Powder Technology 257 (2014) 192–197

Contents lists available at ScienceDirect

Powder Technology

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

The influence of aspect ratio on distributions of settling velocities and orientations of long fibres

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ARTICLE INFO

Article history:
Received 9 October 2013
Received in revised form 7 February 2014
Accepted 18 February 2014
Available online 26 February 2014

Keywords:
Fibrous particle
Aspect ratio
Settling velocity
Aerosol

ABSTRACT

The influence of the aspect ratios of fibrous particles on their settling velocities and orientations is reported under super dilute conditions in which fibrous particles settle in air at Reynolds number of 3–70 based on fibre length and at aspect ratios of 35, 48 and 60. Measurements were performed using Particle Tracking Velocimetry (PTV) to calculate orientation and velocity based on the two end-points, following a method reported previously. With the mean volume fraction of 0.0005, the key findings are: 1) for a constant diameter of 20.1 μm, the absolute mean vertical settling velocity, $\overline{V_{cx}}$, is not independent of fibre length, the long fibre $\overline{V_{cx}}$ is a little higher, while the settling velocity normalized by that of an equivalent sphere, $V_{cx}/V_{eq\text{-}sph}$, decreases with an increase in fibre length over the range 700 μm to 1200 μm; 2) for a constant length of 700 μm, both $\overline{V_{cx}}$ and $V_{cx}/V_{eq\text{-}sph}$ decrease with an increase in diameter over the range 14.5 μm to 20.1 μm; 3) for a constant aspect ratio but different length and diameter, $\overline{V_{cx}}$ slightly increases with an increase in particle size, while $V_{cx}/V_{eq\text{-}sph}$ decreases with an increase in particle size; 4) angular velocities and their distributions for four types of fibrous particles were reported.

1. Introduction

The settling of fibrous particles through a fluid toward the ground is a common phenomenon in nature and also occurs in industrial processes such as paper making. The understanding of the motions of fibrous particles in this basic environment is also a prerequisite to that of their motions in more complex conditions, such as in the turbulent flows of relevance to biomass combustion. The percentage of biomass being used is increasing around the world because it is a renewable and more environmentally "friendly" resource for energy supply. However, biomass is fibrous, there is a paucity of data describing the aerodynamics of fibrous particles and gaps remain in the present understanding of the aerodynamic behaviour of settling fibrous particles. The settling motion of a fibrous particle is much more complex than that of a sphere. While a sphere settles in a purely vertical direction, for a fibrous particle, the instantaneous horizontal drift cannot be neglected. A fibrous particle also exhibits rotation. Many previous works such as those of Qi et al. [1,2], Shin et al. [3], Salmela et al. [4], Lin and Zhang [10], Stover et al. [11] and Zhang et al. [12], have investigated the dynamics of fibrous particles. McKay et al. [5] investigated the settling characteristics of discs and cylinders of aspect ratio (cylinder length/diameter, L/d) from 0.25:1 to 5.0:1 (with the same diameter) in water with particle's Reynolds number of 680–15,350 based on equivalent volume diameter. The particles used in their experiments were large non-spherical particles with diameters of 16 mm and 20 mm. The terminal settling velocity of cylinders of $L/d < 1$ was found to increase with increasing L/d. However for cylinders of $L/d > 1$, the terminal settling velocity was found to be nearly independent of L/d. Importantly it is not yet known whether this finding extends to small fibrous particle with a large L/d.

Lin et al. [6] studied the sedimentation of a single fibrous particle with aspect ratios of 2, 3, 5, 7.5 and 10 in a Newtonian fluid employing the Lattice Boltzmann method at terminal Reynolds number of 1–10. Their simulation showed that the stable orientation of these fibres is horizontal. They also found that the terminal Reynolds number increases with increasing L/d and then remains constant for $L/d > 5$, which supports the conclusion of McKay et al. [5]. They further found that the horizontal component of velocity of a fibrous particle increases with increasing L/d. However, these conclusions are yet to be verified with experimental data for fibres with large L/d.

Fan et al. [7] investigated the settling motion of slender particles of Reynolds number $Re_d = 0.4$–100 based on the fibre's diameter with large aspect ratios from 4 to 40 in stagnant water. They found that the orientation of a fibre approaches gradually from any original orientation to a final stable horizontal orientation which agreed with simulation of Lin et al. [6]. However, this contrasts the finding of Qi et al. [1,2], who found that particles of similar aspect ratio and Reynolds number in a dilute suspension do not retain a fixed orientation, but continue to swing. However, no measurement of the distribution of the angular velocity of fibres has been reported previously. Fan et al. [7] also reported that the

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http://dx.doi.org/10.1016/j.powtec.2014.02.050
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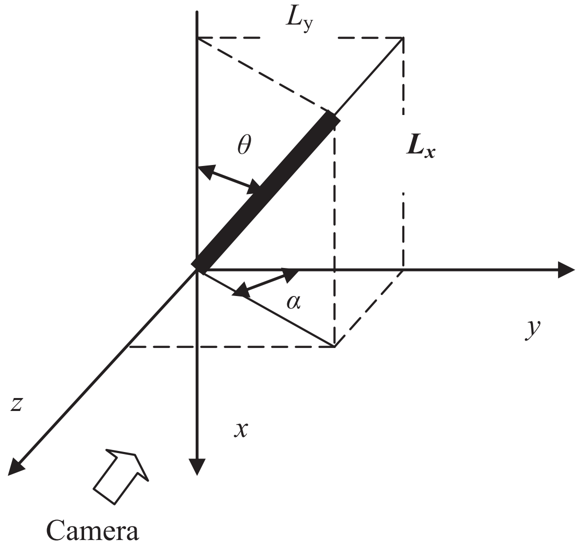

Fig. 1. The notation used to define orientation of a fibre, relative to the *x*–*y* image plane.

behaviour of the drag coefficient for fibres is independent of its aspect ratio. However no direct assessment of the influence of aspect ratio on settling velocities has been reported.

Kuusela et al. [8] simulated the settling of spheroids under steady state sedimentation at $0.5 < Re_L < 3.5$ (Reynolds number based on length) with aspect ratios of 1, 3, 5 and 7 for particles of constant diameter. The authors assessed the role of aspect ratio of fibres and found the maximum dimensionless settling velocity to decease with increasing aspect ratio. They also found that the volume fraction of peak velocity increases with increased volume fraction. These results are in good agreement with Herzhaft and Guazzelli's work [9]. Herzhaft and Guazzelli [9] studied the steady-state settling velocity and orientation distribution of glass-rods in dilute and semi-dilute suspensions for Reynolds number less than 0.0001. The fibrous particles used in their experiments were of length of 500–3000 μm and diameter of 100 μm. They used fibres with aspect ratios of 5, 11, 20 and 32 to investigate the influence of aspect ratio. They found that, over this range, the aspect ratio has little influence on the fibre's orientation, but that the dimensionless settling velocity decreases with increasing aspect ratio for particles of constant diameter. Nevertheless, this dependence decreases with L/d so that the absolute velocity of fibres with aspect ratios of 10 and 20 is nearly identical, while the absolute velocity of fibres with aspect ratio of 5 is much smaller. However, their investigation was undertaken in a configuration that induces a recirculating flow within the working section, so that approximately 40% of their data have negative velocities. In addition, no details of the influence of aspect ratio at higher Reynolds number $Re \sim O(10)$ are available. Hence it is necessary to assess whether their findings extend to free-falling particles at higher Reynolds number.

In the light of the above review, it is clear that previous work suggests that the mean settling velocity depends asymptotically on aspect ratio, to become independent of it at sufficient aspect ratio for particles of the same diameter. However this is yet to be confirmed, particularly for Reynolds numbers of order 10. In addition, to date no detailed statistical assessment of the influence of aspect ratio on other parameters, such as the distribution of the settling velocity or on horizontal velocity, has been reported. Therefore, the aim of the present work is to assess the influences of aspect ratio within the asymptotic regime, i.e. for $L/d > 20$, on the distribution of settling velocity, horizontal velocity and orientation of fibres, using the method developed by Qi et al. [1].

2. Experimental apparatus

Only a brief description of the experimental apparatus and approach is provided here, with details reported by Qi et al. [1]. Fig. 1 presents the notation used to define a fibre's orientation relative to the x–y image plane. The angle α (0°–90°) is defined to be the azimuth of a fibre relative to the viewing plane and θ (0°–90°) its orientation relative to gravity.

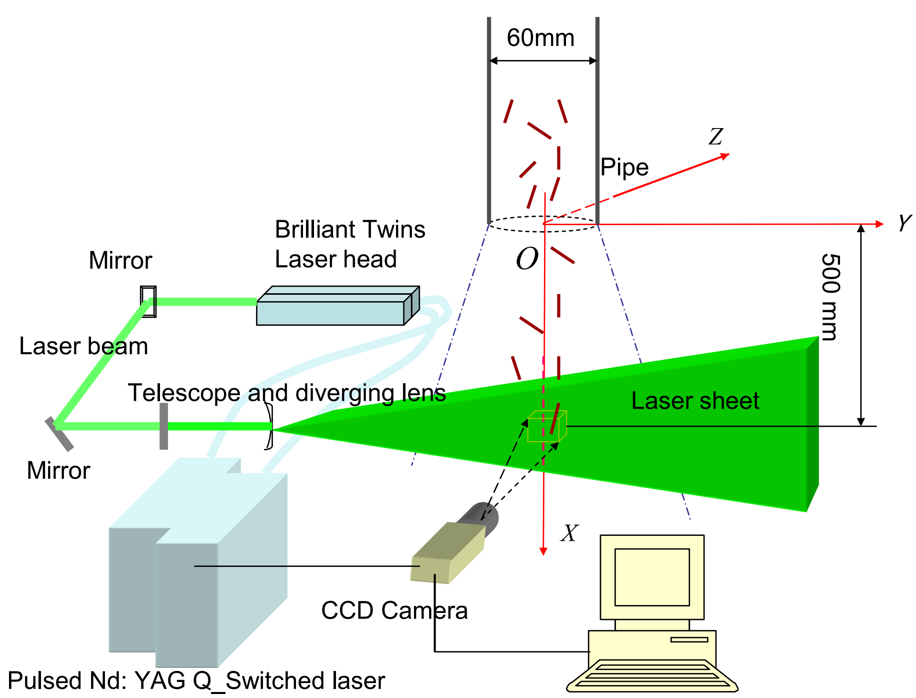

Fig. 2. Experimental arrangement (not to scale). The surrounding settling chamber (650 mm × 620 mm cross section) is not shown for clarity.