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Simple self-diagnostic method to identify the abnormal functioning of a scanning mobility particle sizer

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ABSTRACT

This study suggests a simple self-diagnostic method for identifying the abnormal functioning of a scanning mobility particle sizer (SMPS). Under the operating conditions of a laboratory-made electrostatic precipitator, where the collection efficiency is expected to be at maximum, the efficiency against neutralized particles was measured using a malfunctioning SMPS. The efficiency was compared with the theoretical maximum collection efficiency. The difference in efficiency between experimental and theoretical collection efficiencies was used as an indicator of an SMPS malfunction. Moreover, the effects of the flow rate, neutralizer condition, and inlet particle concentration on the error signal were investigated. The error signal was shown to properly reflect the operational state of the SMPS; thus, a malfunction can be easily confirmed without the need for accurate comparison data. The error signal was also shown to be robust against a radioactive source, period of neutralizer use, and flow rate. The signal was clear when the particle concentration was sufficiently high, but tended to fade with a decrease in the inlet particle concentration. The suggested self-diagnostic method can be used to check the malfunctioning of a SMPS before a main experiment or to determine whether the SMPS requires calibration.

1. Introduction

Nanoparticles are released into the atmosphere through various routes, and have an adverse effect on human health. Nanoparticles are generated as byproducts of combustion processes (Künzi et al., 2013), motor vehicle exhaust (Greenwood, Coxon, Biddulph, & Bennett, 1996), and office equipment use, including laser printers and photocopiers (Tang, Hurraß, Gminski, & Mersch-Sundermann, 2012). Moreover, intentionally manufactured nanoparticles are released into the environment during their synthesis and handling. Nanoparticles suspended in the atmosphere can be deposited into the lungs (Tsai and Pui, 2009; Tsai et al., 2009), and they lead to an increase in the mortality rate in humans (Dockery & Pope, 1994; Donaldson, Li, & MacNee, 1998; Pope, Bates, & Raizenne, 1995). For these reasons, the United States Environmental Protection Agency (EPA) has issued new environmental regulations for PM2.5, and the World Health Organization (WHO) has designated PM2.5 as a first class carcinogen.

The adverse effects of these particles on human health are strongly related to their size and concentration. In a previous study, it was determined that nanoparticles are more toxic than large-size particles, even if they have the same chemical composition and total mass (Ostiguy et al., 2008). Thus, various commercial instruments that can measure the size, distribution, and concentration of submicron-size aerosols have been developed, such as an electrical low-pressure impactor (ELPI, Dekati) (Keskinen,

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Pietarinen, & Lehtimäki, 1992), electrical aerosol detector (EAD, TSI, Inc.) (Woo, Chen, Pui, & Wilson, 2001), opacimeter (OPM, AVL) (McCormick, Graboski, Alleman, Alvarez, & Duleep, 2003), and diffusion-size classifier (me DiSC, Matter Engineering) (Fierz, Burtscher, Steigmeier, & Kasper, 2008). Among these various nanoparticle-measuring instruments, the scanning mobility particle sizer (SMPS) is the most commonly used. A SMPS consists of an aerosol neutralizer, a differential mobility analyzer (DMA), and a particle counter. By passing particles through the neutralizer, the particles attain the Boltzmann equilibrium charge distribution, in which the aerosol carries a bipolar distribution. The DMA classifies the particles by size based on their electrical mobility, and the number concentration of each particle size is measured using a particle counter. In general, there are two different types of particle counters used in the SMPS: (1) a condensation particle counter (CPC), which increases the particle size through condensation of a CPC fluid vapor applied to the particles, and measures the number concentration through a laser-based optical technique; and (2) an electrometer-based particle counter, which measures the current induced by electrical charges applied to the particles, and converts the measured current into the particle concentration.

Although SMPSs have been widely used in numerous aerosol studies and have been selected as reference devices for the performance evaluation of new equipment (Lee, Li, Flagan, Lo, & Chan, 2013; Liu, Jiang, Zhang, Deng, & Hao, 2016; Wang et al., 2016), to the best of our knowledge, there are no self-diagnostic methods available for evaluating the suitability of the data obtained from a SMPS. In general, a SMPS is maintained through a calibration service offered from the manufacturer at regular intervals. It is therefore difficult to determine whether the measured data are correct during an experiment. Because an inaccurate particle size distribution obtained from a malfunctioning SMPS will obviously lead to serious errors in the experimental results and analysis, the functioning state of the device should be checked and monitored before each main experiment.

In this study, a diagnostic method for self-checking the functionality of a SMPS was developed using the difference between the experimental and theoretical collection efficiencies of an electrostatic precipitator (ESP). To verify the proposed method, the size distributions of the test particles were measured using two different SMPSs, a normal SMPS and a malfunctioning SMPS. Moreover, the robustness of the method with respect to the flow rate, neutralizer condition, and particle concentration was investigated. The data obtained from the suggested self-diagnostic method can be used as a reference to check the functionality of a SMPS before conducting a main experiment, or to determine whether the SMPS requires calibration.

2. Materials and methods

2.1. Design of self-diagnostic method

The functionality of a SMPS was evaluated through a comparison between the experimental and theoretical maximum neutralized particle collection efficiencies of an ESP. For monodisperse spherical particles with a Boltzmann equilibrium charge distribution, an equation representing the fraction of particles having n units of charge (f_n) can be expressed as follows (van Dijk et al., 2011):

$$f_n = \sqrt{\frac{K_E e^2}{\pi d_p kT}} exp\left(\frac{-K_E n^2 e^2}{d_p kT}\right) \tag{1}$$

where K_E is a constant (9.0×10^9 N m^2/C^2), e is the unit charge (1.6×10^{-19} C), d_p is the particle diameter, k is the Boltzmann's constant, and T is the absolute temperature. If the residence time in the ESP is sufficient, all charged particles among the particles within the Boltzmann equilibrium charge distribution should be collected in the ESP. Therefore, using Eq. (1), the theoretical maximum collection efficiency (η_{max}) of an ESP for a particle with a diameter of d_p can be expressed as

$$\eta_{max}(d_p) = (1 - f_{n=0}) \times 100 = \left(1 - \sqrt{\frac{K_E e^2}{\pi d_p kT}}\right) \times 100(\%) \tag{2}$$

In this study, a double-cylinder-type laboratory-made ESP was used to capture the neutralized particles, the dimensions of which are 25 mm in inner diameter (D_{in}), 100 mm in length, and 30 mm in outer diameter (D_{out}). The gap between the inner and outer cylinders (S_{gap}) is 2.5 mm, and thus the inner volume of the ESP (V_{esp}) is 2.16×10^{-5} m^3. To obtain the maximum collection efficiency, the travel distance of a singly charged particle using an electric field (S_{ESP}) should be larger than the gap distance, S_{gap}, as follows:

$$S_{ESP} = \int_0^{t_{esp}} \frac{neEC_c}{3\pi\mu d_p} dt = \frac{neEC_c}{3\pi\mu d_p} t_{esp} \geq S_{gap} \tag{3}$$

where E is the electric field strength in the ESP, C_c is the Cunningham correction factor, μ is the viscosity of air, and t_{esp} is the residence time of the particle in the ESP ($t_{esp} = V_{esp}/Q_{esp}$) at the flow rate Q_{esp}. When the applied voltage of the ESP is over the corona onset voltage (V_{onset}), air ions are generated inside the ESP, and the charge state of the incoming particles can be redistributed. Because the collection efficiency of an ESP for charged particles that are within the Boltzmann charge distribution is a key factor for the suggested method, the charge state of the test particles should be maintained while inside the ESP. Thus, the applied voltage of the ESP was determined when considering its corona onset voltage. In the two concentric cylinder configurations, the corona onset voltage is calculated as follows (Kaiser, 2006):

$$V_{onset} = E_{max} D_{in} ln\left(\frac{D_{in}}{D_{out}}\right) \tag{4}$$