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Characterization method of average gas–solid drag for regular and irregular particle groups

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ABSTRACT

The shape and size of particles have a major effect on the fluidization behavior of the particles through the drag force from the fluid phase. Several methods to estimate the particle size exist, but without the consideration of the particle shape of irregular particles these methods can produce varying results. The particle shape can be described in numerous ways, but currently no method can successfully describe irregular particles without ambiguity. Many computational models consider all particles as monodisperse perfect spheres, although the real particles often have size and shape distribution. Especially for biomass materials these distributions are usually wide. Disregarding this in modeling might lead to inaccurate results. Another way to describe material drag force is through experimental testing and without detailed knowledge about the material particle size and shape distribution. This paper describes a characterization method of an average drag force between gas and different materials. Material sizes and shapes are defined with optical measurements and the averaged values are combined with the characterization method for comparison with standard drag curves of single particles.

1. Introduction

Environmental awareness has increased the concern about greenhouse gases and their effect on global warming, leading to the demand for the reduction of CO_2 and other greenhouse gases. Biomass usage is promoted over the use of fossil fuels in the European Union [1], leading to its increased utilization and research in energy production.

A widely applied and studied field is biomass combustion in fluidized beds. Fluidized bed applications utilize a bed of solid particles driven to a fluid-like state by blowing air through the bed. The amount of fuel is small compared to the bed material and the fuel is mixed efficiently and heated up rapidly, allowing the efficient combustion of even wet and low grade fuels such as biomass. The understanding of the hydrodynamic behavior of the bed material and fuel is one of the most fundamental aspects in fluidized beds, as it determines the flow structure of fluid and solids and many aspects of the process through the mixing and flow of fuel in the furnace. The fuel flow directly determines where the fuel reactions occur, affecting to the forming temperature distribution and flue gas composition. In the fuel flow, the drag force between the fluid and the particles has the main role, and although the single particle drag force has been widely studied, comprehensive and realizable models are still not available for systems with a large number of particles found in fluidized beds.

For modeling purposes, it is preferable to have simple and robust models that can be readily applied to a variety of cases. Because of the demand for simplicity and fast computations, the parameters relating to the drag force, such as the particle size and shape, are defined by as few parameters as possible. Hence, many computational models assume particles as monodisperse perfect spheres. Taking into consideration the real shape or size distribution of the particles could provide more accurate results, but would require elaborate examination. Efforts to take into account the particle properties more accurately have been made, for example by Rosendahl et al. [2].

Another way to obtain information about the material behavior in fluidized bed conditions is through experimental methods, characterization. This approach provides information about the average behavior of particles, rather than detailed information about a single particle behavior, without detailed examination of the particle properties. This offers a clear benefit in Eulerian type modeling of large systems in which single particle information is not as easily applicable as the averaged information about the material.

This paper focuses on the role of the drag force between biomass particles and fluid flow. Experiments were performed with a characterization test device with the aims of developing a method for the characterization of materials for the modeling of fuel flow in fluidized beds. The characterization results combined with the image analysis of the particle size and shape are compared with data on a single particle drag. The results of characterization are applicable to average drag force modeling of biomass in fluidized bed applications.

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2. Particles in fluidization process

The moving fluid exerts a drag force on the particle which consists of pressure drag and skin friction. Eq. (1) indicates that the drag force F_D is affected by the fluid density ρ_f, the fluid superficial velocity v_f relative to the velocity of the particle v_s, the particle reference area A and the drag coefficient C_D.

$$F_D = \frac{1}{2}\rho_f A C_D (v_f - v_s)^2. \tag{1}$$

The physical properties of a particle affect the drag force through the reference area and drag coefficient. The particle size and shape determine the reference area and pressure drag, while the shape of the particle surface determines the skin friction. In single particle fluidization, the drag force has to overcome the gravitational force on the particle, which is in direct relation to the particle mass. The mass can be directly measured or computed through the density and particle size, both affected by the particle shape.

In the fluidization of several solid particles, the particles cause disturbances to the fluid velocity field making the fluidization heterogeneous and transient in nature. The fluid velocity field can have high velocity regions, where the fluid is by-passing particle clusters, and low velocity wakes, similar to the boundary layer near the walls. In return, the particle flow field is affected by the changes in the fluid flow. The particles may also collide with each other and the walls. In this paper, only the drag force between the fluid and particles and the gravitational force relationship is considered and discussed.

2.1. Particle size

The determination of unambiguous characteristic dimension, the particle size, is extremely challenging for real particles [3–5], as illustrated in Fig. 1. The same 3D particle, depending on its orientation, can display several apparent sizes and shapes on a 2D projection, compared to the one produced by a sphere. Table 1 presents several characteristic dimension and their definitions, although the *diameter* is commonly used to describe the size with only one variable.

According to Yang [3] for the fluidized bed applications sieve, volume, surface and surface to volume diameters are relevant, with surface to volume diameter being the most relevant, because of its applicability to fluidization and thermo-chemical conversion descriptions [6]. All the suggested characteristic dimensions are affected by the particle shape and taking it into consideration might be difficult. Michaelides et al. [7] used a high speed camera to measure the terminal velocities of free falling regular particles constructed from spheres and determined their drag coefficients. Tinke et al. [8] found non-spherical particles causing the widening of the particle size distribution (PSD) in laser diffraction, a problem which could be remedied with a comparison to the image analysis. Arsenijevic et al. [9] studied Geldart's method to determine the surface-to-volume diameter and obtained sphericities of over unity for glass spheres and argued the method not to be valid in all fluidization systems.

2.2. Particle shape

Mando et al. [5] presented the shape classification shown in Table 2: regular and irregular; these groups could contain spherical or non-spherical particles. Sand and pulverized coal were mentioned as irregular spherical particles, while untreated biomass particles were described as irregular non-spherical [5].

A common method to describe particle shape is to use a *shape factor*, which means that the particle is compared to a sphere and the characteristic dimension is corrected with the selected shape factor. Table 3 presents the shape factors found in literature, and Fig. 2 illustrates some of the most common dimensions of particles related to shape factors.

Cavarretta et al. [10] discussed the challenges of shape characterization between the 2D and 3D shapes, with the conclusion that 2D images are a suitable approximation for the 3D sphericity only if the particles are spherical or very needle-like (elongated and flat). Riley [11] discussed different 2D shape factor definitions and suggested his own one. Podczeck [12] presented a shape factor which compares the main dimensions of a 2D shape to the basic geometrical shapes of a circle, rectangle, and triangle, and by formulating a deviation matrix and taking into consideration the number of corners in a particle, the shapes can be divided into six categories; elliptical, triangular, kite, parallelogram, trapezoidal and irregular. According to Liu et al. [13], Zingg shape factor evaluates the non-spherical particle shape well in fluidization applications. Loth [14] claimed the Corey shape factor to be the most suitable for the irregular particles and advocated its use instead of sphericity, which is widely used in the fluidization literature while being impractical to measure.

Almeida-Prieto et al. [15] presented detailed information about the functionality of image analysis software. The software measure particle projection surface area, dimensions and perimeter and use these to compute the particle shape factors. The non-standardized definitions of shape and measurement of characteristic dimensions lead to the incompatibility between different software [15]. Situations may occur

Fig. 1. The effect of three dimensional irregular shape on the two dimensional size and shape measurement.