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Numerical simulation of concentration interface in stratified suspension: Continuum–particle transition

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ABSTRACT

Behavior of concentration interfaces, which are apparent interfaces between a suspension and pure liquid, was studied using numerical techniques. Two types of numerical simulations were used to classify whether collective or individual behavior occurred in the ratio of the average particle separation to the wavelength of the fastest growing perturbation. The first is Lagrangian tracking of individual particles in fluid, and the second type is interface tracking of two immiscible continuum phases. These two extremely different approaches represent the dual nature of the concentration interface: immiscible with no interfacial tension and miscible with no diffusion. These results reflect the experimentally-observed behavior of particles, which is both collective and individual. Sealing of the concentration interface by particle-induced flow is crucial to collective motion of suspended particles. A proposed dimensionless parameter describes quantitatively the transition from collective to individual settling of suspended particles.

Introduction

Collective motion of fine particles suspended in a liquid is important not only for engineering disciplines such as mechanical, chemical, civil or environmental ones, but also for other scientific fields as biomechanics or geophysics. Collective motion is observed in various processes and phenomena such as solid–liquid separation (Kynch, 1952), magma flow (Michioka and Sumita, 2005), sea sediment layers, (Carey, 1997), sediment transport in river and ocean (Warrick et al., 2008), and bioconvection (Pedley and Kessler, 1992).

The collective nature of suspended particles is frequently revealed in the mode of gravitational settling of inhomogeneously dispersed suspensions, i.e., the particles are locally suspended in a liquid. Such systems are classified in the following three cases according to the orientation of the boundary between the suspended and nonsuspended regions (this is called the "concentration interface"): (1) the normal vector to the concentration interface (from suspended to nonsuspended region) points up in the vessel, (2) the normal vector points down, and (3) the concentration interface forms a closed surface. The first case corresponds to the well-known case of hindered settling in a vessel, and the concentration interface is called the "sedimentation front." Many studies have focused on the behavior of the sedimentation front from both a macroscopic (i.e., trajectory of the sedimentation front, e.g., Kynch, 1952) and a microscopic viewpoint (i.e., hydrodynamic diffusion near the sedimentation front, e.g., Mucha and Brenner, 2003; Bergougnoux et al., 2003, etc.). The collective nature of the suspended particles is manifested as a variance in the hindered settling velocity or as self-diffusion due to hydrodynamic interactions in such systems.

The second case is the main subject of the present research wherein the normal to the concentration interface points down. In such a system, the motion of suspended particles is critically influenced by the macroscopic nature of the concentration interface. In other words, the settling velocity of particles is greatly enhanced by the gravitational instability (Rayleigh–Taylor instability) at the concentration interface. Such instabilities and resultant convection caused by particle settling have been studied experimentally (Kuenen, 1968; Hoyal et al., 1999; Parsons et al., 2001; Völtz et al., 2001; Völtz, 2003; McCool and Parsons, 2004; Blanchette and Bush, 2005), theoretically (Burns and Meiburg, 2012; Yu et al., 2013) and numerically (Pan et al., 2001; Chou et al., 2014) in many engineering and science fields.

A similar instability also occurs in the third system, but in a different form. The third system, in which the concentration interface is closed, is called a "suspension droplet." Many studies on

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suspension droplets have elucidated the collective motion of suspensions (Nitsche and Batchelor, 1997; Machu et al., 2001; Metzger et al., 2007). In these studies, the interfacial instability is found to lead to a characteristic behavior of suspended particles, such as the breakup of droplets in a manner reminiscent of fireworks.

The collective nature of suspended particles is closely associated with the concentration of particles in suspended regions. The suspension droplet is known to essentially maintain a spherical shape for low Reynolds number. Previous studies have claimed that this behavior results from the disturbance flow generated by each particle (Stokeslet) sealing the concentration interface, thereby preventing invasion by outside flow. Some researchers have pointed that the sealing ability at the concentration interface of a suspension droplet is determined by the number density in the suspended region (Nitsche and Batchelor, 1997; Metzger et al., 2007). If the number density is small and the Stokeslet does not fully discretize the suspended region, the concentration interface allows penetration by the outside fluid; therefore, some particles may escape from the droplet.

For the second case in which the concentration interface points down, Harada et al. (2012) have experimentally examined the collectivity of settling particles caused by the Rayleigh–Taylor instability. They found that the transition from individual to collective settling of suspended particles is determined by a dimensionless parameter given by the ratio of the interparticle separation to the dominant wavelength of the instability; this ratio is related to the number density of the suspended particles.

Comparing the concentration interface with an ordinary interface reveals the former's peculiar aspects. The concentration interface of a suspension of micron-sized particles is essentially a miscible interface. However, in contrast with a density interface such as a salt-water/fresh-water interface, thermal diffusion is less significant because the particle size is much larger than the size of molecules in the solvent. Conversely, in contrast with an immiscible interface, the interfacial tension of a concentration interface is almost zero, provided the interparticle force is not too large. Therefore, the concentration interface of a suspension with micron-sized particles can be interpreted as an ambiguous interface at which the suspended particles are not constrained and are not pushed away from the interface. Fernandez et al. (2001) investigated theoretically the wavelength of the Rayleigh–Taylor instability for both miscible and immiscible interfaces between two fluids. Their results indicate that the dominant wavelength of the instability depends on whether the interface is miscible or immiscible; however, the wavelength of a miscible interface with an infinite Péclet number (i.e., no diffusion) coincides with that of an immiscible interface with infinite capillary number (i.e., no interfacial tension). Therefore, a concentration interface with micron-sized particles can be interpreted as an interface that connects miscible and immiscible interfaces. However, the dual nature of the concentration interface has not been fully explained from the microscopic viewpoint, i.e., how particles which form the interface settle relative to surrounding fluid (as miscible interface) and how the disturbance flow created by each particle prevents the invasion of flow (as immiscible interface).

The present study investigates the Rayleigh–Taylor instability at the concentration interface of a particulate suspension by numerically simulating the resultant collective motion of particles. To examine the dual nature of the concentration interface (i.e., immiscible with no interfacial tension or miscible with no diffusion), we used two contrasting numerical models for the simulations. The first model is of an immiscible interface with no interfacial tension and with the suspended region assumed to be a continuous fluid with apparent properties. The second is a point-force model that corresponds to a miscible interface with no diffusion. In this model, we assume each particle has no volume and we calculate the motion of the particles relative to the surrounding fluid. The results of both simulations are compared with previous experimental results. The role of the concentration interface on the collectivity of suspended particles is discussed from various viewpoints.

Numerical simulations

We treat a stratified suspension system in which a particle suspension is set on a pure fluid, as shown in Fig. 1. However, the liquid in the suspension is the same as pure fluid, so the system has no distinct interface. The concentration of particles, however, has a steep gradient at the apparent interface. We made the following two simulations: (1) a Lagrangian tracking of individual particles with two-way coupling to represent a miscible interface with no diffusion, and (2) an interface tracking of two immiscible continuum phases with no interfacial tension to verify whether the concentration interface behaves like a two-fluid interface by comparing the results with those of the Lagrangian-tracking simulation. Pan et al. (2001) simulated the Rayleigh–Taylor instability of a suspension for two-dimensional cylindrical particles. Chou et al. (2014) also simulated the Rayleigh–Taylor instability of a suspension by using a two-fluid model based on complex constitutive equations. In this study, we treat the fully three-dimensional case and our simulations use a simple point-force model and a simple interface tracking model. The particle tracking approach treats particles in suspension individually. On the other hand, the interface tracking is an Euler–Euler approach with no diffusion. Our objective is to understand microscopically the dual nature of the concentration interface. To tackle this issue, we used both the particle tracking and the interface-tracking approaches.

Lagrangian tracking

Consider particle motion with very low particle Reynolds number $Re \equiv d_p U_{rel} \rho / \mu$ (where d_p is the particle diameter, U_{rel} is

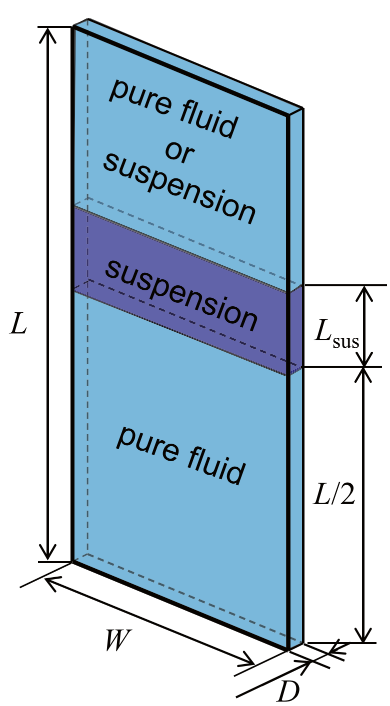

Fig. 1. Configuration of simulations. Upper part is filled with suspension for interface tracking and pure fluid for Lagrangian particle tracking.