10TH INTERNATIONAL SYMPOSIUM ON PARTICLE IMAGE VELOCIMETRY - PIV13
Delft, The Netherlands, July 1-3, 2013

3D APTV measurements on microbubble streaming

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ABSTRACT

Ultrasound-driven gas bubbles can be used as active actuators to create or modify the flow in microfluidic devices. Oscillating bubbles are able to create a steady streaming flow that can be used to perform several tasks in microfluidic devices. In this work, we focus on a specific configuration with a bubble located at a side wall of a microfluidic channel, for applications in size-sensitive sorting of microparticles. The flow in such configuration is often assumed to be two-dimensional, however 3D effects can be expected especially close to the top and bottom walls. In order to investigate the three-dimensional extension of the flow in such devices, we used the 3D Astigmatism Particle Tracking Velocimetry (APTV), to measure the trajectories and velocity of 2-μm-particles moving in the streaming flow. The primary aim of this investigation is to resolve the volumetric flow induced by a bubble with complex vibrational modes with 3D velocimetry methods, to characterize the three dimensional characteristics of the streaming flow.

1. Introduction

The manipulation of microparticles in microfluidic flows is an important task in very diverse fields such as biomedicine or chemical engineering. In order to enhance the control on these systems external forces must be applied on the particles. In this sense *Acoustofluidics*, i.e. the flow control and particle manipulation by using acoustic waves, is a powerful and approved approach with growing interest in the community [1]. Most of these methods require microfluidic chips with certain acoustic properties to maintain a stationary acoustic wave within the channel. This is however not possible with the commonly used Polydimethilsiloxane chips (PDMS-chips). The alternative that will be discussed in this paper will make use of the resonant oscillations of a microbubble through ultrasonic actuation.

The method has been already studied to modify and control flows by using microbubble streaming flows. For instance a single micrometric oscillating bubble was used by Marmottant and Hilgenfeldt [7] for controlled deformation and rupture of 10-100 μm lipid vesicles. These flows are excited by acoustic oscillations in the kHz frequency domain, introduced with an inexpensive piezoelectric transducer that is attached externally to the microdevice, and yields high flow speeds. When a bubble is driven by an ultrasonic wave, even one whose wavelength is much larger than the bubble radius, it absorbs the acoustic energy very efficiently and responds with an oscillatory movement of its interface that generates the streaming flow. This is true for weak acoustic amplitudes. The scenario changes

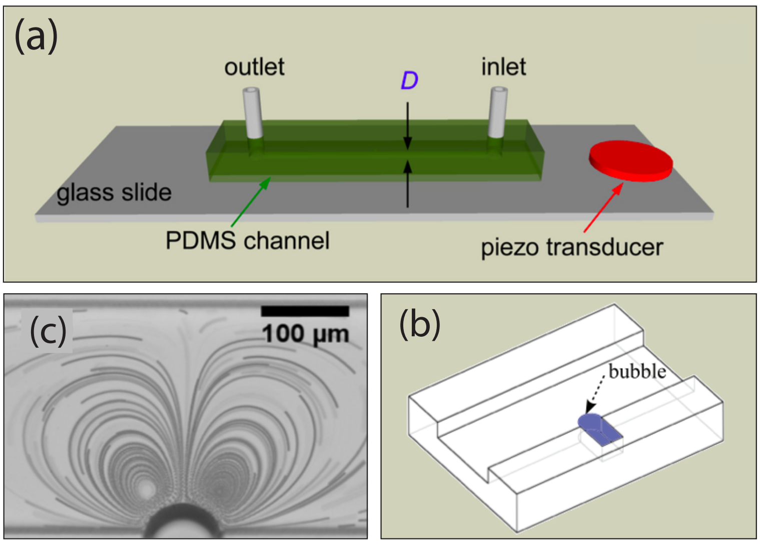

Figure 1: Microbubble streaming with a side bubble (image taken from [9]). (a) Schematic of microchannels with piezo transducer. (b) Detail of micro channel with microbubble trapped in a side blind channel. (c) Streak image of the streaming flow.

dramatically when the bubble is excited at much higher amplitudes, which might induce micro-cavitation (which might cause damage to the device) or even sonoluminiscence [5].

In this work, we focus on a specific configuration with a bubble located at the side of a microfluidic channel used by Wang *et al.* [9, 10] for size-sensitive sorting of microparticles. In this configuration, a blind side channel perpendicular to the main one is present, in which a gas pocket remains trapped when the microchannel is filled with water. The gas pocket forms a bubble with semi-cylindrical shape (see figure 1.a) that is driven by an ultrasonic acoustic field. As a first approximation, the flow generated by the semi-cylindrical bubble can be considered two-dimensional with streamlines as shown in figure 1.b-c.

However, the actual shape of the bubble surface is not exactly semi-cylindrical but deformations result in more complex vibrational modes leading to an actual three dimensional streaming flow. The aim of this work is to use 3D velocimetry methods to resolve the volumetric flow around the bubble in order to characterize the three dimensional extension of the streaming flow. In particular, the Astigmatism Particle Tracking Velocimetry (APTV) [4] method was used to estimate the three-dimensional trajectories and velocity of tracer particles in bubble streaming flow.

2. Experimental setup and APTV analysis

The set up consisted in a rectangular microchannel, with a nominal height of 100 μm and width of 1000 μm, featuring a side pit of 80 μm width. The microchannel was made out of PDMS using a conventional soft lithography method. The experimental measurement of the channel height from stuck particles on the top and bottom wall yielded an actual height of 80 μm. This can be explained from manufacturing uncertainties or relaxation of the PDMS. The channel was filled with water with air bubbles trapped in the pits as described in the previous section. The bubble was actuated with a piezoelectric transducer at a frequency of 81 kHz. Fluorescent polystyrene microparticles of 2 μm-diameter were continuously illuminated with a diode-pumped green laser and and observed through an inverted epi-fluorescent microscope at a 20x magnification. The image acquisition was performed using a Phantom v12 CMOS high-speed camera in order to fully resolve the high dynamic range of the particle velocities. For the present experiment, a recording rate of 200 frames per second was sufficient to resolve velocities ranging from 0 to 10 mm/s. A cylindrical lens with focal length of 150 mm was used for the astigmatic imaging [3].

The astigmatic images of the tracer particles in the flow were used to extract the three-dimensional trajectories and velocities following the method described in [3]. Briefly, the out-of-plane position (Z) of a particle is determined from a calibration curve relating the principal axes of its astigmatic elliptical image to the corresponding Z position. The in-plane position (X and Y) is simply derived by locating the particle image center. For the present evaluation, the position and shape of the elliptical particle images were obtained using a wavelet based algorithm. The astigmatic optical arrangement applied here yields a total measurement depth of approximately 120 μm. The random error in the in-plane direction was estimated from stuck particles scanned through the whole measurement depth and it corresponded to ± 0.13 μm (0.13 pixels) and ± 0.19 μm (0.15 pixels) in the X and Y direction respectively. It must be noted that while the estimated error in pixel units is similar, the corresponding error in real units is different since the magnification in the X and Y direction is not equal due to the cylindrical lens. The random error in the out-of-plane direction was estimated from the euclidian distance of the measured principal axes to the calibration curve as described in [3]. The estimated random error for the complete set of measurement was ± 1 μm on average with a maximum error of 3 μm. The velocities were calculated using the 4-frame approach described by [2].

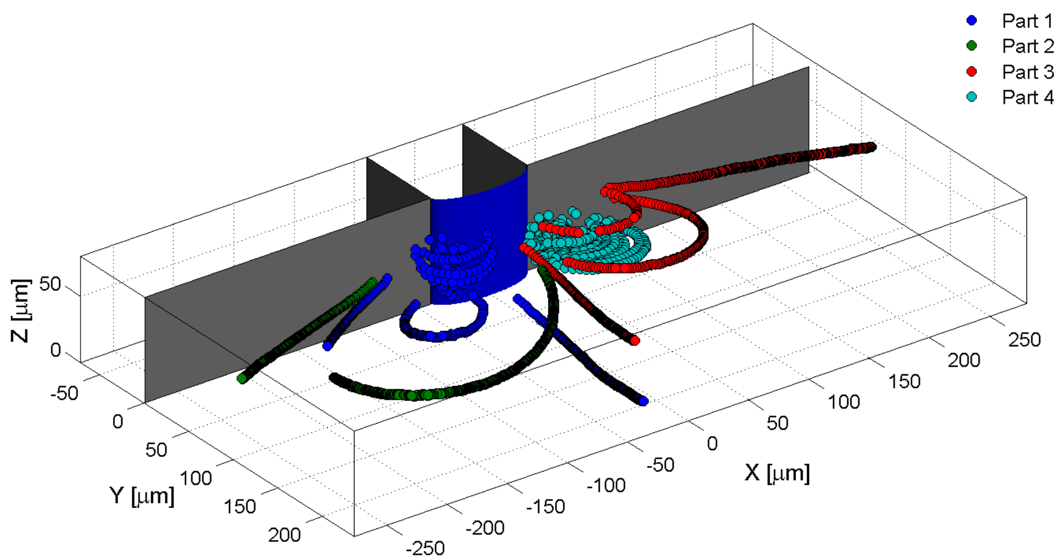

Figure 2: Volumetric particle trajectories in microbubble streaming flow measured with APTV.

3. Results

A result of the reconstructed 3D particle trajectories taken with APTV is shown in figure 2. The side wall is represented by the gray surface on the right with the side pit in the center containing the air bubble (represented in blue, not-to-scale). Particles get attracted from the sides of the bubble and, depending on the streamline on which they travel, they will either get trapped in a loop (particles 1 and 4 in figure 2) or expelled along the frontal line of the bubble (particles 2 and 3). It is interesting to note that those particles that are at a safe distance from the bubble present basically flat trajectories. Only those particles that enter in contact with the oscillating bubble change their Z-position, probably due to effects caused by the 3D deformed bubble surface. It can be also observed that many particles enter the bubble vicinity at a certain Z-coordinate but are expelled at a different one, regardless of their initial out-of-plane position.

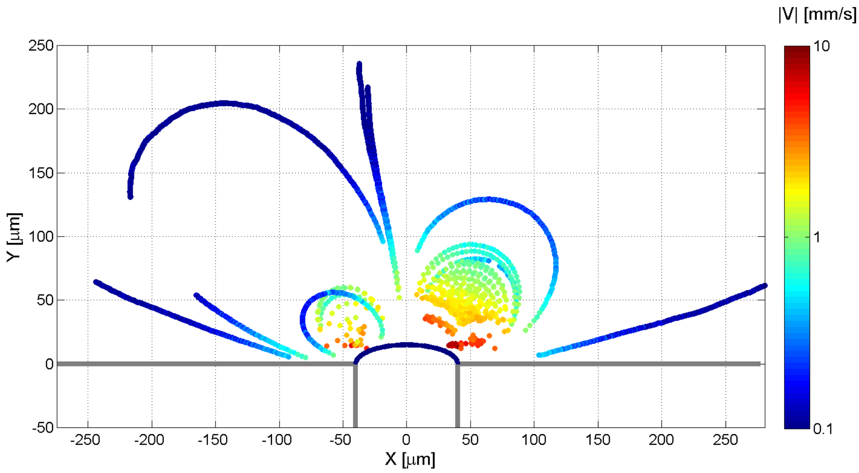

Figure 3: Particle trajectories in microbubble streaming flow measured with APTV. Note that the bubble surface line (blue line) is only approximated. Colorbar in logarithmic scale.

One critical aspect of these measurements is the high dynamic range of the streaming velocity, which is low at the far field loops and extremely fast close to bubble interface. Such characteristic high velocity gradients are interesting to induce deformation and breakup of vesicles of biological interest [6]. The effect can be observed in more detail in figure 3, in which the particle velocities vary by at least two orders of magnitude in the same orbit around the bubble. Another important feature worth to mention in figure 3 is related to the difficulty of tracking particles close to the wall or the bubble interface as a consequence of distortions due to reflection or shading effects. This is shown in figure 4, where a particle traveling close to the wall changes its shape spontaneously not due to a change in its Z-position but due to reflections/shading. Due to this, it was not possible to measure particles closer than 5 μm to the side channel walls. It can be also noted in figure 4 that the shape of the defocused images is not simply elliptical but presents some additional structures (due to other optical aberrations). However this effect does not play a significant role since it is very reproducible and it is accounted by the shape detection algorithm.

The large velocity gradients in the vicinity of the bubble can be observed more explicitly in figure 5A, where the particle velocity modulus is plotted against the particle distance to the bubble center. The velocity of a particle of radius a scales with the distance to the bubble R as $u_p \sim \left(\frac{a}{R}\right)^2$ [8] which is in good agreement with the results shown in figure 5. Most of the particle trajectories are two-dimensional, but this is not entirely true in the vicinity of the bubble as can be observed in figure 5B, where we can see how those

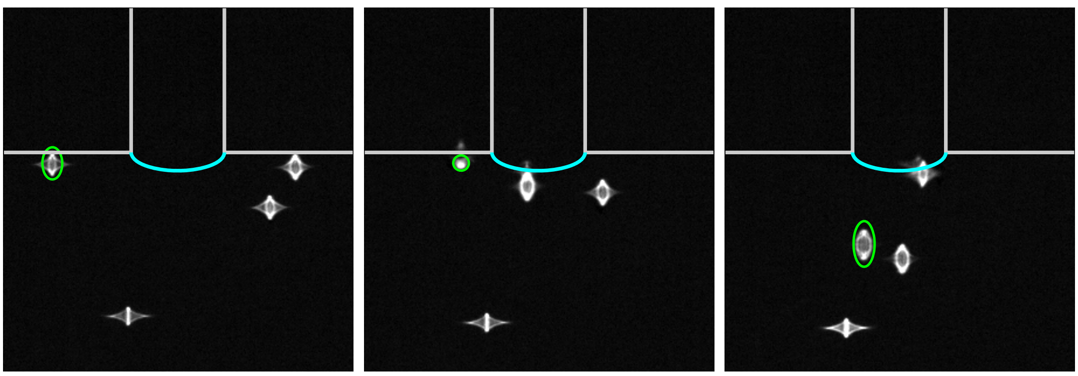

Figure 4: The images of particles close to the wall or to the bubble interface present distortion due to reflections or shading effects and cannot be used for the APTV evaluation. Note that the particle images appear much larger than their actual size due to the astigmatic imaging.

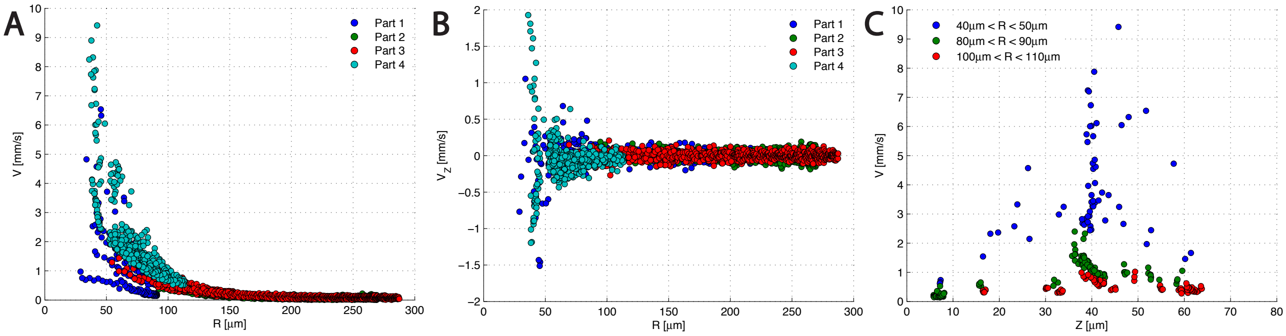

Figure 5: A) Particle velocity modulus plotted against the distance to the center of the semicircular bubble surface, which clearly shows the strong velocity gradients present in the vicinity of the bubble. B) Particle velocity modulus at different heights, the results clearly show the dragging effect of the walls on the particle velocities, which is crucial also for the orbit shapes. C) Particle velocity component parallel to the optical axis

particles orbiting close to the bubble are eventually pushed either up or down and then remain in that position as they travel away. This might be caused by non-axisymmetric disturbances in the bubble oscillations, probably caused by the particles themselves. On the other hand, the fact that the particles follow basically two-dimensional trajectories does not mean that their Z-position is irrelevant: in figure 5C we can observe the dependence of the velocity distribution depending on the particle Z-position. The maximum velocity is found in the central plane of the channel, while the non-slip condition at the channel top and bottom walls decrease the particle velocity substantially as they separate from the central plane.

4. Conclusions

The APTV method was used to measure the three-dimensional trajectories and velocities of tracer particles in a microbubble-streaming flow. The configuration of the bubble-streaming device was a rectangular microchannel and a cylindrical bubble on a lateral pit, used for instance for size-sensitive sorting of microparticles. The principal aim was to investigate the three-dimensional extension of this type of flow. The experiments reveal the three-dimensional features of the flow in proximity of the bubble ($< 80\ \mu$m), whereas outside of this region the flow can be considered two-dimensional. However, even far from the bubble, the velocities and velocity gradients present an important dependence on the Z coordinate. An interesting effect is that particles are attracted/expelled from the bubble substantially with a two-dimensional motion, but their initial and final height will change due to the three-dimensional flow in proximity of the bubble.

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