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Measurement of drag coefficients of non-spherical particles with a camera-based method

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ABSTRACT

The current paper presents a novel experimental set-up which allows the automated determination of the drag coefficients of relatively large particles with complex shape. Typical examples of such types of particles are waste derived fuel (RDF) particles which are non-spherical and have a size up to a few centimeters. In contrast to conventional fossil fuel particles, where the particles may be considered as material points during the calculation of particle tracks in a reacting flow field, the spatial extent of RDF-particles and their lack of sphericity lead to pronounced self-induced movement and associated variations in the drag-coefficients.

The experiments are based on a drop shaft equipped with two digital cameras. This allows to obtain time resolved stereo image sequences from which the settling velocity of particles, the self-induced velocity fluctuations and the corresponding drag and lift coefficients can be derived. As the system is automated, a large number of particles can be examined and statistical information on the distribution of drag coefficients can be obtained.

In this publication, the methodology of these drop shaft measurements and their evaluation will be presented. Additionally drag coefficients of isometric spherical and non-spherical particle geometries (spheres, cubes, square plates and circular disks) were measured and compared with known correlations for drag coefficients. Probability density functions for the properties of typical RDF particles will be presented to highlight the potential of the new set-up.

1. Introduction

In combustion processes such as coal fired power plants, cement kilns or in processes like material classification, centrifugation, dust collection or crystallization, the knowledge of individual particle trajectories is of utmost importance. Questions related to design and operation of these industrial processes can often be answered only if the local flow behavior and the interaction among the solid and fluid phases are known with sufficient detail [1–5]. This is especially true for data on the resistive forces acting on particles dispersed and transported in a turbulent flow. The particles trajectories within a turbulent flow field are obtained by integration of the forces acting on the transported particle over time. For small particles and quite homogenous material, where the actual particle geometry may be neglected and the moving objects can be safely approximated as material points, sufficiently reliable descriptions do exist and are applied routinely. Empirical correlations, commonly used in this context for the drag coefficients, depend on physical particle parameters and the range of the slip velocity between particle and fluid (respectively the Reynolds-number). Depending on the physical complexity of the particle, it is characterized by mass, volume, density, the three perpendicular axes, the projection area, the projection perimeter, surface area, shape (or sphericity) and circularity. Detailed information can be found in Dellino et al. [35] and Nikku [37]. Nevertheless, for a given material it is difficult to choose the appropriate correlation.

Many situations and technical systems are already covered with correlations, but there still exists a broad range of applications where the assumption of material points is invalid and the available descriptions are inadequate [12–15]. Especially if the particles considered are comparably large and thus cannot be regarded as material points and moreover, if the dispersed phase is also heterogeneous in size and shape, much more detailed and statistical information related with particle movement (fluctuating velocity, dispersion) is required to obtain reliable results.

The particle orientation with respect to the local flow induces strong lift forces perpendicular to the drag forces, resulting in particle rotation and particle velocity fluctuations which interact in a complex way with turbulent eddies of the gas phase. In regions with low flow turbulence, especially when the relative velocity between particle and flow approaches the particle settling velocity, the fluctuating self-induced movements become dominant but cannot be considered in simulations so far.

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One quite familiar group of applications, on which the current study is focused, is the co-combustion of biomass and waste derived fuel (RDF) in boilers and industrial furnaces. In these cases, the main "standard" fuel is typically ground to a particle size below two hundred micrometers, while the substitute fuel is comminuted much less due to technical and economic reasons. These particles are very irregular and contain a large amount of flat particles with edge lengths of about 1 cm. Due to the large particle size and thus pronounced self-induced movement relative to the average flow (e.g. falling leaves in autumn), the RDF particle tracks can deviate from the tracks computed from the fluid flow only. In close vicinity of the particle inlets, where the imposed flow field strongly accelerates or decelerates the particles, the effect of geometry-induced fluctuations is small. When shortly later the slip-velocity approaches the particle's settling velocity, the self-induced velocities attain the same magnitude as the velocity fluctuations from flow turbulence. Small initial positional deviations hence can result in largely different positions further downstream. In principle, simulations fully resolving the details of the flow around the individual particles could improve this, but for the time being they are not feasible for systems of technical scale, thus additional experimental information is required to fill this gap. In the experiments conducted so far, particle orientation and self-induced movements have not been taken into account.

2. Previous work on drag coefficients

Analysis of published studies on the determination of drag coefficients shows that correlations based on the global, time averaged behavior are numerous [6–11] compared to results accounting for the local time resolved behavior [31].

Commonly employed correlations for the drag coefficients of non-spherical particles only extend the results obtained for spherical particles; interaction with flow turbulence is introduced solely via a Reynolds number dependence on the average slip velocity and the shape factor plus a stochastic choice of the actual local gas velocity thus mimicking turbulent eddies. The effect of self-induced secondary motion, especially important for large particles in the limit of stagnant surroundings is neglected.

Two basic experimental setups were used in the past to determine time averaged drag coefficients from terminal settling velocities: a) keeping a particle in a stationary position using a counterflow (Fig. 1 left) and b) drop tube test where a particle falls in a stagnant fluid (Fig. 1 right). An easy way to assess the settling velocity is to measure the volume flow in a vertical channel at which the particle is held in suspension (Fig. 1 (left)).

The experimental set-up where a particle is held in a stationary position was used among others by Hartman and Dunnu [21]. Hartmann used a cylindrical glass column with a diameter of 0.085 m and a height of 2 m. The particles were flown from the bottom by air. The gas stream was increased gradually during the tests while pressure loss and gas velocity were measured. The average settling velocity was defined as the value, at which a significant drop in the pressure loss becomes noticeable. Hartman achieved a repeatability with less than 5% deviation [19].

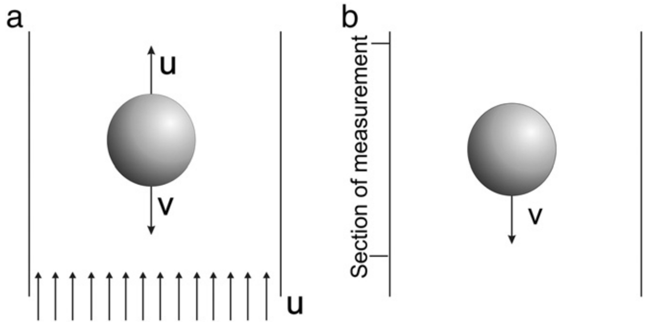

Fig. 1. Experimental arrangement for determining the settling velocity in the stationary flow (left)/in the stationary surrounding (right).

Drop tests — often carried out in liquids (using similarity laws to transfer the results to other media) were carried out, among others, by Pettyjohn and Christiansen [15], Squires and Squires [16], Schmiedel [17], Willmarth [18] and Dellino [35]. It should be noticed here, that the two widely used correlations for the drag coefficient, of Haider-Levenspiel [25] and of Ganser [26], are both based on experimental investigations of Schmiedel [17]. Pettyjohn and Christiansen investigated the settling velocity of non-spherical particles in different fluids. The experiments were performed in a 3.1 m high column filled with different fluids (oil, corn syrup and water) and averaged velocities were obtained. To minimize the effects related to orientation, isometric metal particles of spherical shapes, octahedron, tetrahedron and cubes were used [15].

Dellino conducted drop tests with pumice particles with a shape factor range between 0.34 and 0.9. In addition he analyzed each of the particles in size, density and shape by modern image-analysis techniques with digital high resolution photographs [35]. He used the data to develop a shape dependent model for the calculation of the terminal velocity and the drag force. A detailed description as well as the implementation of the model into a CFD-Code is given in Dioguardi [36].

Schmiedel conducted drop tests in a 0.4 m high glass container using different fluids. The drop distance and the drop time were measured by means of a cinematographic method. Different viscous fluids glycerol and a homogeneous mixture of glycerin and water were used. The circular disks were made of spherical steel, aluminum, silver and gold [16]. Squires and Squires have also performed drop tests with circular disks of different sizes (Ø 4.64 mm, Ø 6.24 mm, Ø 9.5 mm). For these experiments a cylindrical glass container with 40 cm height was used. Markers were attached at a height of 17.5 cm and 5.6 cm. Drop time was measured between the two marks using a stopwatch. Mineral oil of three different viscosities was used as fluid. The experiments were carried out in two variants. Only the experiments in which particles had no rotation were analyzed [17].

Another investigation of the settling velocities of circular disks was performed by W. W. Willmarth. The experimental arrangement is similar to that of Squires and Squires. The fluids used were water and a mixture of water and glycerol. Circular disks made of homogeneous metals and plastics were used. In these experiments, the time the particles required to pass a specific distance was measured [18].

A summarizing list of the correlations typically used for time averaged drag coefficients is contained in Appendix B.

Note that both experimental arrangements do not allow the characterization of the local unsteady movement of irregularly shaped particles like tumbling or rotary motions [17]. Especially for flat shaped particles it is not appropriate to use mean values measured over a long period of time. In a gas flow the fluctuations of the velocity (turbulence) is taken into account by the kinetic energy. Similarly, the local unsteady movement of particles with non-spherical shape must also be taken into account. For this reason it is necessary to consider both velocity fluctuations (turbulent flow and self-induced movement) along the particle trajectory. Furthermore, the self-induced fluctuations introduce additional particle movements orthogonal to the main flight direction, thus considerably increasing the lateral movement and a wider dispersion for a particle collective.

3. Experimental apparatus and measurement procedure

An experimental set-up has been constructed to determine self-induced velocity fluctuations due to the particle shape and the continuously changing particle orientation.

Because movement of particles depends on size, geometry and mass, the analysis with the drop shaft system consists of two steps. The first step includes an analysis of the particle physical properties consisting of a combination of weighing and imaging in order to obtain the geometric characteristics. In a second step, the trajectories of falling