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Analysis of the motion of small-scale ellipsoidal particles in a horizontal laminar flow field

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ABSTRACT

A particle movement model for a horizontal laminar flow field was established in this study, using a modified Basset–Boussinesq–Oseen equation for multiphase fluid dynamics. The motion of ellipsoidal and spherical particles in this flow field was compared to determine the differences in entrainment of ellipsoidal versus spherical particles. Our theoretical results indicate that ellipsoidal particles move more rapidly and smoothly within the fluid than spherical particles under the same conditions. Moreover, this feature is enhanced, as the ellipsoidal degree of the particle increases. Based on a dimensional analysis, flow experiments were carried out to verify the behavior of ellipsoidal versus spherical particles in practice. Both our theoretical and experimental results show that ellipsoidal particles approach the fluid velocity more quickly than spherical particles. Future work would need to address effects of velocity gradients and rotation on particle behavior.

Introduction

The accumulation of marine microplankton on the surfaces of subsea equipment is a great challenge for long-term marine projects. The investigation of the spread and migration mechanisms of the plankton is a step towards the solution to this problem. In addition to vertical sedimentation, adhesion of such particles often occurs on side walls, where fluid flow is horizontal. In this case, plankton and/or other small-scale particles suspended in the fluid aggregate and cover subsea ship surfaces and other equipment. These suspended small-scale particles change their state of motion, when such equipment (e.g., ships, ocean heat exchangers) determines the surrounding fluid flow. In the area near the wall, these suspended particles move along with the fluid. Before attaching to the surfaces of such equipment, these particles occur within this boundary layer. This boundary layer may be characterized by a laminar flow field, a velocity gradient flow field, or a turbulent flow field. Clearly, their motion under these three different flow fields needs to be evaluated. It is essential to study the particle motion occurring as the particle enter the moving boundary layer near the wall to understand how attachment of these small-scale particles takes place on these surfaces. This paper focuses on the particle movement occurring in the mainstream region of the boundary layer. Most likely, the movements of marine microplankton reflect their morphology, especially because the forces on non-spherical particles are more complicated than on spherical ones. Many studies assume such particles have a spherical shape to simplify the mathematical model describing their motion. However, the adhesion of these small-scale particles to surfaces of subsea structures suggests there are many factors affecting their motion, including particle shape. Thus, motion characteristics related to particle shape cannot be ignored within the boundary layer near the wall. An accurate model of the horizontal movement of non-spherical particles in solid–liquid two-phase flow can be applied to many aspects of engineering, including the accumulation of suspended plankton near structural surfaces of a ship's hull.

In recent years, many researchers have been carried out studies of particle movement in a solid–liquid flow field. Meng and Ni (2002) used the Lagrange method to simulate vertical motion of spherical particles in two-phase flow. Qi, Cheng, Xiao, and Chang (2004) derived an equation for single spherical particle motion by analyzing the motion of particles within the boundary layer but did not obtain its exact analytical solution. Others proposed particle kinematic models for particles near the wall. Ma and Fu (2014) presented a framework of stochastic modeling to describe particle kinetics within wall-bounded flow. Liu (2010) depicted the motions of wall-bound particles using a "freedom walk" framework. Wang, Zhang, Wang, and Liang (2011) established a double fluid model

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Nomenclature

d_p	particle diameter, m
d_V	equivalent volume diameter, m
d_S	equivalent surface diameter, m
F_g	gravity, N
F_{bu}	buoyancy, N
F_d	drag force, N
F_P	pressure gradient force, N
F_{VM}	added mass force, N
F_{ML}	Magnus lift force, N
F_B	Basset force, N
F_S	Saffman lift force, N
Fr	Froude number
m_p	particle mass, kg
r_p	particle radius, m
Re	Reynolds number
S	ellipsoidal particle surface area, m^2
t	time, s
u_p	particle velocity, m/s
u_f	flow field velocity, m/s
V_p	particle volume, m^3
V	ellipsoidal particle volume, m^3
κ	correction factor
μ	fluid viscosity, $N \times s/m^2$
v	velocity, m/s
ρ_p	particle density, kg/m^3
ρ_f	fluid density, kg/m^3

based on dynamic theory, and analyzed the influence of different forces on the two-phase momentum transfer process. They adopted computational fluid dynamics to simulate the hydrodynamics of a liquid–solid slurry flow in a horizontal pipeline. Liu (2012) studied the particle sedimentation process via direct numerical simulation, taking into account ellipsoidal particles. Fan, Zhong, Wu, Foufoula-Georgiou, and Guala (2014) studied bed-load transport, selecting rolling and sliding as the main forms of motion. Using numerical simulation, they obtained the particle velocity and acceleration in the vertical direction of fluid flow. Dong (2015) adopted a discrete particle model to calculate the movement of particles in a centrifugal pump solid–liquid flow field using numerical simulation and analyzed the surface pressure on particles in this model. Many of these studies considered the forces on particle; some also considered the processes of rotation and slide that occur in a velocity gradient. Most of the numerical simulations (Edelin, Czujko, Castelain, Josset, & Fayolle, 2015) were based on Lagrange or Euler methods, which do not address the motion of the particle itself. Some studies regarded the particles as a continuous phase, using numerical simulation to describe the distribution of particles under certain fluid conditions. However, the motion of a single particle can reveal an understanding of particle trajectories within the flow field. Thus, we derived an analytic solution to describe particle movement within the flow field.

To date, many studies of particles in fluid flow regarded them as spherical particles; only small number of studies consider other particle shapes (Sugiharaseki, 1993; Swaminathan, Mukundakrishnan, & Hu, 2006). Through direct numerical simulation of the Navier–Stokes equation, Zhang, Ahmadi, Fan, and Mclaughlin (2001) studied ellipsoidal particle transport and deposition in dilute turbulent channel flows. Xia et al. (2009) studied the sedimentation dynamics of a single two-dimensional elliptical particle in a Newtonian fluid within a vertical pipe. They evaluated the effect of boundaries on the flow patterns. Mortensen, Andersson, Gillissen, and Boersma (2006, 2008) presented a direct numerical simulation of ellipsoidal and spherical particles suspended in a turbulent channel flow. They concluded that ellipsoidal particles tend to align with the mean flow direction in the near-wall region; this alignment increases with increasing particle aspect ratio. For polydisperse deposits of general ellipsoids, Baram and Lind (2012) found that the degree of polydispersity played a minor role, when compared with particle shape. Through direct numerical simulation combined with a "point-source" approach including Lagrangian tracking of individual ellipsoids, Zhao and van Wachem (2013) studied the behavior of very small ellipsoidal particles in turbulent channel flow. Huang, Yang, and Lu (2014) studied the sedimentation behavior of an ellipsoidal particle in narrow and infinitely long tubes, using a lattice Boltzmann method. For particles in a laminar pipe flow having various Reynolds numbers, Tavakol, Abouali, Yaghoubi, and Ahmadi (2015) simulated the deposition efficiency of ellipsoidal fibers of different sizes and aspect ratios. Njobuenwu and Fairweather (2015) described a computational approach for simulating three-dimensional motion of a single non-spherical particle in a turbulent channel flow. They simulated translation and orientation of various single ellipsoidal particles (disk-shaped, spherical, and needle-like ones) in such flow. Their work led to an improved understanding of the significance of particle shape on particle behavior. Our literature review indicates that many researchers consider ellipsoidal particles in solid–liquid two-phase flow, using numerical simulation to model their behavior. For theoretical study of single particle movement, the Basset–Boussinesq–Oseen (BBO) equation is very useful. However, its analytical solution, describing the motion of particles under different conditions, is seldom determined. For many practical applications, it is also not sufficient to only study the sedimentation behavior of such particles, given that attachment of such particles to side walls and their transport behavior in a horizontal direction are equally important. To describe the horizontal motion of different shaped particles, it is important to study the effect of shape on the particle motion within a horizontal flow field.

Here, a physical model of an ellipsoidal particle is established, based on the assumption that the particle moves horizontally within a homogeneous steady incompressible viscous fluid. Using the BBO equation (Lei, Jin, Zhu, & He, 2002; Tauro, Pagano, Porfiri, & Grimaldi, 2012), we describe particle motion. A modified particle motion equation can also be obtained from a stress analysis and a parameter analysis. Coupling between the particle and the flow field is based on simple physical assumptions. Velocity change was determined by solving the modified BBO equation for both ellipsoid and spherical particles, moving in a horizontal flow field of low Reynolds number.

Theoretical study of ellipsoid and spherical particle motion

Model assumptions for particles in a horizontal flow field

It is known that inerratic spherical particles are rare in nature, and that most natural particles are non-spherical. Therefore, issues arise in the practical application of many simulation results (Xu, Che, & Xu, 2006). Marine micro-plankton and other natural particles have varied shapes, being often of fusiform or ellipsoid types. For marine micro-plankton, only considering spherical particles is not sufficient to evaluate their behavior in solid–liquid two-phase flow. Other morphologies need to be taken into consideration. This paper discusses the velocity changes of ellipsoidal particles in a horizontal flow field, and compares it with velocity changes of spherical particles. In the near-wall region of subsea structures, small-scale plankton and other natural particles affect the equipment surfaces, as they are driven by the fluid moving along the boundaries of the subsea equipment. Generally, these