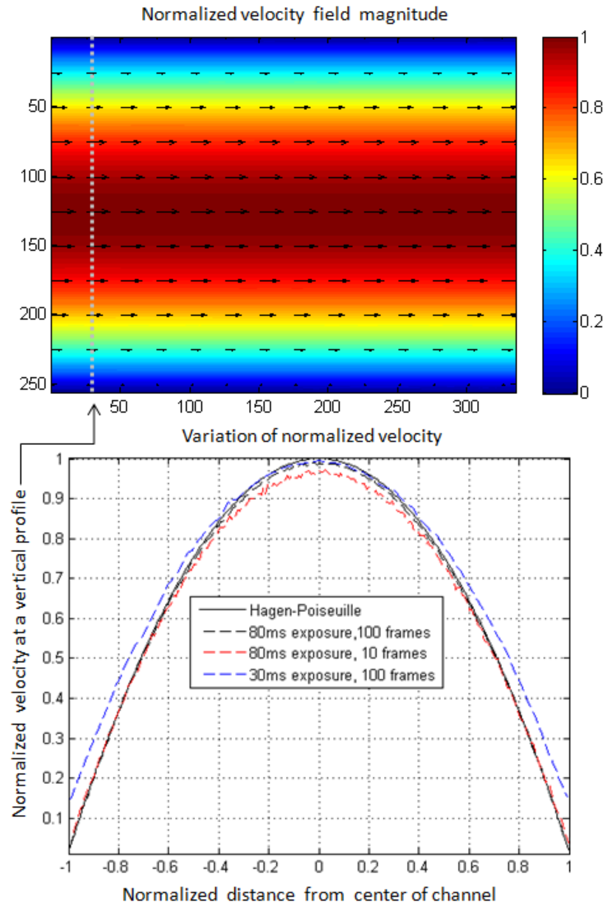

Fig. 5. Velocity estimation results for Hagen-Poiseuille flow. Top figure shows the normalized 2-D velocity field and bottom figure shows the results for a vertical profile (bottom) under different control parameters.

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