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A monodisperse-aerosol generation system: Design, fabrication and performance

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ABSTRACT

Monodisperse aerosols are essential in many applications, such as filter testing, aerosol instrument calibration, and experiments for validating models. This paper describes the design principle, construction, and performance of a monodisperse-aerosol generation system that comprises an atomizer, virtual impactor, microcontroller-based isokinetic probe, wind tunnel, and velocity measurement device. The size distribution of the produced monodisperse aerosols was determined by an optical particle counter. The effects of atomizer characteristics, the rates of minor and major flow, and solution criteria were investigated. It was found that all these parameters affect the generation of monodisperse aerosol. Finally, the expected geometric standard deviation (≤1.25) of monodisperse aerosol particles was obtained with the most suitable atomizer for 10% oleic acid in ethyl alcohol solution with 5%–15% minor flow, where the ratio between the nozzle-to-probe distance and acceleration-nozzle-exit diameter was 0.66. The constructed monodisperse-aerosol-generation system can be used for instrumental calibration and aerosol research.

Introduction

Monodisperse aerosols are traditionally defined as aerosol particles with a narrow distribution having a geometric standard deviation (GSD) less than or equal to 1.25 (Fuchs & Sutugin, 1966). Monodisperse aerosols are used in different applications, including aerosol instrument calibration, filter testing, and the experimental testing of models. Aerosols are used not only for medical applications but also for pest control and combustion technology. For numerous applications of aerosol science, generation, removal, and different technologies of aerosols strongly affect the environment and people. Monodisperse aerosols are used to calibrate the size measurement of aerosol particles and to determine the effect of particle size on sampling devices. The fabrication of monodisperse aerosols with proper equipment is thus important to researchers.

There are a number of methods of generating monodisperse aerosols available in the literature (Nayve et al., 2004). A method of generating monodisperse aerosols with a vibrating orifice aerosol generator has been studied (Berglund & Liu, 1974). A joint vapor–nuclei-type generator has been proposed (Jeng, Kindzierski, & Smith, 2005). An inkjet aerosol generator has been used for the production of monodisperse aerosols (Bottiger, Deluca, Stuebing, & Vanreenen, 1998; Iida, Sakurai, Saito, & Ehara, 2014). A fluidized bed has been applied for aerosol generation (Lind, Danner, & Guentay, 2010). Atomization, spraying, and nebulization have been applied for aerosol generation systems of different designs (Gemci & Chigier, 2016). A number of researchers have at different times attempted to integrate different sampling assisting devices with these generators to maximize sampling efficiency; e.g., the virtual impactor (Chen, Yeh, & Rivero, 1988; Li & Lundgren, 1997; Loo & Cork, 1988; Marple & Chien, 1980) and wind tunnel (Hinds & Kuo, 1995; Ranade, Woods, Chen, Purdue, & Rehme, 1990).

However, most previously designed aerosol generation systems are of complex design. This paper presents the design principle, construction, and performance of a simple monodisperse-test-aerosol generation system that comprises an atomizer, virtual impactor, microcontroller-based isokinetic probe, wind tunnel, and velocity measurement device. This system integrates existing methodologies to optimize the procedure through simplicity of design and maximization of the sampling efficiency. This system can further be used by aerosol researchers in developing countries, many of which lack the technology for installing complex aerosol generation systems and hence need appropriate equipment for conducting research. The system can also be applied to calibrate instruments that measure particle size, to determine the effect of particle size on sampling devices, and to study respiratory deposition in humans.

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Table 1
Design parameters of fabricated atomizers.

Atomizer No.	Diameter for air inlet (mm)	Diameter of constricted area (mm)	Nozzle exit diameters (mm)	Liquid jet diameter (mm)
1	21	6.5	7, 7.5, 8.25, 9.5, 10	2
2	18	2.5	4, 4.5	1.5
3	18	3.75	4.5, 5.5, 6, 6.5	2

Experimental

Formulation components of aerosol

Ethyl alcohol and oleic acid were selected as the formulation components of aerosols. Oleic acid was used because of its availability in the local market and non-volatility. Other non-volatile liquids could have been used. The manufacturer of both formulation components was Sigma Aldrich, USA. The ethyl alcohol was labeled V000107 Vetec and was of ACS reagent grade with purity of 99.8%. The oleic acid was labeled O1008 Sigma-Aldrich and had purity greater than or equal to 99% (as determined by gas chromatography).

Experimental design

Three differently sized atomizers were used in experiments with compressed air. The atomizers drew liquid and air through passages. Specifications of the atomizers are given in Table 1. A liquid solution of different concentrations, such as 5%, 10%, 15%, and 20% oleic acid in ethyl alcohol, was used as the test aerosol in the experiment. Finally, for the required GSD of the aerosol particles, a particular atomizer was selected and the rest of the experiment was completed. A schematic diagram of the experimental setup is shown in Fig. 1.

The produced aerosol moved upward vertically and then impacted on a virtual impactor. This separated the smaller and larger particles. To reduce the contamination of fine particles in the minor flow, a clean air core was provided at the entrance of the virtual impactor. The major flow was drawn from the virtual impactor by a blower and was ultimately released to the atmosphere. A wind tunnel was used to pass the minor flow. Isokinetic sampling probes were used at different locations of the wind tunnel to sample the aerosol while the aerosol passed through the tunnel. Finally, a SOLAIR-3100 optical particle counter (OPC) (Lighthouse Worldwide Solutions Inc, USA) was used to measure the aerosol particle size distribution.

Design and construction

Generation chamber

In the aerosol generation chamber, liquid was atomized by a liquid-siphon atomizer mounted at the bottom of the chamber. A uniform flow of aerosols was directed vertically inside the generation chamber. A vacuum pump was used to draw the atomized aerosol in the correct direction.

According to analytical studies of generation chambers, the chamber was constructed with a height of 122 cm considering the maximum stopping distance that can be reached by the droplets generated by the atomizer. The height was sufficient for the gravitational settling of droplets larger than the cut-off size of the chamber. The cut-off size of the generation chamber is defined as the diameter above which particles will settle and below which particles will be carried forward by air in the generation chamber. This aerodynamic cut-off diameter of aerosol particles depends on the air velocity as illustrated in Fig. 2 (Hasan, Nabi, & Akhter, 2012).

Alternatively, if the cut-off aerodynamic diameter of the aerosol droplet is known or selected according to the air velocity, all droplets larger than the cut-off size at that flow rate will settle in the chamber and the rest will flow to the virtual impactor section. Fig. 2 is used to determine the cut-off aerodynamic diameter of aerosol droplets for a particulate air velocity.

Because a larger diameter of the chamber results in a lower flow velocity for the same flow rate through the chamber, it was decided to keep the inner diameter of the chamber at 142 mm. In most experiments, the chamber flow rate was maintained constant at 0.003 m^3/s. The chamber was made of Perspex pipe having an outlet diameter of 152 mm, allowing the cloud of aerosol to be viewed from the outside. A liquid-siphon atomizer was installed at the bottom of the chamber on an aluminum plate. The bottom plate was provided with a drain line to drain off the settled liquid from the bottom of the chamber.

The larger droplets settled in the chamber and the monodisperse aerosols moved upwards. The generation chamber acted as a vertical elutriator in which droplets having settling velocity greater than the mean air velocity through the chamber were removed by gravitational settling.

Atomizer

The atomizer was designed so that liquid could be siphoned into the atomizer. Bernoulli's principle was considered in designing the atomizer. The atomizer was designed in a manner that air could flow through the atomizer. The atomizer had a constricted inner area that connected a liquid line to the atomizer.

The air velocity increased when air passed through the constricted area of the atomizer. At the same time, the pressure decreased, as a result of Bernoulli's principle, to atmospheric pressure. The pressure of the liquid was atmospheric. The pressure of the vacuum portion of the atomizer was lower than the atmospheric pressure, which created a pressure differential. The liquid could thus be siphoned into the atomizer. The liquid broke into fine small droplets, which were then delivered to the outlet portion.

The atomizer was made of acrylic plastic because of its cheapness, transparency, machining condition, weather resistance, and chemical resistance. The atomizer was fabricated in three parts: an air inlet, main body, and exit nozzle. The air inlet and the exit nozzle were threaded to the main body.

Our experiments show that to raise a liquid to the atomizer, the exit nozzle diameter must be greater than the diameter of the constricted area if we want to avoid back pressure and to siphon liquid. Atomizers of different dimensions were thus fabricated in the laboratory. Parameters of these atomizers are given in Table 1. Fig. 3 shows a schematic diagram of the atomizer.

Wind tunnel

If the diameter of the generation chamber and the sampling area are not equal, the loss rate of particles will be greater at the time of sampling. Considering this issue, a wind tunnel was constructed to sample aerosol particles more efficiently; i.e. to avoid the maximum loss. The wind tunnel was a hollow cylinder. The cross-sectional area of the tunnel was constant so that open and uniform flow could pass through the tunnel. The diameter of the wind tunnel was kept the same as that of the generation chamber. Otherwise, if the tunnel diameter is made greater than the diameter of the generation chamber, the streamline will diverge and wall deposition and the aerosol particle loss will increase. Meanwhile, if the tunnel diameter is made smaller than the diameter of the generation chamber, the streamline will converge and the coalescence of particles will thus increase aerosol particle loss.

The dimensions of the wind tunnel were a diameter of 15.2 cm, vertical length of 106 cm, and horizontal length of 122 cm. Isokinetic sampling probes were separated by approximately 25 cm. Polyvinyl chloride was used to fabricate the designed wind tunnel. The wind tunnel was fabricated in three parts: a vertical part

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