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In situ observation of colloidal particle behavior between two planar surfaces

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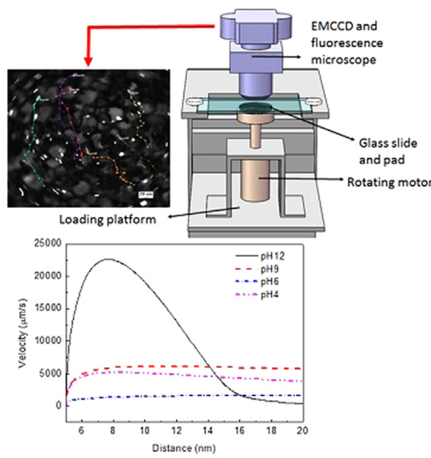
HIGHLIGHTS

- A in situ fluorescence observation system was developed.
- Colloidal particles motion between two planar surfaces was observed.
- The velocity of colloidal particles in alkaline slurry is anomalously high.
- A model describing the particle motion was built to explain the phenomenon.

GRAPHICAL ABSTRACT



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ABSTRACT

The interaction forces acting between colloidal particles and planar plates in liquids play an important role in determining the behaviors of the particles. An anomalously high speed motion of colloidal particles was observed in the present work on the basis of a self-developed fluorescence device. The particle speed is about an order of magnitude higher than the rotation speed of the plate. The particles in alkaline solutions move much faster than those in acidic solutions when the plate rotation speed is identical. Such differences have been explained with a physical model describing the significant contribution to particle motion from the interfacial forces between particles and solid surfaces.

1. Introduction

The interactions between colloidal particles and planar surfaces in aqueous solutions are highly relevant to many natural and industrial processes, such as water purification [1], nematic liquid colloidal behavior [2–4], motion and adhesion of cells [5–7], lubrication [8], chemical mechanical polishing (CMP) process [10–16]. For example, the research of interaction between colloidal particles and different structural surfaces in shear fluids is of help to understand a series of physiological phenomena [5–7]. Colloidal particles behavior in liquid environment can dramatically affect the tribological characteristics of liquid lubricants [8,9]. A variety of work has proven that the pH value and the ionic strength of the polishing

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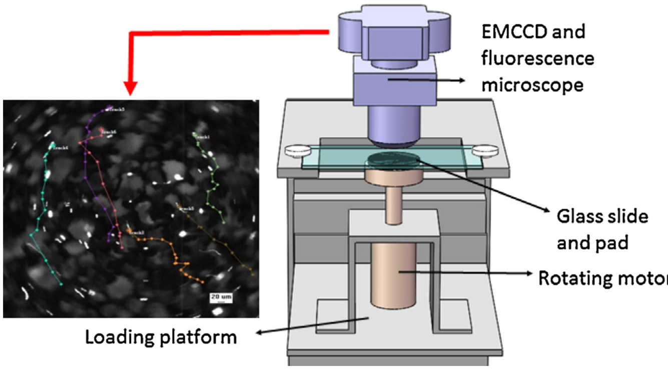

Fig. 1. The schematic diagram of the experimental system and a typical snapshot taken out from the video. (See supplemental material for a typical video of particles movement and trajectories.)

slurry have a great effect on the motion of abrasive particles, which are closely related with material removal rate [10–15]. Apparently, the interaction between colloidal particles and surfaces in contact situations is a very important factor in these phenomena. However, little direct observations of the particles' motion between two planar surfaces have been reported.

Recently, the rapid development of the microscopic observation technique provides us an effective method to directly observe the behaviors of colloidal particles. The particle image velocimetry (PIV) technique was widely used in micro particles observation and quantitative velocity measurements. The colloidal dynamic behavior near a particle-covered surface was directly observed by Eral et al. [16]. The particle deposition process at the second minimum of DLVO interaction potential energy was directly observed by Kuznar and Elimelech [17]. Direct observation was made by Wang et al. [18] to figure out the mechanism of microbial adhesion to membrane. Moreover, experiments carried out by Xu et al. offered a better understanding on the particles behavior in microchannels and evaporating water droplets, etc. [19–21].

In the present study, the behaviors of silica particles in solutions of different pH values have been investigated experimentally with a self-developed experimental system based on the particle tracking velocimetry (PTV) technique [22]. The relationship between the behaviors of colloidal particles and electrostatic interaction will be focused on. Moreover, a rough estimation taking the interfacial forces among the particles and the flat surfaces into account is presented, which would be of help to understand the effects of electrostatic interaction on the particle's movement between two flat surfaces.

2. Experimental

The experimental system is schematically shown in Fig. 1. It consists of a fluorescence microscope, an electron-multiplying CCD (EMCCD), a programmable logic controller (PLC), a platform and a computer. The fluid field is observed with a fluorescence microscope (BX51, Olympus Corporation). A 10× magnification objective lens is used and the field of view is about 800 μm × 800 μm. The 14-bit grayscale images with 512 (H) × 512 (V) pixel resolution is taken by an EMCCD (iXon EMt DU-897, Andor Technology). The spherical fluorescent silica particles with a nominal diameter of 1.4 μm were commercially available from Base-Line ChromTech (China). The concentration of the fluorescent particles in the original solution was 5% g/ml. The particles were diluted with deionized water (volume ratio 1:16,000) and ultrasonically separated for 8 min. NaOH and HCl were used to adjust the pH values of the solutions. The common glass slide was used in this experiment since it is flat and transparent. The slide is 56 mm × 26 mm in area and 1–1.2 mm in thickness. A polyurethane pad Politex Reg.20.E.II (Rohm Hass, USA) was employed. The pad surface is distributed with a lot of peaks and holes. In this work, polyurethane circular pads of 16 mm in diameter were tailored, and the size of holes ranges from 50 to 100 μm, which is much greater than the particle diameter. The pad is mounted on the end surface of a shaft driven by a stepper motor (39BYG250B, SYNTRON). Another stepper motor drives a translation stage up and down for loading and unloading uses. A load cell is located under the translation stage for in situ pressure measurement. The video recording is achieved by using the Anodr Solis software, and the video is then analyzed with Image-Pro Plus. The velocity and acceleration of individual particle could be measured in this manner.

In order to analyze the strength of electrostatic interaction, the zeta potentials of the silica particles and the polyurethane pad need to be determined. The zeta potentials of silica particles in various pH solutions were measured by Zetasizer nano (Malvern, UK) and the zeta potential of the polyurethane pad was measured by SurPASS (Anton Paar, Austria).

The experiments were carried out at a temperature of 25 °C. The experimental conditions were set as: The rotation speed of the pad ranged from 4.8 to 76.8 rpm, so the maximum linear speed of the pad relative to the glass slide ranged from 4.3 to 64.3 mm/s. The rotation speed is limited by the acquisition rate of EMCCD. If the rotation speed is too fast, it is very difficult to trace individual particles. The applied pressure on the glass slide was 15.8 kPa.

3. Result and discussion

Fig. 1 shows a typical snapshot taken out from the video. The focus plane is set at the top surface of the polyurethane pad. The rotation speed is 9.6 rpm. In the image, the darker regions represent the peaks on the pad, whereas the brighter regions represent the holes with part of the solution inside, which also emits weak fluorescence. The pad–wafer contact regions are within the darker region and few particles travel though these regions. The bright dots are silica particles. The fluorescent particles disperse over the peaks and holes. Some of the particles are embedded in the pad, so they move along with the rotating pad. Other particles move freely in the slurry. All of the six trajectories shown in Fig. 1 are those of free particles.

The particles velocities in the same pH solutions are measured at different rotation speeds (7.2–76.8 rpm). At each rotation speed, the speed and the ratio of the particles speed to rotation speed are measured. The rotation center of pad was the observation area, so the local average linear velocity of the pad within the field of view is defined by:

$$V_L = \omega \frac{L}{4} \qquad (1)$$

where ω is the angular velocity, L is the length of field of view (in this experiment, L is 800 μm). For example, when the rotation speed is 7.2 rpm, V_L is 151 μm/s. The experimental conditions are listed as below: the frame rate is 31 frames per minute. The solutions of pH 0.76, 4.93, 6.9 and 12.48 are chosen for observations and measurements in this work.

During the rotation process, 20 particles are randomly chosen to trace and 20 different trajectories are obtained. The average velocity of each particle is measured, and then these average velocities of 20 particles are averaged to get the mean value. Meanwhile the maximum velocity of particles is also calculated. The results are shown in Fig. 2. It could be observed that the mean velocity and the maximum velocity increase with the linear velocity in the solutions at the same pH values. The ratios of the mean