Zeta Potential Measurement of Nanoparticles by Nanoparticle Tracking Analysis (NTA)

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ABSTRACT

A new technique for the automated, particle-by-particle zeta potential analysis of nanoparticles is described. The Nanoparticle Tracking Analysis (NTA) technique visualizes then sizes individual nanoparticles, based on their Brownian motion. Unlike classical light scattering techniques, NTA allows nanoparticles to be sized on a particle-by-particle basis. This results in a higher resolution and therefore a better understanding of polydispersity than ensemble methods and it also yields directly a measurement of count and concentration. This paper introduces an extension of the technique in combination with an electrophoresis system to provide measurement of zeta potential on a particle-by-particle basis.

This may be viewed as a development of traditional microelectrophoresis, with full automation of the particle tracking and electrophoretic mobility measurements and extended to particles as small as 10nm, depending on material type.

Keywords: zeta potential, surface charge, aggregate, nanoparticle, sizing.

1 INTRODUCTION

The zeta potential of a system is a measure of charge stability and controls all particle-particle interactions within a suspension. Understanding zeta potential is of critical importance in controlling dispersion and determining the stability of a nanoparticle suspension, i.e. to what degree aggregation will occur over time. The zeta potential is the measure of the electric potential at the slip plane between the bound layer of diluent molecules surrounding the particle, and the bulk solution. This can be closely linked to the particle's surface charge in simple systems but is also heavily dependent on the properties of the diluent solution. A higher level of zeta potential results in greater electro-static repulsion between the particles, minimizing aggregation or flocculation.

Samples with zeta potentials of between -30mV and +30mV typically tend to aggregate, although the precise stability threshold will vary according to particle type. Determining the stability of a sample, either to minimize aggregation for drug delivery and pharmaceutical applications (high zeta potential), or to facilitate the removal of particles too small to filter out for water treatment applications (low zeta potential) is of great importance in nanoparticle research.

A new method of microscopically visualizing individual nanoparticles in a suspension, called Nanoparticle Tracking Analysis (NTA), allows their position and Brownian motion to be analyzed and from which the particle size distribution profile (and changes therein in time) can be obtained on a particle-by-particle basis [1-3]. The technique offers significant advantages over traditional light scattering techniques (such as DLS- and SLS-based systems) for the characterization of polydispersed populations of nano-scale particles. Independent of particle density or refractive index, NTA dynamically tracks individual particles within the range of 10 - 1,000nm and provides size distributions along with a real-time view of the nanoparticles being measured.

With an electrophoresis system to apply an electrical current to the sample suspension, the charged particles move under the influence of the field. The rate of the movement is tracked and quantified in the same way as Brownian motion. From this result, the zeta potential can be calculated on a particle by particle basis. This is named Zeta Potential Nanoparticle Tracking Analysis (Z-NTA).

2 MEASUREMENT METHODOLOGY

A small (250µl) sample of liquid containing particles at a concentration in the range 10^6-10^{10} particles/ml is introduced into the scattering cell through which a finely focused laser beam (approximately 40mW) is passed. Particles within the path of the beam are observed via a microscope-based system (NanoSight NS500) onto which is fitted a CCD camera.

The motion of the particles in the field of view (approximately 100 x100 µm) is recorded (at 30 frames per second) and the subsequent video analyzed. Each and every particle visible in the image is individually but simultaneously tracked from frame to frame and the average mean square displacement determined by the analytical program. From this can be obtained the particle's diffusion coefficient. Results are displayed as a sphere-equivalent, hydrodynamic diameter particle distribution profile. The only information required to be input is the temperature of the liquid under analysis and the viscosity (at that temperature) of the solvent in which the nanoparticles are suspended. Otherwise the technique is one

of the few analytical techniques which is absolute and therefore requires no calibration. Results can be obtained in typically 30-90 seconds and displayed in a variety of formats.

2.1 MEASURING ZETA POTENTIAL

The Z-NTA technique allows the zeta potential of nanoparticles in aqueous suspension to be measured on a particle-by-particle-basis. The customized zeta potential sample chamber is fitted with platinum electrodes, which allow a variable electric field to be applied to a sample of nanoparticles suspended in aqueous solution.

The electric field causes motion of both the sample particles, (electro-phoresis), and the aqueous diluent, (electro-osmosis). The Z-NTA technique records the apparent drift velocity for each tracked particle, which will be a superposition of these two motions. By observing the total velocity at different depths within the sample chamber, it is possible to separate these components and obtain a measurement of the electrophoretic velocity (due to the force impinged directly on the particles), and hence the zeta potential of the particles.

2.2 CORRECTING FOR ELECTRO-OSMOSIS

With the application of an electric field near to the glass sample chamber surfaces, electro-osmosis will contribute to the apparent particle velocities observed by the Z-NTA technique, and must be corrected for. Glass has an inherent negative surface charge, which for a polar liquid like water, causes a charge imbalance of diluent molecules near the glass boundary. Viscous forces carry the resulting fluid flow through the chamber, causing a parabolic flow profile for a closed system, as shown in Figure 1.

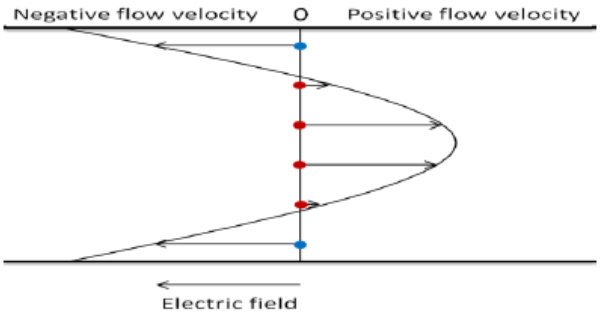

Figure 1. Electro-osmotic velocity profile for water in a closed sample chamber under the influence of an applied electric field

In a closed system the electro-osmotic velocity component will always have an overall value of zero when summed over the entire channel depth. Any offset which causes the total measured velocity profile to not sum to zero represents the average electrophoretic velocity of all particles tracked.

By tracking particles at depths throughout the channel and subtracting this offset it is possible to obtain a measurement of the electro-osmotic profile of the diluent within the channel, as shown in Figure 2.

The electro-osmotic contribution to the total observed velocity can then be found for any of 6 channel depths at which particles are tracked, and removed from the total observed drift velocity. This electro-osmotic profile is measured for each experimental run, providing data sets which automatically account for the electro-osmotic effect, without the need to assume that the diluent flow profile or the chamber surface chemistry remains constant.

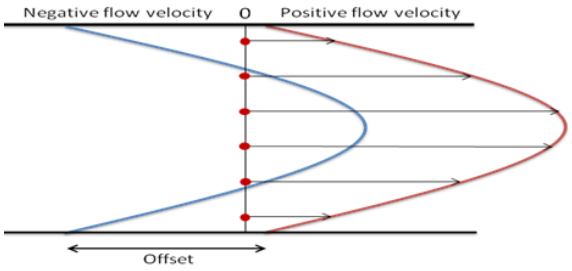

Figure 2. Total velocity profile measured using NTA (red) and electro-osmotic velocity profile (blue) inferred by subtraction of a contact offset to obtain a velocity profile that sums to zero over the channel depth

2.3 CORRECTING FOR THERMAL EFFECTS

As well as electro-osmotic motion, any other effect which causes particles tracked by Z-NTA to move must be accounted for and removed in order to obtain a measurement of the true electrophoretic particle velocity. Thermal effects due to laser heating or joule heating from the electric current passing through the sample between the electrodes can cause convection flows in the diluent. By reversing the voltage polarity, any velocity component which is not dependent on the electric field direction can be characterized. For each capture position, particles are tracked under positive and negative polarity electric field, and any bias is removed from the raw data.

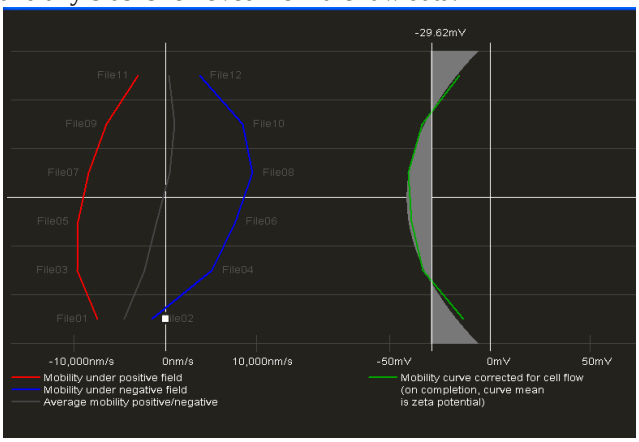

Figure 3. Velocity profile for a filled sample chamber displaying significant convection flow.

Figure 3 shows the velocity profile in sample chamber where particles have become attached to the bottom glass surface. This causes increased heating near the interface where the laser enters the sample, resulting in a convection flow. Using the voltage reversal technique, this flow can be subtracted from the measured flow profile (shown in red and blue for positive and negative field polarity respectively) to give a corrected flow profile (shown in yellow).

4 CALCULATING ZETA POTENTIAL

Once the velocity components due to electro-osmosis and thermal convection have been removed, the corrected drift velocities, calculated on a particle-by-particle basis, then provide a measure of the electrophoretic velocity of each particle in the sample.

The electric field strength (E) within the flow cell is determined using the Voltage (V) applied through the sample by the electrodes, and the distance between the electrode surfaces (d). The particle velocities can then be converted into electrophoretic mobilities (velocity divided by electric field strength).

$$E = \frac{V}{d} \qquad (1)$$

By application of the Henry equation using the Smoluchowski approximation (appropriate for aqueous diluent media with moderate electrolyte concentration) the zeta potential (ZP) for each particle can be calculated:

$$ZP = \frac{\mu \eta}{\varepsilon_0 \varepsilon_r} \qquad (2)$$

where μ is the electrophoretic mobility of the particle, ε0 is the permittivity of free space, εr is the relative sample solution permittivity and η is the sample solution viscosity.

5 POLYSTYRENE MEASUREMENT EXAMPLE

The ZetaSight technique was used to analyze NIST 100nm polystyrene size standards from Duke Scientific, diluted in deionized water to a concentration of 4 x 10^8 particles/ml. The measured zeta potential distribution is shown in Figure 6, with a modal peak at a value of –48mV.

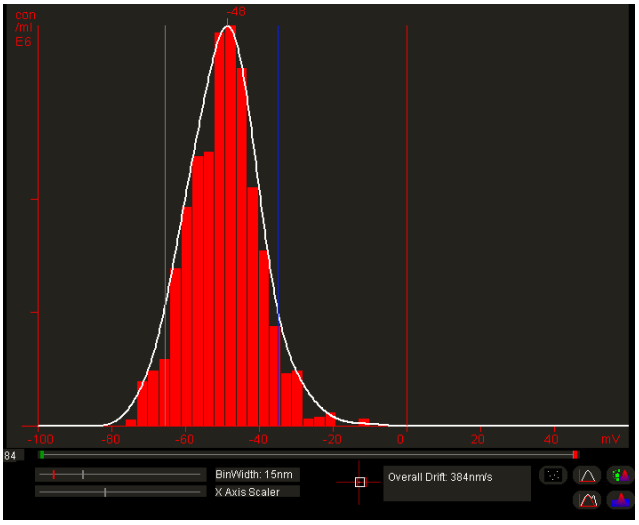

Figure 4. Zeta potential distribution for 100nm polystyrene microspheres diluted in deionized water shows number concentration as a function of zeta potential.

The distribution shows a spread in the zeta potential, with most particles lying within the range from –35mV to –65mV. This confirms the high stability of polystyrene particle standards when diluted in clean deionized water. The particle size is measured simultaneously. The measured Brownian motion is corrected for any net drift velocity, so that the calculated size is reported correctly at 100nm, even when the particles are also moving under the influence of an electric field.

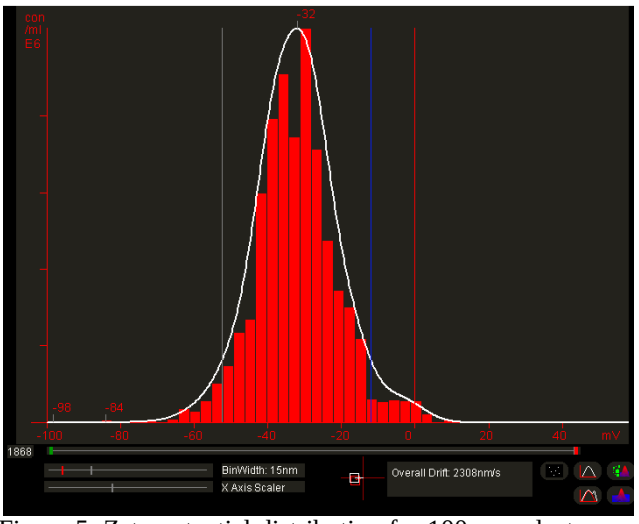

Figure 5. Zeta potential distribution for 100nm polystyrene microspheres diluted in laboratory tap water, showing the shift in zeta potential compared with Figure 4.

The same analysis run on 100nm polystyrene diluted to the same concentration in laboratory tap water shows a peak in the distribution at a much lower zeta potential. This demonstrates how the zeta potential of a sample is heavily dependent on the diluent used, as well as the properties of the solid particles.

The results displayed in Figure 5 show that polystyrene standards diluted in tap water are near the limit of stability in terms of the zeta potential, with a modal peak in the distribution at –32mV.The distribution indicates significant numbers of particles with a zeta potential between –30mV and +30mV. These particles will have a tendency to aggregate over time. Contaminating aggregates are seen in standards diluted in tap water over a period of several days, which is in agreement with these results.

6 SIMULTANEOUS MEASUREMENT OF SIZE, ZETA POTENTIAL AND SCATTERING INTENSITY

The Z-NTA technique allows the simultaneous measurement of size, zeta potential and light scattering intensity for individual nanoparticles in solution. This allows particle populations to be separated in terms of any one of these parameters, and for the relationship between parameters, for example the dependence of zeta potential on particle size, to be studied.

Figure 6 shows 2-dimensional slices from a 3-dimensional plot, taken from the NanoSight Z-NTA software display, that demonstrates the analysis of two separate particle populations. Results for the 100nm NIST polystyrene size standard in tap water are shown in blue. The white scatter points are for the zeta potential transfer standard (DTS1230), with a size of approximately 300nm.

The top panel shows the relationship between light scattering intensity and size, the bottom panel shows the plot rotated to display the relationship between zeta potential and size.

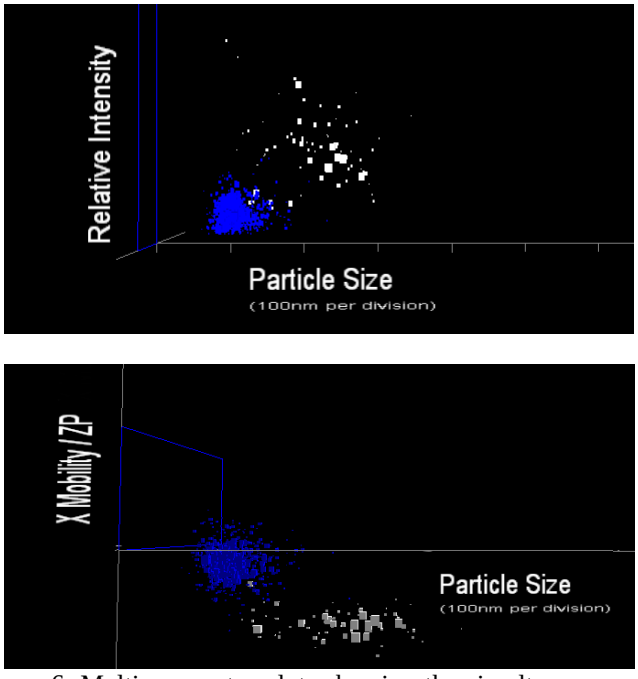

Figure 6. Multi-parameter plots showing the simultaneous measurement of light scattering intensity, size and zeta potential for two analyzed samples

7 CONCLUSION

The Zeta Potential Nanoparticle Tracking Analysis (Z-NTA) technique is a robust and direct method for multi-parameter characterization of nanoparticle systems. The technique uniquely allows the user a simple and direct qualitative view of the sample under analysis (perhaps to validate data obtained from other techniques) and from which a quantitative measure of sample size, size distribution, zeta potential and concentration can be immediately obtained [4-6].

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