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A microflow velocity measurement system based on optical tweezers: A comparison using particle tracking velocimetry

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ABSTRACT

Lab-on-a-chip devices have become useful to study substances not available in macrometric amounts. To manipulate the substances under study, ways to induce flow within such devices have been developed and, at the same time, methods to measure flow velocity have been required for the micro-scale. Several velocimetry techniques have been adapted from the macro to the micro scale, such as micro-particle image velocimetry (micro-PIV) and micro-particle tracking velocimetry (micro-PTV). However, the use of a system based on optical tweezers (OT) to measure flow velocity, specifically in microenvironments is possible. With the aim of highlighting the capabilities of an OT-based velocimetry system (OTV), we report the use of such system to measure flow velocity in a rectangular microchannel. Velocity measurements at different depths from the channel wall were carried out. As expected, an increment of the flow velocity with depth was observed. The results obtained with the OTV system were compared with measurements carried out by means of a time-averaged particle tracking velocimetry (TA-PTV). We found that both techniques provided similar results, therefore we demonstrate the capability of the OTV system to measure flow velocities in micrometric scale. The advantages of the OTV system are: (1) better space resolution, (2) minimization of the Brownian motion influence in the measurements and (3) the possibility to have submicrometric spatial resolutions without the employment of high particle concentrations, special data processing, or complex illumination systems like in other microvelocimetry techniques.

1. Introduction and theoretical background

With the interest to produce chemical reactions and biological studies in micrometric size devices (lab-on-a-chip devices), methods to induce flow at such a scale have been developed. At the same time, techniques to measure flow velocities in micrometric scale have also been required. To approach this problem, macro-scale velocimetry techniques, like particle image velocimetry (PIV) [1–3] or particle tracking velocimetry (PTV) [3,4], have been adapted to the micro-scale. Such techniques are based on the observation, by means of a video camera, of the motion of particles seeded in the flow. However, when low velocities are measured with those techniques, special attention must be paid to avoid the influence of the Brownian motion induced to the suspended particles due to fluid thermal energy. The range of velocities in which Brownian motion affects significantly the results from micro-PIV or micro-PTV is not well defined, because it depends on several parameters like particle size, fluid temperature, fluid viscosity and frame recording rate [5].

To avoid the influence of the Brownian motion, spatial or temporal averages of the velocities measured using micro-PIV or micro-PTV have been found in the literature [2,4]. In these studies, a minimization of the error in the velocity measurement introduced by Brownian motion can be achieved by increasing the number of measurements according to Eq. (1) [5]:

$$\varepsilon = \frac{1}{u}\sqrt{\frac{k_B T f_s}{3\pi n \eta a}}, \tag{1}$$

where ε is the relative error, u is the magnitude of the flow velocity to be measured, k_B is the Boltzmann constant, T represents the temperature of the working medium, f_s is the recording frame rate, n is the number of measurements taken into account to minimize the influence of Brownian motion, η represents the dynamic viscosity of the trapping medium, and a is the radius

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of the trapped particle. Nevertheless, micro-PIV and micro-PTV require elaborated illumination and observation systems due to the necessity to use particles between 200 and 300 nm in diameter in high concentrations [1,4,6–8], which may affect the performance of the lab-on-a-chip devices or the flow behavior. Furthermore, it is difficult to achieve a submicrometric spatial resolution with those techniques [1–4,6] when flow velocities in the order of 1 μm/s are wanted to be measured.

Several micropumps have been proposed as solution for lab-on a-chip devices that require flow velocities near 1 μm/s [9–11]. Flows at such velocity scale present high influence of Brownian motion for the typical particle size employed in micro-PIV or micro-PTV [5]. As an example, for 0.25 μm in diameter particles suspended in a 1 μm/s water flow at room temperature, recorded at 10 fps, the error produced by the Brownian motion is estimated to be of 627%, in accordance with Eq. (1). Even though such an error decreases with the inverse of the square root of the number of measurements taken, it increases with a higher recording frame rate, which can be necessary in order to keep an acceptable spatial resolution. In this context, an OTV system is an attractive method for microflow velocity measurements due to its capability to avoid the influence of the Brownian motion in the flow velocity measurements (even at low mass flow rates), its high spatial resolution and the possibility to avoid the use of high concentration of nanometric particles.

An OT is a potential with the capability to trap dielectric particles with diameters between 40 nm and 10 μm [12], approximately. The potential associated with optical trapping is created due to the forces induced by the change of momentum of the photons of a highly focused laser beam that reflect off, refract through and leave the particle. The refractive index of the particle must be larger than that of the medium to achieve the trapping. Theoretically, considering the beam propagation direction as axial direction: (a) the force exerted in the transverse direction is proportional to the light intensity gradient due to the beam's intensity radial distribution, while (b) the force in the axial direction is proportional to the intensity gradient due to the beam's focusing condition; the latter has an extra component due to the light scattered by the trapped particle [13,14] pushing the particle forward. If the trapping laser has a TEM_{00} mode, the intensity profile of the beam near the focal point will have a Gaussian shape in both axial and transverse directions [14], producing a conservative force that attempts to keep the particle located near that point.

If the gradient force is higher than the scattering force, then a stable tridimensional trapping region is created, where the forces due to the laser-particle interactions limit the movement of the particle (the movement caused by the Brownian motion or by any other external field). Such forces can be modeled like a spring with k_i stiffness constants [15] according to

$$F_{i_{OT}} = -k_i \Delta_i, \tag{2}$$

where $F_{i_{OT}}$, k_i and Δ_i are the force exerted over the particle by the OT, the OT stiffness constant and the displacement of the particle from the center of the trapping potential (point where the force exerted on the particle by the OT is zero) in the i direction, respectively.

There are several experimental methods to determine the OT stiffness, one of them is based on the equipartition theorem, described in the methodology section of this paper. Furthermore, although the random motion is still present in a trapped particle, for a large enough statistical data set, it can be considered that the average position of a trapped particle coincides with the center of the trapping potential because the particle follows Boltzmann statistics [15].

The drag force induced in the i direction by a flow around a sphere at low Reynolds numbers (typical situation in lab-on-a-chip devices) is described by Stokes law according to

$$F_{i_d} = 6\pi \eta a \beta u_i, \tag{3}$$

where η is the dynamic viscosity of the fluid, a is the radius of the particle, u_i is the flow velocity in the i direction and β is a correction factor of the drag coefficient due to the wall influence. Combining equations (2) and (3), (4) makes it possible to determine the velocity (magnitude and direction) of the flow at the location of a trapped particle.

$$u_i = \frac{k_i \Delta_i}{6\pi \eta a \beta}, \tag{4}$$

To do so, once a particle is trapped in a fluid, it is necessary to experimentally obtain the particle's average position before and after the flow is induced. Fig. 1 shows a schematic representation of a trapped particle (due to its interaction with a Gaussian distribution of light shown in green) in a trapping region without flow where Brownian motion is limited due to OT forces, and a particle in a region with flow in which the particle's position is shifted in the direction of the flow. The trapping region can be defined as the region where the trapped particle can be found, and thus depends on the ratio between the thermal energy (the higher the temperature the more intense the Brownian motion) and the energy associated with the trapping, which has an important laser power dependence. A key characteristic of the OTV technique is that, even with the trapped particle presenting Brownian motion, it can be considered that the shift in the average position of the particle caused by the flow drag is not influenced by such random motion, since it is calculated from a large enough number of statistical data.

Although the OTs have been mainly used in the biophysics field as a tool to manipulate, measure or exert forces in the pN range on diverse biological entities [16–18], these also have been employed to measure velocity [19–22], viscosity [23–25] or both [26] at the micro scale. Nevertheless, most of these studies use the optical tweezers to carry a particle to a point of interest where it is released in presence of flow, carrying out the velocity measurement by means of PTV [19–21]. In other cases, the particle has remained trapped during the velocimetry but the use of the OT stiffness has not been taken into account in the measurements [19]. Recently, the use of an OT and its stiffness constant to measure flow velocity by means of the Stokes law has been reported [22]; in that investigation, results obtained using the OT-based system were compared with a theoretical model. In this work we report the use of an OT-based system (OTV system) to measure flow velocity at different depths within a rectangular microchannel. The measurements carried out with the OTV system were compared with averages obtained by tracking of individual free particles (TA-PTV). The above with the purpose of validating the OTV system with another experimental technique.

2. Methodology

2.1. Experimental set up

Fig. 2a shows a schematic of the home-made OT system used to measure flow velocity. It employed a CW, 2 W max power, 532 nm wavelength laser TL (Opus532, Laser Quantum), attenuated by a factor of 10 using a neutral density filter (NF) that avoided the laser reflections to enter in the laser cavity, improving the laser stability. The telescope, composed by lenses L1 (f=25.4 mm) and L2 (f=125 mm), expanded the laser beam by a factor of 5 in order to improve the trapping efficiency [13]. The expanded beam was brought to a 100x oil immersion microscope objective MO1