Powder Technology 323 (2018) 186–194

Contents lists available at ScienceDirect

Powder Technology

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

Measurement of dispersity of ISO A2 fine dusts by shadowgraph method

Seungkoo Kang [a], Wing-Tak Lai [b], Sheng-Chieh Chen [a,*], David Y.H. Pui [a]

[a] Particle Technology Laboratory, Mechanical Engineering, University of Minnesota, 111 Church St. S.E., Minneapolis, MN 55455, USA
[b] TSI Inc., 500 Cardigan Rd., Shoreview, MN 55126, USA

ARTICLE INFO

Article history:
Received 2 August 2017
Received in revised form 28 September 2017
Accepted 1 October 2017
Available online 06 October 2017

Keywords:
Shadowgraph
A2 dusts
Size distribution
Particle/droplet image analysis
Particle transport loss
Noninvasive measurement
Dust filtration

ABSTRACT

ISO dust injectors are generally applied to re-suspend standard dust particles, e.g. ISO A2, to challenge air filters used in internal combustion engines. The size distribution of the re-suspended dust particles is very important for acquiring the size fractional efficiency and loading performance of the filter. Generally, the existing size distributions provided by the powder manufacturer are directly applied or real-time aerosol instruments are used to measure the particles. Various instruments, however, report different size distributions for the same dust sample and also they are quite different with that provided by the manufacturer. The main reasons are likely due to the particle transport loss during the sampling by the real-time instruments, especially for dust particles larger than 1 μm, as well as the different measurement principles and different sizing ranges of the instruments. In addition, the provided size distributions by the manufacturer are not ideal to represent the re-suspended dust particles because those distributions are measured in liquid when they are highly deagglomerated by the aids of chemical agents and ultra-sonication. In this study, therefore, the in-situ and noninvasive shadowgraph technique with an image analysis technique (particle/droplet image analysis, PDIA) were applied to measure the size of the re-suspended dusts at the moment they are being generated. The experimental system consisted of an 8 Mpixel CCD camera equipped with a high magnification micro-lens, up to 28×, to allow the measurement of small particles down to 1.5 μm. Monodisperse PSL particles with diameters of 5, 17 to 26 μm were generated from a home-built generator and used to validate the sizing accuracy of the system. The validated system was then applied to measure the size distribution of the widely used ISO A2 fine dusts re-suspended by different dust dispersers, including the ISO light-duty and ISO heavy-duty injectors. Results showed that there was a large discrepancy between the size distributions determined by the powder manufacturer and those from ISO injectors by PDIA, indicating the ISO injectors did not deagglomerate A2 dusts well. This study first reported the reliable size distributions for A2 dusts re-suspended by ISO injectors under different operation conditions.

1. Introduction

ISO dust injectors (ISO 5011, 2014) and commercial dust dispersers are generally used to re-suspend standard dusts, e.g. ISO A2 fine (ISO 12103-1, 2016), for challenging the air filters used in internal combustion engines and compressors for automotive and industrial applications [1,2]. However, the A2 dusts tend to form agglomerates easily due to adhesive forces, i.e. van der Waals and electrostatic forces [3], when they are packed in a container. For an accurate evaluation of filter performance, a complete deagglomeration when re-suspending the dusts is desired. Otherwise, the size fractional efficiency of the filter based on the labeled size distribution by the manufacturer will not be reliable. Thus, the results will not be applicable for refining and designing new generation filter products. However, to the best of our knowledge, there has been no validation study reported to confirm whether the re-suspended dusts are completely deagglomerated by the ISO injectors. Instead, it is highly suspected that there is a severe difference between the measured size distribution by the user and the labeled distribution by the manufacturer. There could be several reasons causing the discrepancy, and one of the most important reasons is that the manufacturer, e.g. Powder Technology (Power Technology Inc., Arden Hills, MN), typically measures the distribution of dusts in the liquid with the laser diffraction instrument, e.g. Microtrac S3500 (Nikkiso Co, Ltd., Tokyo, Japan). During the measurement, chemical agents are added and ultra-sonication is applied to enhance the dispersity and to prevent the agglomeration of the dusts. In comparison, the users usually measure the distribution of the re-suspended dusts using real-time aerosol instruments. Therefore, if the dusts are not deagglomerated properly by the dust injectors, the same distribution as that measured in liquid phase cannot be obtained. Nevertheless, although it is unlikely for general dust injectors to aerosolize the standard dusts with a similar size distribution as that in liquid phase, the data obtained from the measurement in liquid phase could be regarded as the reference size distribution and can be used to evaluate the performance of a dust disperser for re-suspending and deagglomerating dusts.

* Corresponding author.
E-mail address: chens@umn.edu (S.-C. Chen).

https://doi.org/10.1016/j.powtec.2017.10.004
0032-5910/

In addition to the size distribution discrepancy caused by the re-suspension and low deagglomeration rates of the particles, the transport loss during the sizing measurement is another reason causing the discrepancy. Transport loss can alter the size distribution for microsized and super-microsized dust particles, i.e. >1 μm, because of the electrostatic, inertial, and gravitational settling effects when they are transported inside the tubing [4–6]. For example, Von Der Weiden et al. [4] has pointed out that transport loss can occur for particles larger than 0.5 μm when they are sampled by aerosol instruments. The loss will be more significant when improper tubing materials and tubing with small curvature are used [7]. For example, tubing curvature (bend) is usually required for adapting the isokinetic sampling and orientation of the instrument when introducing dusts from the generation point to the instrument inlet. In addition to the transport issues, many instruments employed to determine the size distribution usually have their own limitations, such as the sizing ranges and identification capability for particle shapes. For example, the aerodynamic particle sizer (APS, TSI 3321, Shoreview, MN) is widely used for measuring the size distribution of microsized and super-microsized particles [8–10], but it has a sizing range only from 0.5 to 20 μm. Moreover, the APS is generally calibrated with spherical particles and irregular shaped particles will be interpreted as a certain aerodynamic diameter. Therefore, there needs a conversion between effective density and dynamic shape factor depending on the real drag acting on the particle for further acquiring the informative and indirect shape information [3]. In comparison, the laser diffraction instruments have relatively wider sizing range than the APS. However, particles to be measured are assumed to be spherical in this instrument, thus particles with irregular shapes and changes in refractive index can lead to erroneous results [11,12]. Moreover, this method cannot provide the velocity of particles. The phase-Doppler anemometry (PDA) is also a well-known particle sizing instrument for microsized particles with good accuracy. However, it is typically applicable for transparent and semi-transparent spherical droplets. Non-spherical particles may be measured [13,14] but may have various results dependent upon the orientation of the particles going through the measuring volume of the system. Since the A2 dusts are in irregular in shape, hence the PDA technique may not be a suitable technique.

Again, accurately characterizing the size distribution and shape of the dust particles from the dispersers are essential because the performances of filters are closely correlated with these parameters [15–18]. Hence, it is desirable to find a method which not only can accurately measure particle size and shape over a wide size range, e.g. 1.5–1500 μm, with no sampling transport loss, but also can be independent of the dust dispersion methods and the types of dusts. One of possible and available methods to overcome those limitations is the shadowgraph image analysis technique (or the Particle/Droplet Image Analysis, PDIA). This noninvasive technique allows a direct measurement and analysis of individual particles for their sizes and shapes.

The shadowgraph technique has been widely applied such as for measuring the size, shape and velocity of sands [19], ice particles [20] and spray droplets [21–25]. Up to now, no attempts have been made to evaluate the ISO dust injectors for ISO dusts dispersions by this method. It is very meaningful to examine the feasibility of using the PDIA to characterize the re-suspended ISO dusts.

In the present study, the PDIA technique was adopted to measure A2 fine dust distributions and to investigate the performance of ISO injectors. In order to verify the accuracy of the PDIA, we first measure the size of monodisperse Polystyrene Latex (PSL) particles with diameters of 5, 17 and 26 μm aerosolized by a homemade disperser. The PDIA was then applied to measure the polydisperse ISO A2 fine dusts dispersed from different dust dispersers, including the ISO light-duty and ISO heavy-duty injectors. In addition, the size distributions from the two dispersers and that from manufacturer were compared. The goal of this study is to demonstrate the capability and viability of the PDIA system to accurately determine the size distributions of dust particles dispersed by the ISO injectors since there is no any sampling tubing involved in the measurement which avoids the transport loss of the dust particles.

2. Materials and methods

2.1. Experimental setup

The optical system of the PDIA consists of a Nd:YAG laser with 200 mJ/pulse (Solo 200XT, New Wave™ Research, Inc., Fremont, CA), light illumination optics, diffuser, synchronizer (Model 610,035, TSI Inc., Shoreview, MN), CCD camera with 8 million pixel resolution and 5.5 μm pixel size (POWERVIEW Plus, TSI Inc., Shoreview, MN), and a high magnification lens (14× Navitar micro-lens and an extra 2× adapter, maximum 28×). Fig. 1 shows the schematic diagram of the PDIA system. Typically, the laser is placed behind a light diffuser and a camera positioned opposite to the diffuser plate. The dust laden flow is situated between the diffuser and the camera. Fundamentally, the shadowgraph imaging relies on the re-direction of light due to refraction. Light rays diverted by the dusts will travel elsewhere causing a lack of photonic energy on the image sensor then translating to a dark portion of the image and illustrating a 'shadow'. Thus the lack of light typically indicates the presence of the dust particle medium. In the current system, Nd: YAG laser was used as an illumination source, and the laser was generated as a cone of uniform light by using two cylindrical lenses oriented perpendicular to each other at the laser head. The diffuser plate was placed in the path of the illumination for the purpose of providing a uniform background. Uniform illumination is essential because any inconsistence in the illumination may cause an inaccurate result of the particle size. In addition to the measurement of size and shape of particles, the PDIA system can also measure the velocity of individual particles.

2.2. Experimental procedure and depth of field determination

The CCD camera was typically operated at a capture rate of 2.15 Hz with 10 μs time interval between a pair of laser illumination when the velocities of particles were also able to be measured, although it was not the major focus in the present study. The camera has a pixel resolution of 3312 × 2488 with a pixel size of 5.5 μm. With the 28× magnification, the size of each pixel can be reduced to about 0.2 μm, and the corresponding sampling region, i.e. field of view, is about 0.58 mm (length) by 0.44 mm (width). The high pixel resolution is necessary for capturing small particles as a sufficient number of pixels can be used to cover and represent the particle images. We used 8 pixels as a minimum number to determine the size of a particle to avoid errors from background noise. Therefore, the sizing limit of current PDIA is about 1.5 μm. In comparison, a lower magnification is preferred when particles are larger and with broader size distribution, e.g. ISO A2. Thus, the majority of particles can be captured. In this study, the micro-lens was set at 7× to take images of PSL calibration particles and ISO A2 particles. The images were automatically taken by the Insight 4G software (TSI, Inc., Shoreview, MN) once the preferred operation parameters were set, including the aforementioned capture rate and time interval. Then the image analysis for the sizes and shapes of particles from the captured images was conducted by an in-house MATLAB script.

Clear images of captured particles are desirable but not always available. When a particle is positioning within the focal depth (or depth of field, DOF, or effective focus range, the spatial location where the image of the particle is acceptably sharp), a focused image will be obtained and its shape can be recognized clearly because there is a sharp contrast between the particle and the background as shown in Fig. 2 (a). On the contrary, a particle sitting outside of the field will be defocused and blurred with a reduced intensity level, as shown in Fig. 2 (b) and (c), depending on the defocus distance (DD). It has been found the DOF varies as a function of particle size and it is also