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Collective settling of fine particles in a narrow channel with arbitrary cross-section

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HIGHLIGHTS

- Collective settling of particles in liquid-filled narrow channels is examined.
- The aspect ratio of channel cross-section is important for the settling behavior.
- The velocity of particles in channels with arbitrary cross-section is predicted.

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ABSTRACT

Gravitational settling of fine particles in a liquid-filled narrow channel has been studied experimentally and theoretically. Previous studies have shown that the particulate suspension with concentration interface toward gravitational direction behaves as a continuous fluid for high concentration and small particle size, and the gravity-induced instability at the interface enhances the settling motion of particles. The purpose of this study is to investigate how such a concentration interface behaves and how particles settle by gravity in various finite-sized channels. The experimental and theoretical results indicate that the aspect ratio of the channel cross-section is an important parameter for describing the settling behavior of particulate suspension. Moreover, we predict the velocity of the collective settling of particles in channels with arbitrary cross-section.

1. Introduction

Transport of particulate materials in liquid-filled channels, such as water-saturated porous media, soils or cracks in rocks, are widely seen in industrial applications and natural phenomena. There have been numerous studies in various fields of chemical engineering (Sharma and Yortsos, 1987; Biggs et al., 2003), environmental engineering (Mondal and Sleep, 2012), mechanical and civil engineering (Adler et al., 2002). The dispersion process of materials in these channels is crucially difficult to predict quantitatively because it depends on geometric characteristics of channels in addition to fluid and particle properties. There are many parameters describing channel characteristics such as size, length, cross-sectional shape, inclination, bifurcation, confluence and so on. In most cases, these characteristics have been considered together as macroscopic properties like porosity or tortuosity (Epstein, 1989; Jury and Horton, 2004; Shen and Chen, 2007).

In particular, gravitational dispersion of particles in liquid-filled channels is commonly seen in various processes such as contaminant transport. However, even if the channel has simple geometry and the filling liquid is stationary (no advection), the gravitational motion of particulate materials is quite complicated. The particles do not always settle independently with their terminal velocity and sometimes they settle collectively (Nitche and Batchelor, 1997; Machu et al., 2001; Metzger et al., 2007). In some cases, suspended particles move with the interstitial fluid as one continuous fluid as if it is immiscible in surrounding fluid. Consequently the collectivity of suspended particles brings about the variation of the whole dispersion behaviors.

If the concentration gradient is positive in vertical direction, i.e., the upper part is denser, hydrodynamic instability (Rayleigh–Taylor instability) occurs at suspension–pure fluid interface (Völtz et al., 2000, 2001; Völtz, 2003). Such instability of suspension–fluid interface greatly influences the settling motion of constituent particles. Fig. 1 is the settling behavior of particulate suspension arranged in laminae for various particle and fluid conditions in quasi two-dimensional closed channel (Harada et al., 2012). If the particle size is small and the concentration is large, the

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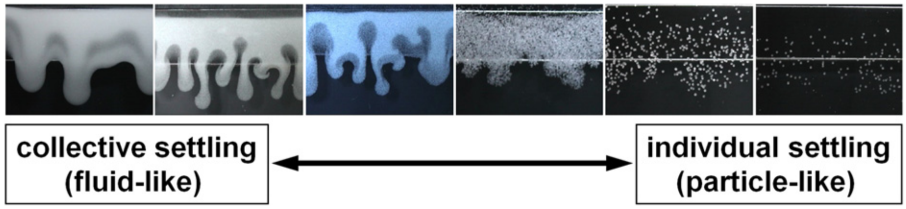

Fig. 1. Settling behavior of stratified suspension in quasi two-dimensional vessel for various particle and fluid properties. Detailed conditions are described in Harada et al. (2012).

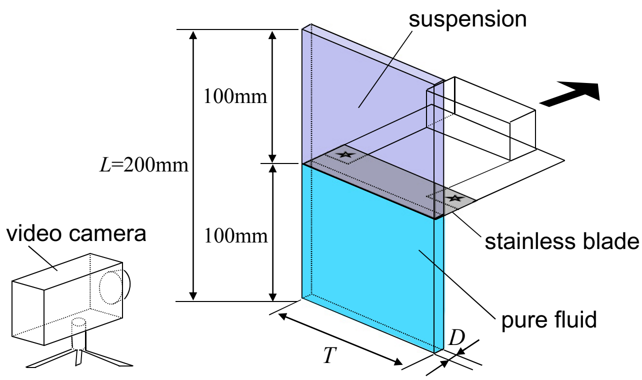

Fig. 2. Schematic diagram of experimental system. Short side length D varies from 3 to 12 mm, while long side length T varies from 6 to 100 mm.

suspension behaves as an immiscible fluid even though there is no definite interface and the suspended particles settle with the growth of fingering instability at lower suspension–fluid interface. In this case, the settling velocity is hundred times larger than that of an isolated particle. Therefore, the collectivity of suspended particle is quite important for quantitative prediction of gravitational dispersion of particles in channels.

The lengthscale and the growth rate of Rayleigh–Taylor instability greatly depend on the geometric condition of channels (Fernandez et al., 2001, 2002; Martin et al., 2002). In consequence, the velocity of collective settling also depends on the channel geometry. The purpose of this study is to investigate how such instability occurs in a narrow channel and how the suspended particles settle by gravity. This paper indicates the importance of channel geometry, particularly cross-sectional shape, for the gravitational settling of particulate suspension in a narrow channel through the consideration of simple system.

2. Experimental method

Fig. 2 shows the schematic diagram of experimental apparatus. The test cell is quasi-two dimensional closed channel with a height $L=200$ mm. The channel is made by acrylic plates except for the front glass. The thickness D and the width T of the channel are adjustable from $D=3$ to 12 mm and $T=6$ to 100 mm respectively. There is a horizontal slit on the back side of the channel. A thin blade is put into the slit for dividing suspension from pure fluid. The blade is made from a stainless steel plate with a thickness 0.5 mm.

At first pure fluid (silicone oil) is filled into the lower part of the channel until the surface reaches the position of the slit. Then the blade is put into the channel and the suspension is filled above it. After that the blade is removed backward and the settling behavior of the suspended particles by gravity is recorded by a digital video camera.

The suspension is made of glass particles and silicone oil. The diameter of particle d_p is 30 μm and the mass density ρ_p is 2500 kg/m^3. The density of the silicone oil ρ_f is 972 kg/m^3 and the viscosity μ_f is 1.94 Pa s. The corresponding Stokes settling velocity $U_0=(\rho_p-\rho_f)d_p^2 g/18\mu$ is 3.85×10^{-4} mm/s. In this experiment, the particle concentration is set to be constant and is $\phi=0.05$. The suspension is mixed by stirring for several hours and is deaerated well in constant temperature (22 ± 1 °C). The pure fluid which is used to fill the lower part of the channel has the same properties as constituent fluid of the suspension. Therefore the initial state can be interpreted as partially suspended particles in a static pure fluid.

After the blade is removed, the suspension–pure fluid boundary can be observed definitely (see initial conditions in Fig. 3). However, there is physically no definite border because the suspension is made of the same fluid as the lower one. It should be considered that the particles are suspended partially in a static fluid. Such an ambiguous boundary between suspension and fluid is called concentration interface. At the concentration interface of micron-sized particles, the interfacial tension can be considered zero. If there is a dominant interparticle force such as van der Waals force in the system, it is possible to consider the pseudo-interfacial effect on the suspension–fluid boundary. However, it appears that there is no significant force compared to gravity force and fluid force acting on micron-sized particles we used here.

3. Results and discussion

3.1. Settling behavior of suspension

The settling behavior of suspension was observed with keeping the channel thickness (short side) constant and changing the channel width (long side). Fig. 3 shows the settling behavior of suspension for a channel thickness $D=5$ mm with various channel widths T. The moment the dividing blade is removed backward is set to be $t=0$. As can be seen, finger-like instability develops at concentration interface and the settling of suspended particle is subject to macroscopic motion of the interface instabilities. As described in our previous article (Harada et al., 2012), such fingering instability is fundamentally the same as Rayleigh–Taylor instability and it behaves as immiscible fluids if the particle size is small and the concentration is high, more quantitatively phrased, if a non-dimensional parameter $d_p/\phi^{1/3}\lambda$ (λ: wave length of the instability) is less than 0.03.

It is found from Fig. 3 that the settling behavior of suspension depends on the channel width T. In cases of small channel width (Fig. 3a, b), only one finger grows up near the center of the channel. In these cases, the width of finger is larger for larger channel width. However, if the channel width is moderate (Fig. 3c), a few fingers are observed. If the channel width is adequately large (Fig. 3d), many fingers grow up and the finger width does not depend on the channel width.

Fig. 4 shows the change in the length of fingers with time under the same conditions as Fig. 3. The fingers appear to grow in an exponential manner at the beginning and then their growth velocity becomes constant. These behaviors are similar to the