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Fluid dynamic forces acting on irregular shaped particles: Simulations by the Lattice–Boltzmann method

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A B S T R A C T

Commonly numerical calculations of particle-laden flows are based on the assumption of spherical particles. In practice however, particles are mostly irregular in shape and therefore the spherical particle approximation has to be mistrusted in such cases. Information on the fluid dynamic forces acting on irregular shaped particles is though quite rare. Consequently, the Lattice-Boltzmann method with local grid refinement and curved wall boundary condition was applied to simulate laminar plug flow about fixed irregular shaped particles. For a large number of particle orientations and two sets of four irregular particle types, each with about the same sphericity (i.e. 0.71 and 0.87), the drag, lift and torque coefficients were calculated. From these results distributions of the resistance coefficients were derived for particle Reynolds numbers between 1 and 200. These distributions could be reasonably well approximated by normal distribution functions which are defined by a mean value and a standard deviation. The mean values and the standard deviations of the simulated coefficients for drag, profile lift and torque very well correlate with the particle Reynolds number and are of course depending also on sphericity. Expectedly, the drag coefficient increases with decreasing sphericity. This information may be now used for developing a statistical model for the fluid forces acting on irregular particles in the frame of a Lagrangian approach. Hence, in each tracking time step instantaneous values of the drag, lift and torque coefficients may be drawn from the distributions with given mean value and standard deviation. This approach should mimic the random behaviour of irregular shaped particles.

1. Introduction

Handling of powders by transportation in a fluid flows (i.e. gas or liquid) is common for numerous industrial and technical areas. Generally, these powders are not spherical but have a certain shape, such as fibres, cylinders and discs or are quite often even irregular in shape. Such irregular shaped particles have naturally a size distribution and also the shape is not uniform as illustrated in Fig. 1, so that it is not possible to define a unique major and minor axis. The fluid dynamic forces (i.e. drag, lift and torque) on such particles are largely unknown. Therefore, in most numerical calculations of particle-laden flows by either the Euler/Euler or the Euler/Lagrange approach, it is assumed that the particles are spherical (see for example Lain and Sommerfeld, 2007). This however might be a strong simplification yielding incorrect results regarding the two-phase flow characteristics (e.g. concentration and velocities) as well as the resulting integral properties, e.g. the pressure drop in pipe systems.

During the past 15 years research on non-spherical particle behaviour, mainly related to regular shapes, has considerably expanded and new approaches in modelling the fluid dynamic forces acting on such particles were developed. A classification of the different regimes of modelling the motion of regularly shaped particles with respect to particle Reynolds-number and the particle size in relation to the Kolmogorov length scale was recently introduced by Voth and Soldati (2017).

Irregularly-shaped particles however were rarely considered in the past, although they are very often found in industrial and technical processes. For improving this situation, there are two options in dealing with irregular-shaped particles.

First, one may conduct numerical calculations just tracking point-particles without considering their orientation and only use available average drag correlations for non-spherical particles depending on a shape index. In the work of Haider and Levenspiel (1989) numerous experimental data were considered for deriving drag coefficient correlations for non-spherical particles in dependence of the sphericity. The sphericity ϕ is defined as the ratio

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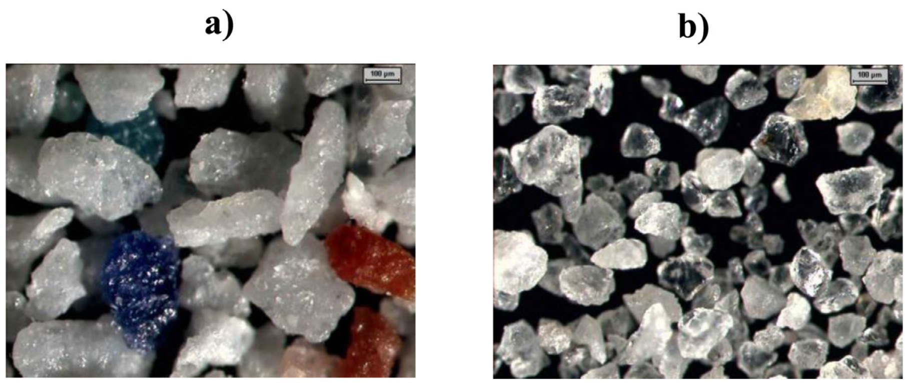

Fig. 1. Photographs of irregular shaped particles; a) Duroplast particles volume equivalent mean diameter 240 µm, mean sphericity $\phi = 0.7$; b) Quartz sand volume equivalent mean diameter 185 µm, mean sphericity $\phi = 0.87$ (Kussin, 2003).

of the surface area of the volume equivalent sphere to the surface area of the considered non-spherical particle. Haider and Levenspiel considered two sets of experiments; one for close to isometric particles with higher sphericities $0.67 < \phi < 0.906$ and the other for disc-like particles with lower sphericity $0.026 < \phi < 0.23$. It must be emphasized that these correlations are averaged values where the particles have mostly a distinct orientation relative to the flow. Such experimentally derived drag coefficients were obtained from wind tunnel studies with fixed particles or from a sedimentation analysis. Here the particles have a certain preferential orientation maximising the drag or are oscillating around such an equilibrium orientation; e.g. a disc is sedimenting more or less horizontally aligned and may also tumble around this position at higher particle Reynolds numbers. For such a situation the derived drag correlations are trajectory averaged values (Voth and Soldati, 2017). Although numerically very efficient, these correlations have limited application since they are based on a certain orientation of the particles with respect to the relative flow which of course is not observed in turbulent flows. Moreover, this approach will not account for non-sphericity in the transverse lift forces if considered.

In the second approach it is assumed that irregular shaped particles may be approximated by regular shapes such as ellipsoids or cylinders. With that a major and minor axis can be defined, allowing also the tracking of particle orientation in a Lagrangian calculation. This was the motivation of Ouchene et al. (2015) for conducting direct numerical simulations for ellipsoids with different eccentricity (i.e. ratio of minor axis to major axis) at a range of inclinations. Having all these data correlations for drag, lift and torque coefficients in dependence of particle orientation could be derived and used to conduct Lagrangian calculations for point-particles solving for the change of linear and angular velocities in combination with following the non-spherical particle orientation. This was for example done by van Wachem et al. (2015) in calculating a horizontal particle-laden channel flow where the behaviour of large and hence inertial, non-spherical particles (i.e. large particle Reynolds numbers) was analysed in this way. The drag and lift coefficients were obtained in dependence of non-spherical particle orientation (here ellipsoids of different axis ratio) from particle-resolved simulations (Zastawny et al., 2012) and used by applying correlations and blending functions. As suggested by the early work of Rosendahl (2000) the drag coefficient was approximated from results obtained at zero and 90° angle of incidence and the profile lift coefficient was correlated with the drag coefficient and the angle of incidence. For the lift coefficient however improved correlations compared to the previous work of Rosendahl (2000) and Mando and Rosendahl (2010) were developed. For the horizontal channel flow (Wachem et al., 2015) it was shown that non-spherical particles have higher mean velocities in the stream-wise direction than spherical particles with the same volume due to their preferential orientation perpendicular to the mean flow direction. This is also in accordance with the measurements conducted by Kussin (2003) for different non-spherical particles in comparison to spherical ones.

In point-particle tracking of non-spherical particles with following their orientation, quite often low particle Reynolds number approximations (i.e. Stokes flow) are used for calculating the translational and rotational motion of non-spherical particles. For the hydrodynamic drag acting on ellipsoidal particles often the Stokesian resistance tensor proposed by Brenner (1963) is used and for the torque on ellipsoidal particles the expressions derived by Jeffery (1922) are applied. Sometimes also shear-induced lift forces valid for the Stokes regime are considered as for example done by Zhang et al. (2001). A number of studies were conducted based on DNS (direct numerical simulation) with Lagrangian tracking of point-particles and following their orientation using the Stokes approximations (Zhang et al., 2001; Mortensen et al., 2008; Marchioli et al., 2010). Zhang et al. (2001) put the main focus on particle transport and deposition in a turbulent channel flow. The studies of Mortensen et al. (2008) considered the preferential orientation of ellipsoids with several aspect ratios in a channel flow. Based on such simulations Marchioli et al. (2010) found that Stokes-fibres do not show a preferential orientation in the centre region of the channel. A thorough discussion on the behaviour of regular non-spherical particles in turbulence and associated preferential orientation effects is also presented by Voth and Soldati (2010). Since in most practical situations larger non-spherical particles exist, particle orientation-dependent resistance coefficients (i.e. drag, lift and torque) are required, as for example considered by van Wachem et al. (2015).

In the past a number of studies were performed applying direct numerical simulations to derive drag, lift and torque coefficients in dependence of orientation for different particles such as cuboids, cylinders and fibres (Hölzer and Sommerfeld, 2009; Vakil and Green, 2009; Zastawny et al., 2012; Ouchene et al., 2016). Moreover, a drag correlation which accounts for particle orientation was suggested based on these simulations (Hölzer and Sommerfeld, 2008).

Considering however irregular shaped particles, as for example illustrated in Fig. 1, showing quartz and Duroplast particles (Kussin, 2003), it is obvious that they have a size distribution and in addition a more or less wide distribution of shapes. Therefore, it is also not possible to define a unique major and minor axis of such types of particles. Typically the sphericity of such particles is rather large, let's say above 0.7. Besides that also the surface structure of the particles may considerably vary. Hence, the approaches

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