Strong DC and low-frequency AC fields for the manipulation of particles and fluids in microfluidics

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ABSTRACT

We present a technique for measuring simultaneously the fluid and the particle velocity under strong DC and low-frequency AC electric fields in a microchanel filled with an aqueous suspension. We also report observations of a reversible aggregation of particles that can be tuned by varying the field strength and frequency of an applied AC field.

Keywords: Electrokinetic fluid pumping, free solution electrophoresis, field-induced particle manipulation

When a DC or low-frequency AC electric field is applied to a channel filled with an aqueous liquid, it generates a bulk fluid flow, referred to as *electroosmosis*, while the motion of any particles dispersed in the liquid is referred to as *electrophoresis*. These phenomena are used in a wide variety of basic colloid and separation science applications. Currently they are also being considered as the main means for transporting aqueous liquids and dispersed particles in microfluidic devices because electric field based techniques do not require any moving parts and therefore can be incorporated more favorably into micro-analytical systems [1, 2]. In contrast to traditional applications, involving relatively low fields and highly viscous media in millimeter-sized capillaries, the use of micron-sized channels enables one to employ strong fields (up to ~kV/cm) and use fluids of low viscosity since undesirable electroconvection and Joule heating are suppressed in such tiny channels. The quantification of the motion of fluids and suspended particles in microchannels under these conditions is critical for the design and operation of electrokinetic microfluidic devices.

The experiments were conducted in the experimental setup shown schematically in **Fig. 1**. The working principle involves the transport of an aqueous suspension by applying a voltage difference across the two ends of a fluid-filled microchannel joining two reservoirs (**Fig. 1**). The downstream reservoir, connected to the ground electrode, is further connected to a microsyringe collection device via a needle as shown in Fig 1. The plunger of the downstream reservoir is pushed forward just far enough for a meniscus to be observed inside the microsyringe. The whole assembly is attached onto a stage and is kept horizontal to eliminate gravitational effects. An applied DC field causes both the fluid and the particles to move inside the channel toward the grounded electrode. The fluid motion is measured by recording the displacement of the meniscus in the microsyringe using a digital camcorder. The "apparent" particle motion (i.e., its motion due to electrophoresis plus the action of the electroosmotic bulk flow) is recorded using a high-speed camera (Kodak Motion Analyzer, SR-Series) connected to the microscope. The slope of the fluid volume collected in the microsyringe as a function of time gives the electroosmotic flow rate of the fluid. The electrophoretic particle velocity is then computed by subtracting the electroosmotic fluid velocity from the apparent particle velocity.

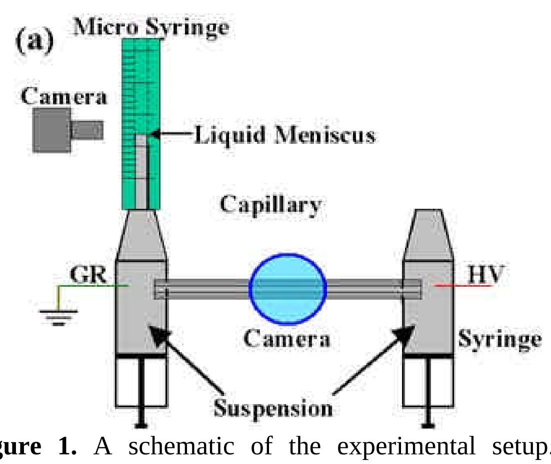

Figure 1. A schematic of the experimental setup. A microchannel bridges the gap between the two reservoirs and is made of a 6cm long capillary with ID= $50\mu m$. The suspension consists of carboxylated polystyrene particles (mean particle diameter $4.13\mu m$) suspended in DI water (pH~6.0).

Typical data for the fluid volume collected at the downstream end and of the apparent particle velocity in a DC field are presented in Figure 2. These data clearly show a constant flow rate of the fluid and a narrow particle velocity distribution.

Experiments were also conducted in strong AC electric fields by varying the root mean square (rms) field strength (from 100 to 600V/cm) as well as the frequency (from 5 Hz to 50Hz). Under these conditions, no net fluid motion was observed while, as expected, the particles underwent an oscillatory motion about their mean position along the field direction. Their oscillatory amplitude was recorded using a Kodak Motion Analyzer at 250 frames per second (FPS) connected to the microscope. Typical data showing the effect of varying the frequency for a given applied field strength are presented in Figure 3. The AC field experiments reveal that the particle oscillatory amplitude is directly proportional to the applied field strength and inversely proportional to the field frequency. The proportionality factor between the amplitude and the field strength divided by its frequency yields the apparent particle mobility whose magnitude is found to be close to that in DC fields. In this regard, our experiments extend the quasistatic approximation for AC fields used in the literature into the range of strong field strengths. We also observed a reversible aggregation of particles upon changing the frequency from 100 Hz to 3kHz. Specifically, for a field strength of ~100V/cm (rms) at 100Hz, several particles came together and formed chains aligned along the field direction. An increase in the frequency to 3kHz caused the chains to disintegrate, while when the frequency was decreased back to 100Hz, the chains were observed to reform as shown in Figure 4. We believe that, as is the case with other field-driven aggregation phenomena [3, 4], this reversible particle chaining could be used as an effective method for the control and manipulation of particles in microdevices.

In conclusion, we presented a method for measuring simultaneously the fluid and particle velocities under strong DC fields and also provided a means for measuring the particle apparent velocity under AC electric fields. This technique could be utilized in a wide variety of applications involving free-solution electrophoresis (i.e., without using a viscous polymer solution as a sieving matrix). We also reported observations of reversible chaining of particles along the channel in strong AC fields that can be tuned by varying the field frequency. Our study would benefit the design of upcoming microdevices where a controlled fluid pumping is desired.

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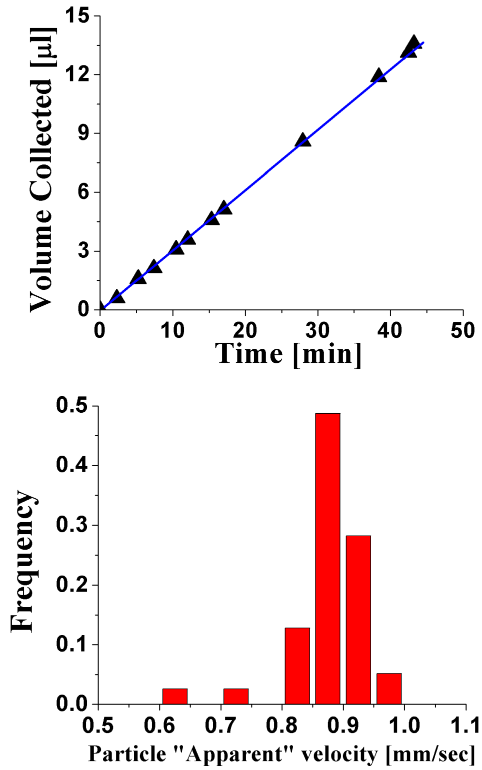

Figure 2. Data on (a) the fluid volume collected at the downstream end and (b) the apparent particle velocity for an applied DC field strength of 570V/cm across a 6cm long capillary. The particle velocity histogram is obtained by measuring the time required for each particle to cover a 1.1mm length of the microchannel (ID=50 µm) along the observation window viewed under the microscope. The fluid flow rate was ~0.34 l/min.

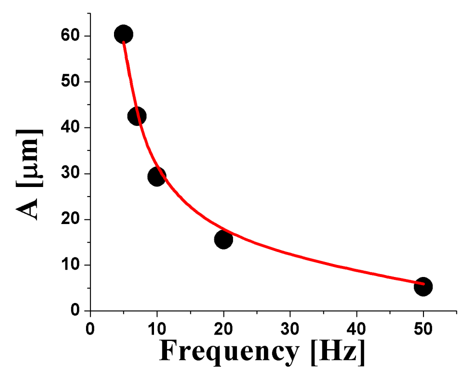

Figure 3. Plot showing the experimental data (symbols) and a curve fit (A [m]=293/frequency [Hz]) obtained by measuring the oscillatory amplitude of particles subjected to a sinusoidal AC electric field of strength 570V/cm (rms). The data are averaged over three measurements.

Figure 4. The reversible aggregation and de-aggregation of particles by varying the field frequency from 100 Hz (a) to 3 kHz (b-d) and to 100 Hz (e); all at a fixed amplitude of the field strength. The particle volume fraction 1/4000 (v/v). Insets present magnified images

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