



Sedimentation behavior of poly(methyl methacrylate) spheres in water upon application of a DC vertical electric field of the order of a few V/mm

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ARTICLE INFO

Article history:

Received 11 May 2017

Received in revised form 17 July 2017

Accepted 20 July 2017

Available online 25 July 2017

Keywords:

Electrically induced rapid separation

Vertical electric field

Horizontal electric field

Electrical double layer

Transmitted-light intensity

ABSTRACT

Recently, our group discovered the phenomenon that the sedimentation velocity of colloidal particles in water increased drastically when a *horizontal* electric field of the order of a few V/mmDC was applied. The authors call this the electrically induced rapid separation (ERS) effect. Regarding the mechanism, it is highly plausible that the particles gather each other in the horizontal electric field. In this study, the sedimentation velocity of poly(methyl methacrylate) (PMMA) spheres in water under a *vertical* electric field of the order of a few V/mmDC was investigated via transmitted-light intensity measurement. When an upward electric field was applied, the sedimentation velocities of the spheres, whose zeta potential was negative, increased due to the electrophoretic migration toward the cell bottom. When a downward electric field was applied, the sedimentation of PMMA spheres was not observed for a prolonged time, and eventually some of the spheres adhered to the upper positive electrode, and the other spheres settled out in the bottom negative electrode. As a result, in the *vertical* electric field, rapid sedimentation by forming an aggregation of PMMA spheres has not been observed. These results indicate that the electrical double layers around the spheres play a crucial role in the ERS effect. It is clear that the direction of an electric field plays a crucial role in the ERS effect.

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1. Introduction

An elimination of colloidal particles in muddy water is substantially important for environment protection. In water, an electrical double layer formed around the particles, which prevents the particles from aggregating. In order to separate the particles from the water, an aggregation treatment and subsequent filtering are generally required. To aggregate the particles in water without an aggregating agent, we have proposed a novel method to induce rapid sedimentation of colloidal particles by the application of an electric field of the order of a few V/mm [2]. The authors call this the electrically induced rapid separation (ERS) effect. In the previous study, it was discovered that the sedimentation velocity of colloidal particle (poly(methyl methacrylate) (PMMA) spheres and montmorillonite (Mt) particles) in water increased drastically upon applying an electric field of the order of a few V/mmDC. These particles showed up to several hundred times the sedimentation velocity, at least in the case that the volume fraction of particles was 0.0001–0.001, and the electric field strength was less than or equal to 1.0 V/mmDC. The mechanism of the phenomenon can be considered to concern the aggregation due to a deformation of the electrical double layers. If the particles gather with each other, the floc would have a large difference in density from water, which leads to the rapid sedimentation.

Sakai et al. [4] observed that polystyrene particles (5 μm in diameter) in water formed a chain-like structure parallel to an AC electric field (7.5 V/mm in effective electric field strength, 100 Hz to 2 MHz) between two plate electrodes. Furthermore, Trau et al. [5] reported that colloidal silica and polystyrene particles in water move toward one another across the surface of a positive electrode when an electric field of 2.5–7.5 V/mmDC was applied. Similar behaviors were also reported by other researchers [1,3]. In an insulating liquid, the formation of chain-like structures or flocs of particles under an electric field was frequently observed [6]. In general, the particles formed particulate flocs at a lower electric field strength and chain-like structures at a higher electric field strength. Thus the formation of flocs or chain-like structures of particles was often observed when an electric field was applied to various suspensions.

In this study, we investigated the sedimentation velocity under a vertical DC electric field in order to clarify a more detailed mechanism of the electrically induced rapid sedimentation of colloidal particles in water.

2. Experimental

2.1. Sample

Monodisperse poly(methyl methacrylate) (PMMA) spheres were purchased from Sekisui Plastics Co., Ltd. The diameter and the density are $5.0 \pm 0.2 \mu\text{m}$ and 1.2, respectively. The monodispersity of PMMA

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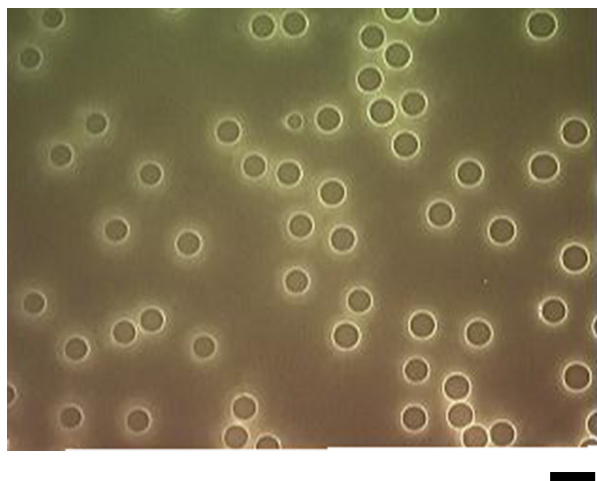


Fig. 1. Microscopic photograph of poly(methyl methacrylate) (PMMA) spheres in water. The length of the bar is 10 μm .

spheres was high, as shown in Fig. 1 by using an inverted reflected-light microscope (Axiovert 25 CA, Carl Zeiss, Inc.). The PMMA spheres were carefully dispersed into purified water whose density is 1.0 (Milli-Q Advantage A10, Millipore Co.) using a magnetic stirrer, with the coexistence of ion-exchange resins (AG501-X8 (D), 20–50 mesh, Bio-Rad Laboratories, Inc.). A treatment of exhaustive deionization has been carried out for more than 10 years. It should be noted here that the long-term preparation condition is not essential for observing the phenomenon presented in this study; it was carried out in order to simplify the system and clarify the importance of the electrical double layers. The zeta potential of the PMMA sphere was -40 mV, which was measured using an electrophoretic spectrophotometer (ELS-8000, Otsuka Electronics Co., Ltd.). The volume fraction of the PMMA sphere, ϕ , of sample suspension was prepared to be 0.0005.

2.2. Measurement of sedimentation velocity of PMMA spheres

A rectangular quartz cell (inner size: 10 mm $\times$ 10 mm $\times$ 45 mm) was used for the measurement of transmitted-light intensity. As electrodes, thin platinum plates were set parallel to each other inside the cell wall. The gap of the electrodes was 9.8 mm. After the observation cell was filled with the sample suspension, it was covered with a Parafilm sheet (Bemis Company, Inc.) in order to prevent spilling when the cell was laid down. The laser beam, 632.8 nm in wavelength and 0.5 mm in beam diameter, entered perpendicular to the cell wall (Fig. 2). The observation points are 2.0 mm and 4.0 mm in depth from top of the suspension. The sedimentation velocity was calculated from the rate of movement of the boundary between the water phase and the opaque colloid-rich phase obtained by the time dependence of transmitted-light intensity at different observation depths. In this measuring

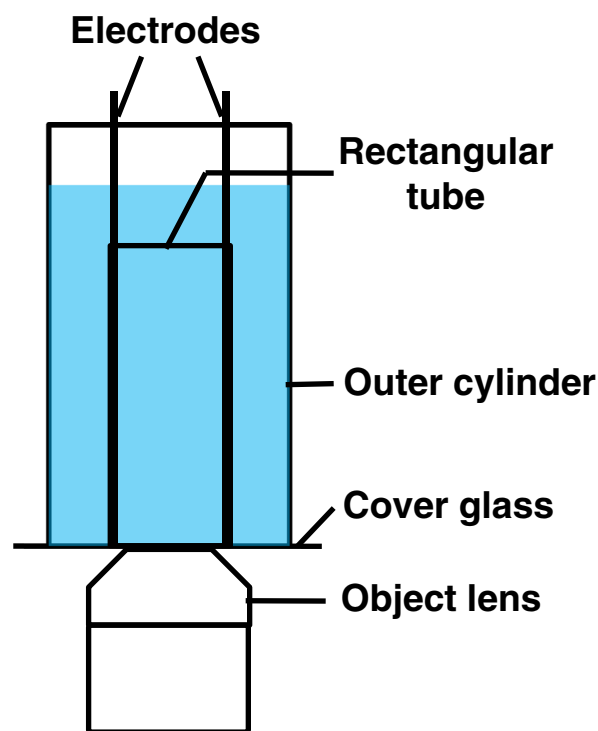


Fig. 3. Scheme of a cell for measuring electrophoresis migration under a horizontal DC electric field.

condition, the settling velocity without an electric field can be considered to have reached a terminal velocity at once. The sedimentation velocity was calculated from the difference of elapsed times as the transmittance reached 50% at the observation depth between 2.0 mm and 4.0 mm. A DC electric field was applied to the sample suspension using a synthesized function generator (FG110, Yokogawa Meters & Instruments Corp.). The electric field strength, E , ranged from 0.10 to 1.0 V/mmDC. All measurements were made at 25 $^{\circ}\text{C}$.

2.3. Measurement of electrophoretic migration of PMMA spheres

First, an outer cell was made using a glass tube (20 mm in diameter, 60 mm in height) that had a cover glass at one end. Next, a rectangular plastic cell (inner size: 10 mm $\times$ 10 mm $\times$ 45 mm) was prepared, and the cell bottom was cut off, creating a rectangular tube. The electrodes were set the same as mentioned in the previous section. The gap between the electrodes was 9.8 mm. The prepared PMMA suspension ($\phi = 0.0005$) was first introduced into the outer cell, and then the modified rectangular tube, in which the electrodes were set, was put on the cover glass at the bottom of the outer cell (Fig. 3). The

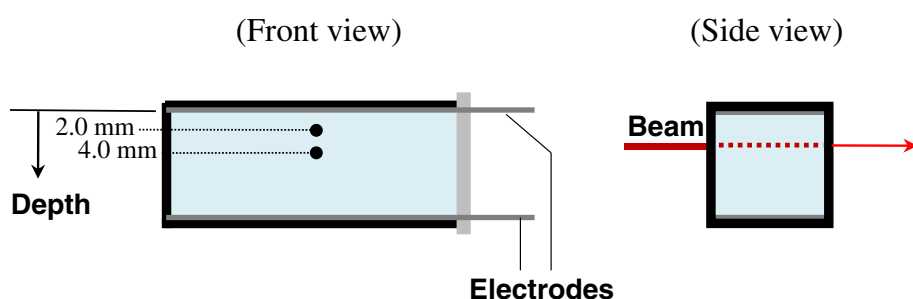


Fig. 2. Scheme of a cell for measuring transmitted-light intensity under a vertical DC electric field.

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