International Journal of Multiphase Flow 83 (2016) 217–231

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmultiphaseflow

Settling velocity of small inertial particles in homogeneous isotropic turbulence from high-resolution DNS

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ARTICLE INFO

Article history:
Received 18 November 2015
Revised 4 March 2016
Accepted 5 April 2016
Available online 14 April 2016

Keywords:
Settling velocity
Inertial particles
Cloud droplets
Turbulence
DNS

ABSTRACT

The gravitational settling velocity of small heavy particles in a three-dimensional turbulent flow remains a controversial topic. In a homogeneous turbulence of zero mean velocity, both enhanced settling velocity and reduced settling velocity have been reported relative to the still-fluid terminal velocity. Dominant mechanisms for enhanced settling include the preferential sweeping and particle-particle hydrodynamic interactions. The reduced settling could result from loitering (falling particles spend more time in the regions with upward flow), vortex trapping, and drag nonlinearity. Here high-resolution direct numerical simulations (DNS) are used to investigate the settling velocity of non-interacting small heavy particles, for an extended range of flow Taylor microscale Reynolds numbers (up to $R_\lambda = 500$) with varying particle terminal velocity (relative to the Kolmogorov velocity) and particle inertia, by changing the particle-to-fluid density ratio and energy dissipation rate. For the parameter regimes considered here, the preferential sweeping has a dominant effect leading to an increase of the average settling velocity relative to the terminal velocity; and this increase is mainly governed by particle Froude number (the ratio between the particle inertial response time and the residence time of the particle in a Kolmogorov eddy) and its magnitude depends linearly on the square root of the energy dissipation rate. The reduction of settling due to loitering rarely occurs in a homogeneous turbulence without organized large-scale vortical structures, but is found to emerge only if the particle horizontal motions are blocked (thus removing the preferential sweeping effect), as shown in Good et al. (2014). The DNS results were used to develop a parameterization that relates the settling velocity to the particle inertia (St), Froude number, and R_λ. Finally, sensitivities of the DNS results to the large-scale forcing method and to the drag nonlinearity are also briefly discussed.

1. Introduction

The settling velocity of small heavy particles is relevant to many applications such as pipeline pneumatic transport (Fokeer et al., 2004; Lain and Sommerfeld, 2013), coal combustion (Zhou et al., 2004; Smoot, 2013), transport of biogenic substances in the oceans (Noh et al., 2006), sediment transport in water bodies (Papanicolaou et al., 2008; Keshtpoor et al., 2015), modeling of dust storm (Tsidulko et al., 2002), and warm rain formation (Grabowski and Wang, 2013; Ghosh and Jonas, 2001). More generally, the dynamics of small heavy particles in a turbulent flow affects the spatial distribution of particles (Squires and Eaton, 1991; Wang and Maxey, 1993), particle deposition rate (Kallio and Reeks, 1989; Li et al., 2001), and turbulent collision rate of inertial particles (Zhou et al., 2001; Sundaram and Collins, 1997).

Small heavy particles have a diameter less than the Kolmogorov scale of the carrier fluid turbulence and a density much larger than that of the fluid. These particles could have a significant inertia, as quantified by a finite Stokes number St (the ratio of their inertial response time τ_p to the flow Kolmogorov time τ_K), and a significant terminal velocity, in terms of the ratio $S_V = V_T/v_K$ with V_T being the particle still-fluid terminal velocity and v_K the flow Kolmogorov velocity. In this work, we concern mainly the average settling velocity of such particles in a homogeneous turbulent flow, under the assumption that the particle mass loading is very low so that the effect of particles on the fluid turbulence is weak (i.e.,

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.04.005
0301-9322/

Table 1
Relations between dimensional and nondimensional parameters.

	St	S_V	Fr	R_λ
a	$St \propto a^2$	$S_V \propto a^2$	$Fr \propto a^6$	no effect
$\mathbf{g}$	no effect	$S_V \propto \mathbf{g}$	$Fr \propto \mathbf{g}^2$	no effect
ε	$St \propto \varepsilon^{0.5}$	$S_V \propto \varepsilon^{-0.25}$	no effect	$R_\lambda \propto \varepsilon^{-0.5}$
ν	$St \propto \nu^{-1.5}$	$S_V \propto \nu^{-1.25}$	$Fr \propto \nu^{-4}$	$R_\lambda \propto \nu^{-0.5}$
$\sigma = \frac{\rho_p}{\rho_f}$	$St \propto \sigma$	$S_V \propto \sigma$	$Fr \propto \sigma^3$	no effect
N	no effect	no effect	no effect	$R_\lambda \propto N^{2/3}$

one-way coupling) and particle-particle local hydrodynamic interactions can be neglected. It is well known that the average settling velocity, relative to the mean flow, may differ from V_T for a variety of reasons, to be discussed below.

The motion of small heavy particles depends on two governing parameters which can be expressed in terms of other physical parameters as follows (Wang et al., 2006):

$$St = \frac{\tau_p}{\tau_K} = \frac{2}{9}\frac{\rho_p}{\rho_f}\frac{\varepsilon^{0.5}}{\nu^{1.5}}a^2, \quad S_V = \frac{V_T}{v_K} = \frac{2}{9}\frac{\rho_p}{\rho_f}\frac{g}{\varepsilon^{0.25}\nu^{1.25}}a^2, \tag{1}$$

which implies that, in real applications, there are five physical parameters affecting the dynamics: the particle radius a, the gravitational acceleration $\mathbf{g}$, the energy dissipation rate ε, the fluid kinematic viscosity ν and the particle-to-fluid density ratio $\sigma = \rho_p/\rho_f$.

An important derived parameter combining St and S_V is the particle Froude number, namely, the ratio of particle response time τ_p to the residence time of the particle in a Kolmogorov eddy (Davila and Hunt, 2001)

$$Fr = \frac{\tau_p}{\Gamma_{vort}/v_p^2} = \frac{\tau_p V_T^2}{\eta v_K} = St S_V^2 = \frac{\tau_p^3 g^2}{\nu} = \left(\frac{2}{9}\right)^3\left(\frac{\rho_p}{\rho_f}\right)^3\frac{g^2a^6}{\nu^4}, \tag{2}$$

which is independent of flow energy dissipation rate. Here, η is the Kolmogorov length scale. For water droplets in air, this parameter reaches one when $a \approx 20$ µm. Ayala et al. (2008) showed that the sedimenting particles obtain a maximum relative settling-velocity enhancement at $a \approx 20$ µm (see also Table 4 in Section 3.1). Another parameter affecting the level of settling velocity is the flow Reynolds number (R_λ) which defines the range of flow length scales or the large-to-small scale ratio in the flow. $R_\lambda = u'\lambda/\nu$ where u' is the rms fluctuating velocity and λ is the transverse Taylor microscale. The effects of key parameters on the dimensionless parameters are shown in Table 1.

Based on the simplified equation of motion we assume that the difference between average settling velocity $\langle V_S\rangle$ and the terminal velocity V_T is an unknown function of the following parameters

$$\langle V_S\rangle - V_T = \mathbf{F}(\tau_p, V_T, \varepsilon, u', L_f, \ldots), \tag{3}$$

where, L_f is the integral lengthscale of the turbulent flow. Since $L_f \sim \eta R_\lambda^{1.5}$ and $R_\lambda = \sqrt{15}(u'/v_K)^2$ the integral lengthscale can be omitted from Eq. 3. The dimensional analysis leads to three equivalent representations of Eq. 3, namely

$$\frac{\langle V_S\rangle - V_T}{v_K} = \mathbf{F}_1(St, S_V, R_\lambda, \ldots), \tag{4}$$

$$\frac{\langle V_S\rangle - V_T}{V_T} = \mathbf{F}_2(St, S_V, R_\lambda, \ldots) = \frac{\mathbf{F}_1}{S_V}, \tag{5}$$

$$\frac{\langle V_S\rangle - V_T}{u'} = \mathbf{F}_3(St, S_V, R_\lambda, \ldots) = \frac{15^{0.25}}{R_\lambda}\mathbf{F}_1. \tag{6}$$

In each of these three equations, the change in the settling rate can be expressed in terms of the same function $\mathbf{F}_1$. This function, depends only on the dimensionless parameters such as St, S_V (or Fr), and R_λ.

In a homogeneous turbulence of zero mean velocity, both enhanced settling velocity and reduced settling velocity have been reported. The dominant mechanism for enhanced settling velocity of small heavy particles in a turbulent flow is the preferential sweeping (Wang and Maxey, 1993). In their pioneering work, Maxey and Corrsin (1986) demonstrated that inertial particles can distribute very non-uniformly in a steady non-uniform flow, and consequently sedimenting particles may converge to a path located on the downward side of a vortex, leading to a higher settling velocity. Maxey (1987) extended the above study to a time-dependent non-uniform flow, and found both analytically and numerically that inertial particles accumulate in regions of low vorticity and high strain rate, a phenomenon now known as the preferential concentration. He found that the preferential concentration leads to a bias of particle trajectory and an enhanced settling rate. Wang and Maxey (1993) performed direct numerical simulations to show that the preferential concentration is strongest when St and S_V are of the order one in a realistic turbulent flow. They also demonstrated that the mean particle settling velocity is significantly enhanced under similar conditions, with the level of enhancement depending on the large-scale flow statistics.

Fung (1997) modeled the motion of small spherical particles in an infinite, two-dimensional unsteady flow. He showed that enhancement of the settling velocity occurs when $V_T/\sigma_u \leq 0.7$. Here σ_u is a characteristic velocity of the flow. The maximum increase occurs when $V_T \approx 0.5\sigma_u$. In the steady flow (flow with one length scale), however, the total suspension takes place when V_T is of order of the characteristic fluid velocity. Lillo et al. (2008) studied the settling velocity of heavy particles in two-dimensional turbulent and laminar flows. They showed that at large flow velocities particles are effectively guided to the down-flow regions and the actual settling velocity is larger than V_T. Afonso (2008) investigated the settling of inertial particles in 2D cellular flow. He found that for square, static cellular flows and at relatively small St the settling velocity, is larger than the terminal velocity. However, starting from a certain critical value of St, the falling velocity becomes lower than V_T. Although the author does not state explicitly what mechanism reduces the settling velocity, we assume that the reduction may be due to vortex trapping.

Using both DNS and large-eddy simulation (LES), Yang and Lei (1998) examined the role of turbulent scales in the settling velocity of heavy particles. They found that large-scale flow plays a significant role in determining the increase in settling velocity, namely, the increase in settling scales with rms fluid velocity (u'), not v_K, but peaks at $St \approx 1$.

The problem of settling rate of inertial particles has also been investigated experimentally. Zhou and Cheng (2009) monitored the settling velocity of low-inertia solid particles in turbulent water flow generated by an oscillating grid. They found that the actual settling velocity of the particles is generally smaller than the corresponding terminal velocity. The authors showed that the reduced settling velocity correlates with the vertical velocity fluctuation. Ruiz et al. (2004) measured the settling velocity of phytoplankton cells in turbulent flows generated in water by different mechanical devices. They concluded that the larger settling velocity observed in the experiment is likely due to mechanism of preferential sweeping. Cuthbertson and Ervine (2007) investigated the behavior of fine sand particles in turbulent open channel flow generated over rough, porous bed condition. Based on the experimental data they concluded that the settling rate of the suspended fine sand can be significantly enhanced over the terminal velocity.

Other mechanisms for enhanced settling, discussed in the literature, include the influence of local particle-particle hydrodynamics interactions (Aliseda et al., 2002; Alipchenkov and Zaichik, 2009) and the effect of two-way coupling (Dejoan, 2011; Yang and Shy, 2005; Bosse et al., 2006).