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An experimental study of the aerodynamic dispersion of loose aggregates in an accelerating flow

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ABSTRACT

The dispersion of powders in gas flows is relevant in some powder processing techniques, in dry powder inhalers and in particle size analysers, among others. When using small particle sizes, the powder tends to form stronger aggregates and the dispersion becomes more difficult. There are many approaches to the dispersion process but most include collisions as one of the possible agglomerate break-up mechanisms. This is not always a satisfactory solution as particles may get contaminated or reduced. In the present work we explore the dispersion of powder aggregates in an accelerating flow with no particle-wall collisions. We built a fluid-dynamic device with a simple geometry consisting of a sharp slit, producing a rapidly converging flow at the entrance and a planar jet at the exit. A powder feeder exited with an ultrasonic actuator was used to generate single powder aggregates. The stationary flow field was calculated numerically and the velocity and degree of aggregate dispersion were assessed based on imaging results. In all the cases tested, erosion of the aggregates could be observed. In the case with the highest suction pressure, a different mechanism arises, which leads to the disintegration of the aggregate and a significantly better dispersion of the powder.

1. Introduction

Many processes involving powders require them to be suspended in a gas stream. The behaviour of the powder suspension and the outcome of the process depend on whether the particles are well dispersed or if they are part of larger aggregates. A dispersed powder suspension will have a more consistent fluid-dynamic behaviour, will stay suspended for a longer period of time and will have increased mass, heat and momentum transfer.

The dispersion process consists basically in the separation of the particles that are held together by different inter-particle forces. In general this means the application of mechanical energy to overcome these forces. There are different approaches to achieve this, depending on the powder to be dispersed and on the application constrains, a good review can be found in the work of Calvert et al. [1].

The problem of dispersing powders in gas streams is common to various applications. Industrial processes like blown powder-based deposition systems [2,3] and thermal powder processing such as the manufacturing of micro-spheres or micro-balloons require powders to be well dispersed to achieve satisfactory results [4–7]. There are even cases where a perfect dispersion is required while attrition of the particles is unacceptable, like in the seeding for particle image velocimetry [8] or in powder size analysers [9,1]. Lately the use of equipment capable of sizing powders in dry suspensions is becoming more common, with manufacturers such as Malvern, Horiba or Microtrack offering such devices. These devices present advantages when the powders to be measured are fragile, soluble, or reactive, but they usually require a careful adjustment of the operation parameters to achieve a good dispersion while keeping particle attrition at acceptable levels.

In recent years Dry Powder Inhalers (DPIs) have gathered attention as a non-invasive administration method, not only for lung specific treatments (local) but also for systemic treatments (via alveolar absorption) [10]. For the powders to reach the lungs of the patient, the dimensions of the particles have to be in the order of 3 μm or less [11,12], and have to be well diseprsed. Most DPIs rely on the patient suction power rather than using a propellant, the pressure difference and volumetric flow rate that are available to produce aggregate breakup are therefore limited. There have been numerous efforts to improve the dispersion characteristics of the powder formulations but also to assess and improve the design of the dispersers, being a very active field of research. There are many DPI devices on the market, with the majority using either turbulence or particle impaction to disperse the active pharmaceutical ingredient. However, only a few research works have focused on isolating the mechanisms of particle de-agglomeration in these devices. Most works evaluate the device efficiency, for example the fine particle dose values, for different operating conditions [13,14]. Recently,

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Kou et al. [15] performed a microscale particle image velocimetry (PIV) study on an experimental device simulating a Rotahaler® DIP. In their study they follow the aggregates as they are dispersed by drag force, particle-particle of particle-obstacle impactions. Their study is an interesting antecedent to the present work in the sense that it aims at directly observing the mechanism of destruction of the aggregates.

Dry powder inhalers achieve dispersion mainly by promoting particle-particle or particle-wall collisions, while turbulence and other purely fluid-dynamic stresses have a minor contribution. Wong et al. [16] analysed entrainment tubes with a combined approach where computer fluid dynamics simulations were combined with experimental measurements of the output product of the device. Their results suggest that the collision of aggregates with the walls play a dominant role in the dispersion process while naturally occurring pipe turbulence had a negligible effect, apart from increasing the number of wall collisions.

Shear stress and turbulence are often mentioned as important dispersion mechanisms [1]. These mechanisms have been studied in the context of aggregation and break-up in liquid suspensions [17–19]. Saha et al. [20] used water as fluid and generated the aggregates in a simple shear flow. These aggregates were then introduced in a turbulent flow field and followed as they broke-up. Simple shear flows and turbulence are of interest for suspensions in liquids with high viscosity and density. In gas flows, on the other hand, the flow is strongly affected by the presence of the particles, which normally have a much higher density than the gas. As a result the flow field becomes much more complex, generating shear forces by the high relative velocity between the aggregate and the gas, as can also be appreciated in the results of the present work.

Dispersion devices which promote aggregate collisions, while proven effective for medical applications, may cause the attrition of fragile particles and contamination with the material of the device walls, making them less desirable for applications such as particle size analysers, or in the processing of high purity materials. In those cases dispersers based on flow acceleration or shear forces alone would be preferred. When evaluating presently used aerodynamic dispersion devices, all of them present impaction as a possible dispersion mechanism [1]. A good candidate for dispersion without impaction in gases would therefore be a fluid dynamic device capable of producing a rapid acceleration of the flow, as proposed by Sosnowski et al. [21] or by Gerde [22].

Lately the availability of very high power light emitting diodes (LEDs) and high power, high speed electronics made it possible to achieve inexpensive but high performance illumination systems. Pulsed LED illumination has been used for particle image velocimetry [23,24] and is particularly well suited for high speed shadowgraphy [25]. The availability of this technology enables us to obtain photographs of fluid-dynamic processes that occur in extremely short periods of time, as is the case of the dispersion of powder aggregates. Furthermore by using colour LEDs we can colour-code two images in a single RGB (red-green-blue) image, making velocity estimations also possible [26].

The present study is therefore aimed at improving the understanding of the mechanisms of particle de-agglomeration produced by flow acceleration alone. We expect the acceleration of the flow to produce normal and shear stresses on the aggregate that will eventually erode or break-up into smaller aggregates or individual particles. In the present study the dispersion device was designed in such a way that impaction with the device walls is eliminated as a possible dispersion mechanism and turbulence is absent in the region of interest. The flow was also modelled numerically to obtain the velocity field. This imposed the requirement of having a flow that was well suited for numerical modelling. For this purpose we have chosen a suction slit formed between two sharp edges. High speed photography based on pulsed LED illumination was used to obtain images of the agglomerates and to estimate their velocities and sizes at different positions in the fluid-dynamic device. These measurements allow estimating the type of dispersion mechanism that is involved, either erosion or break-up in smaller aggregates, and the conditions at which these occur.

2. Experimental method

The objective of the experimental device is to capture two successive images of a single breaking aggregate. The overall scheme of the measurement system is shown in Fig. 1. The powder aggregate is produced by the powder feeder and falls into the fluid-dynamic device that will

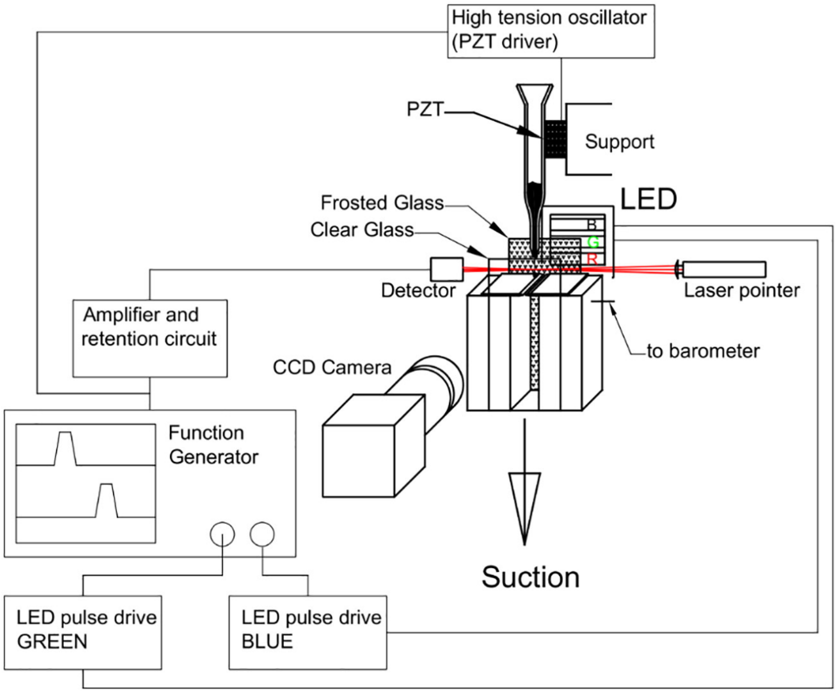

Fig. 1. Scheme of the experimental device. The light pipe between LED and the frosted glass was omitted for clarity.