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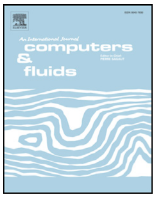

Lattice-Boltzmann lattice-spring simulations of two flexible fibers settling in moderate Reynolds number flows

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ABSTRACT

Dynamic motion of two flexible fibers settling in an infinitely long fluid column at moderate Reynolds numbers is numerically simulated in a three-dimensional space by using a lattice-Boltzmann lattice-spring method. In the simulations, rectangular and cylindrical flexible fibers are used. The fiber rigidity, density, shape, initial distance, and aspect ratio are varied at different levels and their effects on drafting, kissing, and tumbling (DKT) behavior are studied. It is demonstrated that the fiber rigidity has a profound impact on settling velocity, fluid structures, and DKT phenomenon.

1. Introduction

Liquid-solid particle handling systems, such as fluidized beds in reactors, screening, filtration, and sedimentation, are commonly encountered in chemical, pharmaceutical, petroleum, food process, paper, and biological engineering [1]. For example, in water treatment sedimentation is used to remove precipitants coagulated in water softeners [2]. In the paper engineering, since fines have huge surface areas, receive larger drag forces, and settle much slower than long fibers, the fines can be separated from the long fibers. The sedimentation is also used as a primary stage in modern waste water treatment plants to reduce the content of suspended solids and the pollutants embedded. Due to importance to industries, many experimental, theoretical, and computational studies are conducted to understand the mechanisms of dynamic motion of solid particles in fluid [3], either coagulation or dispersion. This may help engineers to design a fluid-solid particle handling system with a high operation efficiency.

In 1987, Fortes et. al. [4] observed experimentally that when two particles sediment vertically in a channel filled with a Newtonian fluid, the trailing particle may accelerate and approach the leading particle, called drafting, due to the suction effect of the low pressure in the wakes behind the leading particle. When the trailing particle attaches the leading particle, called kissing, the suction effect is reduced and the two particles become unstable, and they exchange their positions. The trailing particle may pass the leading particle and become the leading particle, called tumbling. This drafting, kissing, and tumbling (DKT) phenomenon, closely associated with inertial effects, may repeatedly take place during settling process. Late, Feng et. al. [5] used finite element method to simulate the motion of particles settling in a vertical channel and numerically confirmed the DKT phenomenon. Further, many others [6] used different methods to simulate the particle motion and revealed that particle density, initial vertical distance, and diameter ratio have a profound influence on the DTK behavior. Recently using lattice Boltzmann simulations, Wang et. al. [6] reported that when the diameter ratio of two circular particles is smaller than 1.21, DKT phenomena are repeated many times and when the diameter ratio is larger than 1.22, DKT occurs only once.

A recent literature search reveals that most studies concentrated on either rigid particles or flexible particles at zero Reynolds number flows and very limited results were reported on flexible or deformable particles at moderate Reynolds numbers, where inertia cannot be ignored, although sedimentation of fibers [7–9] at the Stokes fluid were extensively studied. The work for flexible fibers at moderate Reynolds numbers was reported by Wu et. al. [10], who employed a flexible particle method, based on lattice Boltzmann method, to simulate single and multi-flexible fibers. They demonstrated that a flexible fiber has a larger settling velocity than a stiff fiber and multi-flexible fibers have significantly larger settling velocity than the corresponding isolated single fiber. However, they did not explore the DKT behavior of two flexible fibers. Therefore, the present work will employ a lattice-Boltzmann

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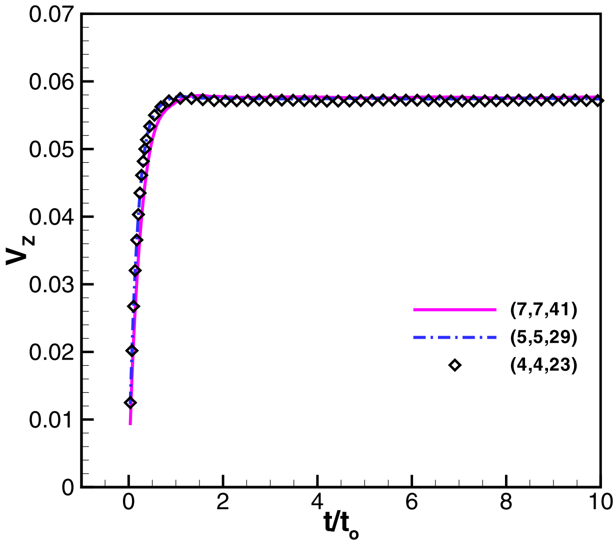

Fig. 1. The settling velocity as a function of time for the same case at three different resolutions.

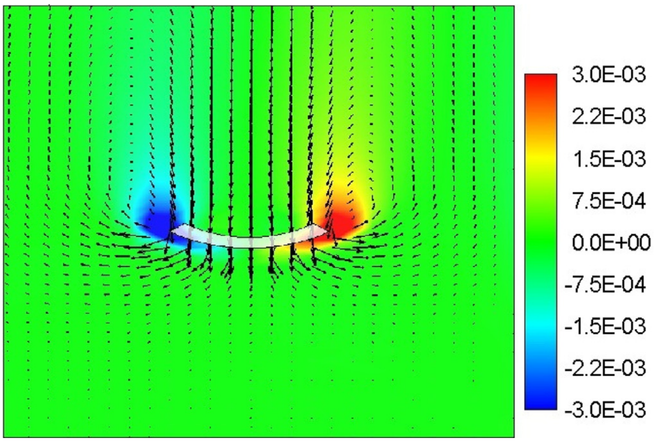

Fig. 2. The velocity fields and tip vortices around the area of the two ends of the single fiber at $EI = 0.048$.

lattice-spring method to mimic DKT phenomenon of two flexible fibers settling down in an infinitely long rectangular fluid channel at moderate Reynolds numbers. In the simulations, flexibility, fiber shape, Reynolds number, shape, and, aspect ratio are varied at different levels and their effects on the DKT behavior and fluid structures are investigated.

In next section, the LBLS method is briefly introduced and a non-dimensional elasto-gravitation number is defined and used to analyze possible deformation. The simulation results of single and two flexible fibers are reported in Section 3. Effects of rigidity, aspect ratio, initial distance, fiber shape, and Reynolds number on DKT are studied. Conclusions are made in the last section.

2. Simulation methods

2.1. Non-dimensionalization

Dynamic motion of fluids follows the Navier–Stokes equations while fiber motion and deformation can be approximated by a beam motion equation. The sedimentation behavior of a fiber in fluids is mainly determined by hydrodynamic force, fiber elasticity, and gravity. These equations can be non-dimensionalized if the length, velocity, time, and force are re-scaled by the fiber length L, reference velocity V_0, time L/V_0, and $\mu V_0 L$, respectively, where μ is the viscosity. The non-dimensional Navier–Stokes equations for fluids can be written by

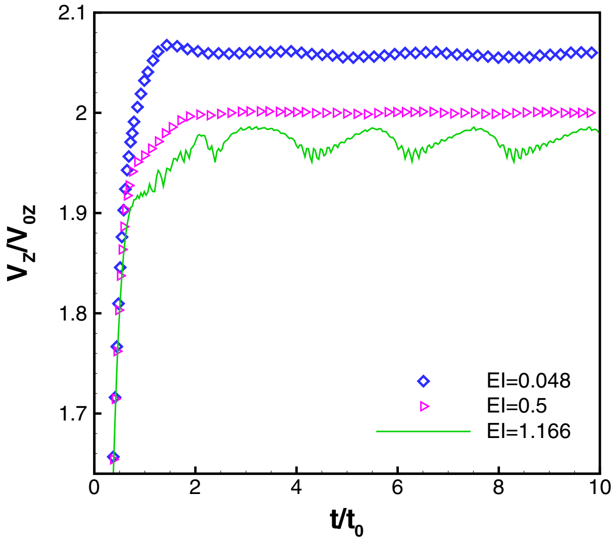

Fig. 3. Comparison of the fiber settling velocity as a function of time among three different levels of rigidity. The vertical velocity V_z is normalized by the Stokes velocity V_{0z} and the time t is normalized by $t_0 = L/V_{0z}$. The same applies to other figures.

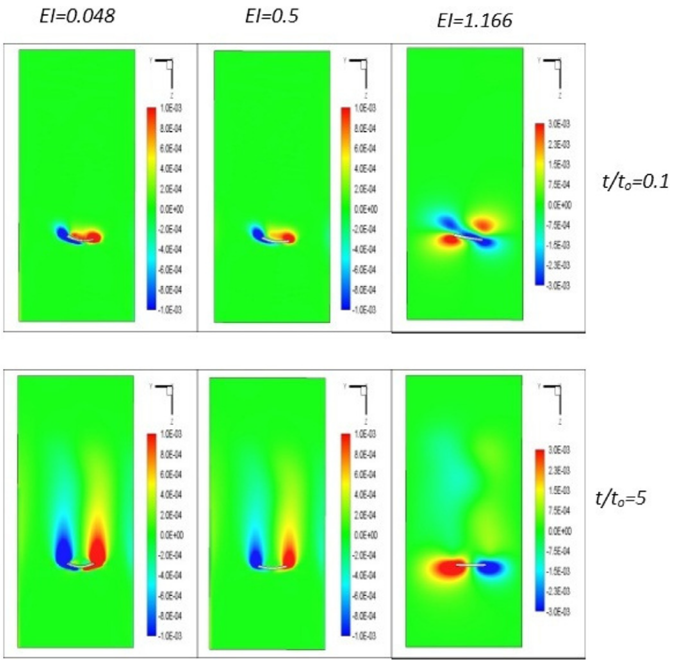

Fig. 4. Comparison of the vorticity in the X-direction in the cross section of $x = 30$ among three different levels of the rigidity at two different time instants a) $t/t_0 = 0.01$ (top) b) $t/t_0 = 5$ (bottom).

$$\triangledown \cdot \mathbf{u} = 0, \tag{1}$$

$$Re(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \triangledown \mathbf{u}) = - \triangledown p + \triangledown^2 \mathbf{u}, \tag{2}$$

where $Re = V_0 L/\nu$ is the particle Reynolds number, p is the pressure, and the non-dimensional beam equation can be written by

$$EI\frac{\partial^4 w}{\partial l^4} + \frac{\rho_s}{\rho_f}\frac{\partial w^2}{\partial t^2} = \frac{L^2 F_f}{DBR_{sd}} + \left(\frac{\rho_s}{\rho_f} - 1\right)Fr^{-1}, \tag{3}$$