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Dynamic Ultrasound Scattering Studies on the Velocity Fluctuations of Settling Microspheres under Spatial Confinement

動的超音波散乱法による空間制限下におけるマイクロ粒子の沈降速度ゆらぎに関する研究

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1. Introduction

In our previous works, we have developed a novel technique called dynamic ultrasound scattering (DSS) [1, 2]. This technique utilizes scattered ultrasonic pulse from microspheres in a suspension. By using ultrasound, several advantages were obtained. First, DSS can be used in a highly turbid solution where no signal from transmitted light is detected. Second, in contrast to visible light, the location of the particles in the sample can be obtained since it allows us to record the time-evolution of the pulse wave by using a high-speed digitizer. In the previous studies, we investigated the sedimentation velocity and velocity fluctuations of microspheres with the diameter ranging from several to several tens of micrometers. If settling is hindered by particle collision or other external forces, the velocity fluctuations and sedimentation velocity are simultaneously observed. The velocity fluctuations play an impotant role in determining the dispersibility of the particles in a suspension. Nevertheless, its fluctuations are still not well understood due to complexity of hydrodynamic interactions. The characteristic length scale is suprisingly long comparable to the cell size. Therefore, the motivation of this study is to investigate the effect of spatial confinement on the velocity fluctuations of micron sized particles. The cell-depth dependence of the velocity fluctuations was examined together with effects of the smallest dimension on the interaction.

2. Experiments

Monodisperse polystyrene microspheres with different particle diameters (d=10 and 20 μm) were purchased from Sekisui Chemical Co. Ltd. The particles were dispersed in an aqueous solution containing 0.2 % sodium dodecyl sulfate (SDS) to obtain a suspension followed by a brief immersion in a low power ultrasonic bath prior to DSS experiments in order to avoid aggregation. The acrylic rectangular vessels used in this study were schmetically drawn in **Fig. 1** with the definition of the dimensions and the beam direction. The cell width W are fixed to be 3 or 10mm, while the depth D are variable from 1 to 30mm. An ultrasonic transducer and the cell container were carefully aligned by using a custom-made stainless stage prior to the DSS experiments. All the experiments were performed at 20.0 ± 0.05 °C.

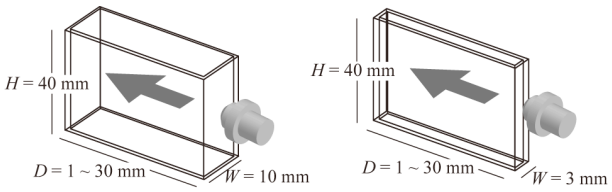

Fig.1 Schematic of the experimental setup.

Negative impulse emitted from a pulser/receiver (Olympus, model 5800PR) was transferred to a 10 MHz-longitudinal plane wave transducer (KGK, 1mm in sensor diameter) immersed in a water bath to generate broadband ultrasound pulses. The reflected or scattered ultrasound wave was received by the same transducer for the backscattering experiments. The obtained signals were then amplified by the receiver, followed by successive recording with a 14 bit high-speed digitizer (GaGe, Compuscope CS14200) at the sampling rate 200 MS/s. The signals were repetitively recorded to calculate the standard deviation of the particle velocity $\Delta V \equiv \left\langle \delta V^2 \right\rangle^{1/2}$. The pulse repetition rate and the number of sampling points for successive pulses were tunable.

3. Results and Discussion

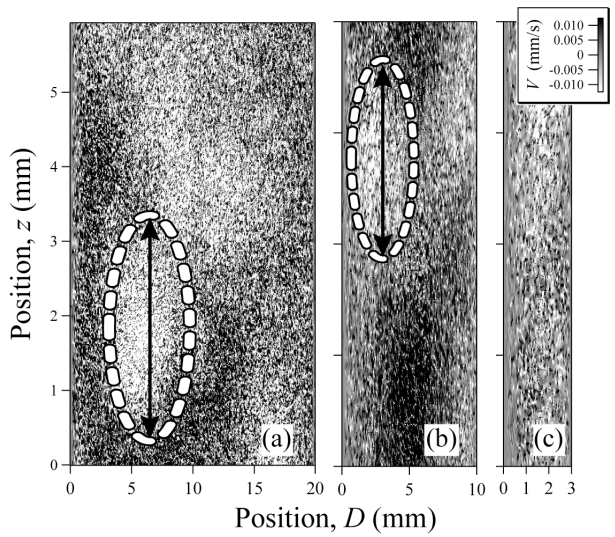

Fig.2 Collective motions of the particles reveal the cell-depth dependence of the velocity images. (d =10μm, 1wt%)

The terminal velocity for the settling particles can be obtained by balancing the buoyant and the effective gravitational forces. As the number of the particles increases, a solvent flow induced by a particle affects the motion of other particles. This is called the hydrodynamic interaction. The effects of the hydrodynamic interactions are known to persist over a long distance, which could extend to the cell size used in the experiments. As has been extensively studied in the literatures, the motion of the particles is known to be cooperative with a cut-off length ξ where the region specified by ξ is hereafter called blob. The origin of the velocity fluctuations is considered to be the number fluctuations of the particles contained in such a blob. **Fig.2** shows the 2D-velocity images for the microspheres with d=10μm. When the cell width, W, was fixed at 10mm, the existence of the blob was visually confirmed for D>3mm (Fig.2 (a)(b)). **Fig.3** shows the depth dependence of the velocity fluctuations with different sample depth D. The open triangle and solid circle respectively indicate the results for W=3 and 10mm, respectively.

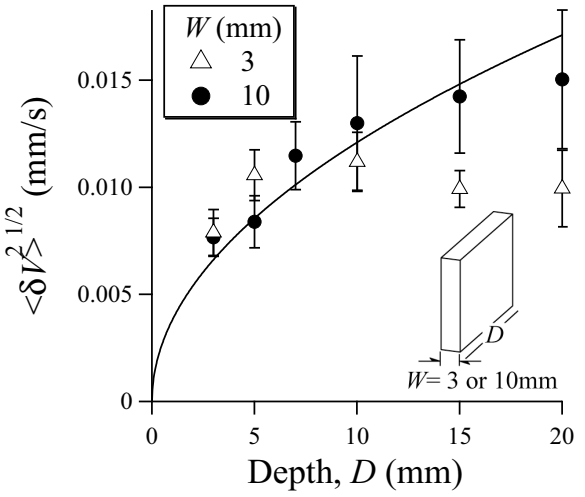

Fig.3 The cell depth dependence of the velocity fluctuations. (d=10μm, 1wt%)

The cell-size dependence of the velocity fluctuations has already been predicted by the Caflisch-Luke[3] theory. According to this theory, the relation $\Delta V = CV_0\sqrt{\frac{2\phi D}{d}}$ is expected. The solid line in Fig.3 was thus reproduced by the theory with D=10mm. On the other hand, ΔV with W=3mm level off at D=5mm. This result suggests that the velocity fluctuations of the particles were fairly suppressed by the sidewalls. However, if it is true, similar level-off at D=10mm should be observed for the case of the solid circles. In order to investigate the effect of the shear stress from the walls, particle-size dependence of ΔV was investigated. The result shows that the ΔV becomes constant with D when the particles become larger. From the results, it was concluded that the velocity fluctuations strongly depend on the cell width, the ratio of the particle size to the cell width, and more importantly the minimal dimension of the sample cell.

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