입자계 유변학의 재조명

안경현, 현규, 남중건, 탁형주, 이승종
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Suspension Rheology Revisited

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Introduction

The rheology of suspension has been the subject of serious research for many years, mainly because of its obvious importance in a wide range of industrial applications. Suspensions include cement, paint, printing inks, coal slurries, drilling muds and many proprietory products like medicines, abrasive cleaners and food stuffs, for example. As the particles can form diverse microstructures in a viscous medium, control of the microstructure and flow properties is vital to the commercial success of the product or of its manufacture. Therefore rheological properties as well as their microstructures are needed to understand the phenomena encountered and the changes occurring during processing.

Suspension rheology has been studied intensively for many years. They have been focused mainly on the effect of system parameters on viscosity: the effect of continuous phase, the effect of dispersed phase, the effect of concentration in both continuous and dispersed phase, the effect of particle size and its distribution, the effect of particle shape, for example. Some abnormal behaviors relative to polymer solution or melt has also been focused, including thixotropy, shear thickening, apparent wall slip, stability, to list a few. In the meanwhile, the particle system is getting more important from the industrial viewpoint. First, the system finds new applications in rapidly emerging industries like electronic or display industry. Second, it becomes more important to precisely control the process probably due to the advance of technology as well as due to hard competition on the market side. Therefore, there is an input at least from industry to be more concerned on suspension rheology, and we need to re-eluminate the field of suspension rheology with a new insight which has been formulated and advanced recently rather than with an insight of traditional rheology. In this talk, we will take a few aspects of suspension rheology which has not been focused in the past into account. There will be more aspects to think about with a new insight, but we will talk about the reproducibility of the experimental data, or the inherent instability of the particle systems, fractal nature, behavior of higher harmonics, among many others.

Tools for investigation

Rheometry. Rheological measurements were carried out on strain controlled rheometer (RMS800) and stress controlled rheometer (Bohlin) using a parallel plate fixture with a diameter of 50mm (RMS 800) and 35mm (Bohlin). For the raw data acquisition, a 16bit ADC card (PCI-6052E; National Instruments, Austin, USA) with a sampling rate up to 333kHz was used. This ADC card was plugged into a stand-alone PC equipped with LabView software (National Instruments).

Modeling. Brownian dynamics simulation technique has been used to investigate the particle trajectory, microstructure, and rheological properties of the model system. In the Brownian dynamics simulation, the Langevin equation of the form is solved for every particles, and the stress is determined by the sum of the product of position and the forces.

$$m(dv_i / dt) = -\varsigma v_i(t) + F_i(t) + F_i^R(t)$$

The first term on the right hand side is the friction force, the third term is the random Brownian force, and the other forces including potential forces are included in the second term.

Results and Discussion

The reproducibility or inherent instability of the suspension attributes to some factors, mostly particle-particle interaction, particle-fluid interaction, thermal fluctuation. The effect of thermal fluctuation is shown in Fig. 1. Such a strong fluctuation deteriorates the stress signal, and it is very hard to get a meaningful data analysis. The importance of thermal motion can be estimated with some dimensionless parameter like a Peclet number, but it is not always possible to use a specific algorithm and time scale should be carefully estimated to make a reasonable calculation. Effect of preshear is shown in Fig. 2. The result has been analysed in terms of fractal dimensions. As preshear is applied, fractal dimension increases, which means that more compact structure is formed during preshear. Cluster statistics can also be used as a measure of microstructure, and rheo-optical tools need to be used for microstructural changes of the suspension. When large strain is applied to the suspension system, the microstructure changes significantly depending on too many system parameters, and it is very difficult to quantitatively analyse the system. Fig. 4 shows the rheological properties and their Fourier transformation results. Intensities of higher harmonics first increase as strain amplitude increases, but it decreases after critical strain. This is the characteristic of particular suspension systems, but detail of the mechanism is yet unknown. This interesting behavior has been analysed in terms of microstructure as well as cluster statistics. There remain more questions and problems to be solved. They will be related with nonlinear rheology, description of microstructure, structure-rheology relationship, for example.

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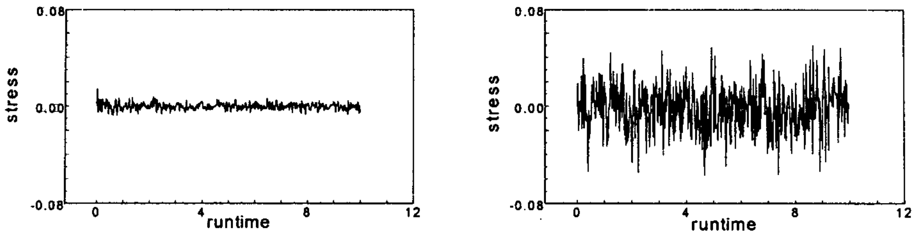

Fig. 1 Effect of thermal motion (left: without brownian force, right: with brownian force).

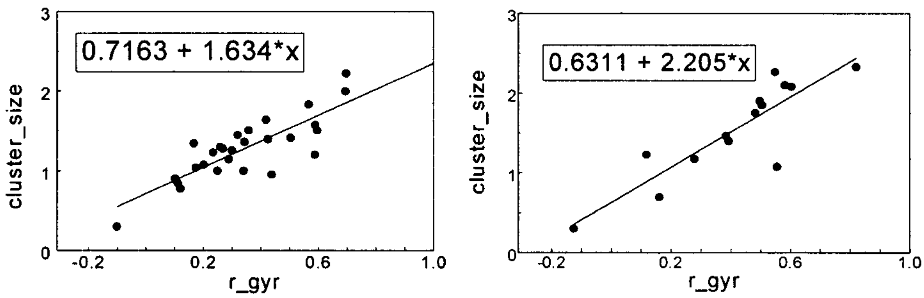

Fig. 2 Effect of preshear (left: before preshear, right: after preshear)

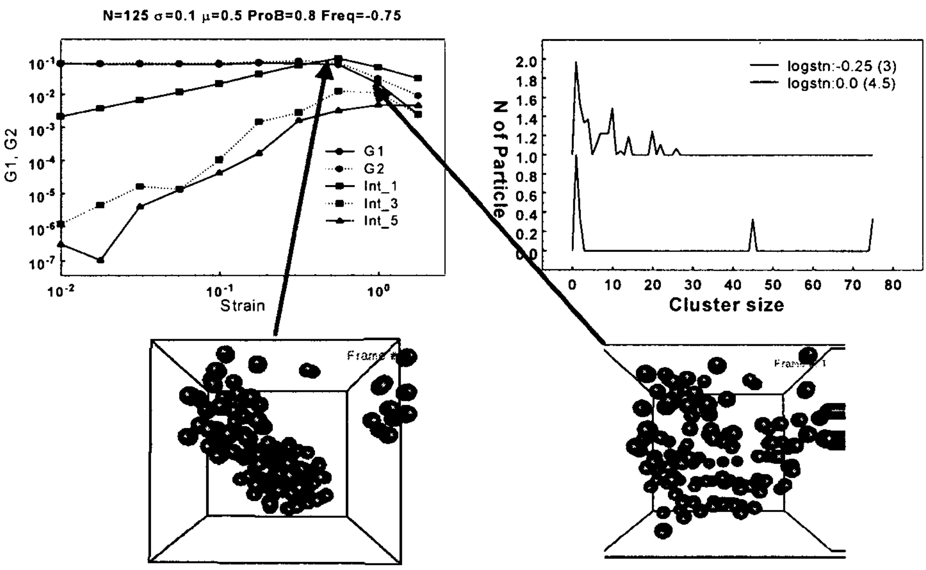

Fig. 3. Microstructure and nonlinear rheology relationship.