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Development of a Test Set for Motoring Fine Particulate

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ABSTRACT

In indoor and outdoor atmospheric environments, fine particulate has been recognized as hazardous substances that may cause respiratory diseases. Thus, proper countermeasures to monitor and reduce fine particulate are required. In particular, atmospheric environments can be deteriorated by higher levels of $PM_{2.5}$ when fine mineral particles such as fly ash from coal-fired power plants are discharged into the atmosphere. To resolve this problem, effective monitoring of $PM_{2.5}$, among various other countermeasures, is important for fine dust management. The monitoring performance can be enhanced by integrating the monitoring with information technology (IT), which has been developing rapidly. For fundamental research to test the effectiveness of a monitoring system, it is desirable to select a test particulate with a single composition (alumina: Al_2O_3) and a narrow range of particle sizes (~0.5 μm) to minimize unknown variations of particle behaviors with composition and particle size. In addition, a test chamber can reduce the sensitivity and possible occurrence of errors resulting from changes in air conditions. Therefore, in this study, a test set was proposed through the construction of a test chamber and a low-cost PM sensor for fine particulate experiments integrated with sensor monitoring. This study is expected to contribute greatly to the development of a future IT-based intelligent program capable of predicting the behaviors of fine particulate.

Key words : Fine particulate ($PM_{2.5}$), Sensor, Test Chamber, Alumina, IT-based intelligent program

Introduction

The amount of fine inorganic particles emitted from industrial facilities, e.g. fly ash generated from coal power plants, has been increased [1], but the particulate has not been properly reduced or recovered, and therefore polluted atmospheric environments and threatened human health [2]. For example, the fine particulate of coal ash generated from coal-fired power plants is only partially recycled to the raw materials of cement or concrete admixtures, and other large portions of the coal ash particles are just abandoned in yards exposed to outdoor air [1]. The discarded particles with various size ranges may contain fine sizes of the particles such as fly ash in coal ash, which can spread to nearby areas by airflow, become serious atmospheric pollutants. Generally, "Suspended particulate matter" (or PM_{10}) refers to the dust with diameters equal to 10 μm or less, in which the particles can reside in atmospheric environments for a long time. "Fine particulate matter" (or $PM_{2.5}$) and "Ultrafine particulate matter (or $PM_{1.0}$) represent the particulates with diameters equal to or less than 2.5 μm and 1.0 μm, respectively [1]. Those are recognized to be harmful substances that adversely affect human health, such as increasing disease incidence and mortality. In particular, PM exposure is associated with an increased risk of lung cancer, asthma, ischemic heart disease and stroke [1]. Also, PM may contribute to the occurrence of chronic obstructive

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Fig. 1. The photographs of the test set, before the test particle presence (Left) and after the particle deposition (Middle and Right).

pulmonary disease, diabetes, and dementia. Fine particles may enter the blood circulation system through air/blood barriers. In addition, those may cause a light scattering effect, deteriorating atmospheric visibility. Thus, various activities of regulation and prevention have been prepared to reduce the harmful effects of fine or ultrafine particulate on human health and the environments [1].

For effective management of fine particulate, it is important to understand its behaviors from pollution sources (e.g. fly ash yards in a coal-fired power plant). The mechanisms to describe fine particulate behavior includes suspension, transport (dispersion or convection), and deposition [3,4]. For example, the particles remained in waste dumps may be suspended by external airflow and moved into nearby atmosphere. Some particles may be deposited by gravitational force, or attached to wall surfaces by adhesion forces. Others may continue to be transported through the airflow [5]. The primary forces affecting those behaviors are classified into 1) aerodynamic forces, 2) gravitational force, and 3) the surface forces (such as adhesion and electrostatic forces) exerted between particles or between a particle and a solid (wall) [3,4]. The behaviors of particles are determined primarily by the balance between the forces above. For example, the fly ash in an outdoor yard may be suspended as a result of the force balance between gravitational and aerodynamic forces by e.g. wind [3,4]. In another example, fine dust may be suspended by e.g. human movements in a room. For those cases, the settling velocity of the particles should be decreased as the particle sizes decrease. Therefore, the suspension of fine particles may continue to be suspended in the room for a long time, which adversely affects human health. Therefore, understanding of the behaviors of the fine particles is one of the most significant in predicting their concentrations and risks.

In addition, it is important to select an appropriate sensor to measure fine particulate concentrations. The most common reference techniques for monitoring PM are use of TEOM (Tapered Element Oscillating Microbalance) and BAM (Beta Attenuation Monitor). Those instruments can provide reliable data but too expensive and difficult to operate. Thus, use of low PM sensors that are convenient to operate [6]. These low-cost PM sensors can generally detect particles with diameters ranging 0.3-10 μm mainly through light scattering principles. The particles smaller than 0.3 μm in diameter do not scatter light sufficiently while those larger than 10 μm cannot readily enter the sensor [7,8]. These sensors detect the presence of particles, so the actual PM mass for the concentration unit should be inferred.

Based on the mechanisms and the monitoring technologies, this study would construct an ultimate goal to build a test set to understand and quantify the mechanism of particle behaviors from waste sites such as fly ash yards. As a beginning stage to achieve the ultimate goal, this study would select test particles with a single component and particle size range, in order to minimize the factors affecting the behaviors. A test chamber was constructed to reduce the possible occurrence of errors due to various environmental changes leading to complicate particle behaviors and the relevant data analyses. The performance of this test set would be examined by measuring and observing the behavior of test particles in the chamber by using low-cost sensors and smartphones, respectively.

Materials and Methods

The test chamber for fine particle suspension, transport, and deposition test had 2.0 m × 0.8 m × 0.6 m of dimension located in a commercial ventilation hood (Chemical Fume Hood, Samil, Korea). The main equipment inside the test chamber included a low cost PM sensor (SDS011, TZT, China) for continuous particle monitoring, a smartphone (iPhone6, Apple, USA) to capture particle movements, and a fan (Iris PCF, Iris, Korea) to generate airflow and thereby particle suspension and convective transport. The airflow velocity along the distances from the fan was measured using an anemometer (SP-7000, Lutron, Taiwan) which could also measure the air humidity and the temperature inside the chamber. The test particulate for the experiment, obtained from KIGAM (Korean Institute of Geoscience and Mineral Resources) was alumina (Al_2O_3) mineral with a narrow particle size range around 0.5 µm. Dark wallpapers were attached to the inside wall around the chamber to provide strong light contrast when the particle images were to be captured by the smartphone. A slide glass or an aluminum foil was utilized to support the test particles. The slide glass was used for a particle suspension experiment, while the aluminum foil was utilized in the particle spraying experiment (Fig. 1). The detail procedures of the two experiments would be described subsequently.

The data obtained from PM sensor were the concentrations of $PM_{2.5}$ and PM_{10}, and delivered to a desktop computer through a USB cable connection. To display the PM data on the computer screen, the software named "PMMonitor" was installed on the computer prepared by the sensor manufacturer. The main configurations of baud rate, data bits, parity, stop bits, and handshake were set as "9600", "8", "None", "One", "None", respectively. Then, the $PM_{2.5}$ and PM_{10} data obtained every one second and the corresponding two X-Y plots. For each plot, the horizontal X-axis denoted the measuring time points with second unit while the vertical Y-axis described $PM_{2.5}$ or PM_{10} concentrations with µg/m^3 unit, measured at their corresponding time points (Fig. 2).

The experimental procedure to monitor particle suspension with the slide glass are as follows: (1) attached dark wall papers to the inside wall of the test chamber (2) adjusted the fan speeds and, using the anemometer, measured airflow velocity, temperature, and humidity according to the distances from the fan (3) placed the test particles onto the slide glass and measured the weights of the particles and the slide glass using a precision scale (PAG2140, OHAUS, USA) (4) placed the slide glass, containing the test particles, at 45 cm - distance from the fan (5) turned on the fan, the smartphone camera, and the PM sensor as well as PM data display software (6) detected the particles suspended by fan airflow using the PM sensor and the phone camera (7) after deposition of the suspended particles, turned off the equipment (8) removed the slid glass from the chamber and measured the weight of the remaining particles on the glass (9) finally, turned on the hood fan and removed the wall paper to clean the chamber. The indoor air temperature of the lab including the chamber is controlled within 25–27°C. The procedure with the spraying particles on the aluminum foil was almost the same as that with the slide glass, except the procedure (3) measured the weight of the aluminum foil using a precision scale (4) placed the aluminum foil at 45 cm - distance from the fan.

Fig. 2. Display of the PM sensor data.

Results and Discussion

As a result of the experiment on suspension the alumina mineral particle suspension by the fan airflow, little particles were suspended from the slide glass even the strong fan airflow velocity up to 2.0–2.7 m/s. Accordingly, little increase of $PM_{2.5}$ or PM_{10} concentration was observed (data are not shown). Only a slight amount of the particles as low as 1 mg among the initial amounts about 4.9–5.0 g moved out of the glass by rolling or sliding. This phenomenon can be explained by the force balance and its resultant motions. The aerodynamic forces due to the horizontal airflow to a single particle are mainly divided into the drag and lifting forces according to the force directions. Both of the two forces create the rolling moment away from the fan which is the origin of the airflow. Additionally, the drag force by the airflow contributes to sliding the particle away while the lift force leads to the particle to be suspended from the bottom (the glass) [3,4]. Therefore, when the fan was turned on to create airflow, aerodynamic forces were exerted to the particles. little motion of any

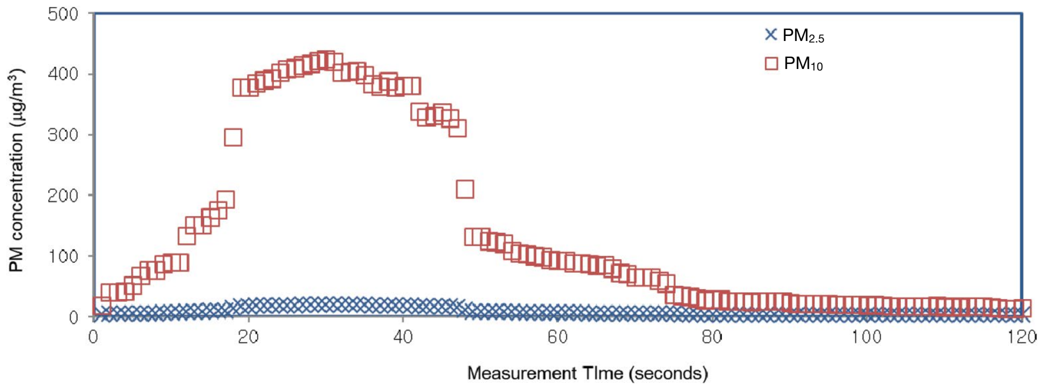

Fig. 3. PM concentrations measured by SDS011 in this study.

particle on the glass implies there was little rolling, sliding nor lifting movements by the fan airflow. The "no motion" condition can be analyzed with the force balance concept and the details can be explained as follows [3,9]:

- No rolling condition: The summation of the moments, resulting from the adhesion (F_{AD}) and the gravitational (F_G) forces, exerted to the edge of each particle is greater than the moments from the aerodynamic (drag F_D and the lift F_L) forces.
- No sliding condition: The summation of the adhesion (F_{AD}) and the gravitational (F_G) forces, multiplied by a friction coefficient between particle and solid, is greater than the drag force F_D.
- No lifting condition: The summation of the adhesion (F_{AD}) and the gravitational (F_G) forces solid is greater than the lift force F_L.

In spite of the strong airflow and the small sizes of the particles, the little motion of the particles on the glass implies the dominance of the gravitation and/or the adhesion forces over the two aerodynamic forces. The primary factor deciding the gravitational force should be the density of the alumina (≈4 kg/m^3); other factors are gravitational constant that is supposed to be constant in the small test chamber and air density (≈1.2 g/m^3) to suppress the particle should be far smaller than alumina density. The main factors of the adhesion force can be the thermodynamic surface energy of alumina crystals and the surface electrical potential energy. Those of oxides minerals including alumina are generally large due to strong chemical bonding providing high stability of oxides and high electricity. In addition, the contact structures between a particle and other particles on a multilayered particulate should be significant because of their roughness. The particulate dump on the glass surface in this experiment provided favorable for the adhesion force. Instead, the particles under the slight moving by rolling or sliding were mostly those on the far side of the smooth surface of the slide glass, which supports the smooth glass surface should relive the adhesion force.

In contrast, another experiment with alumina particles sprayed onto the aluminum foil clearly showed a convective transport following the fan airflow, when the particles were close to the fan. Along with the convection, the particles in the transport were also dispersed laterally due to the turbulence of the airflow [5]. As those moved far from the fan, the transported particles mostly fell to the bottom of the chamber. The decrease of the airflow effect was also evident in that the airflow velocity was decreased about 0.1 m/s as the distance from the fan increased 2 cm approximately. Then, the particle in falling with dispersion should be deposited over the bottom of the chamber. Unlike the immovable particles on the glass during the previous experiment (Fig. 1-middle and right sides), the sprayed particles had no adhesion force, so only the gravitational force should resist the aerodynamic forces to move the particles. As a result, the aerodynamic forces should be dominant and thus the particles were subject to convection along with the strong airflow near the fan. Conversely, at the point distant from the fan, the airflow velocity and accordingly the aerodynamic forces were far reduced and the gravitational force became dominant. The measured PM data are described in the plot of Fig. 3.

Based on the force balance as stated above, an immobile particle on the glass surface can be expressed as follows [9]:

$$F_G + F_{AD} > F_D + F_L \quad (1)$$

In contrast, the movement of a particle sprayed and transported along with the fan flow is subject to the following condition:

$$F_G < F_D + F_L \tag{2}$$

Among the terms, the gravitational force (F_G) is described as follows [5]:

$$F_G = (\rho_p - \rho_{air})\frac{\pi d^3}{6}g \tag{3}$$

where, the symbols ρ_p and ρ_{air} stand for the density of the test particle and air, and d and g mean the representative particle diameter (~0.5 μm) and the gravitational acceleration. Actual particles show a variety of shapes and sizes but this equation assumes that those as the sphere shape and 0.5 μm, respectively. Also, the drag force F_D is expressed as follows [9,10]:

$$F_D = \frac{\pi f_D C_D}{C_c}\frac{\rho_{air} d^3}{8}v^2 \tag{4}$$

where v stands for the effective airflow velocity (m/s). The correction factor f_D, which is assumed to be 1.71 [11], and the Cunningham slip correction C_c are given as follows [9]:

$$C_c = 1 + Kn(1.257 + 0.4\, e^{-1.1/Kn}) \tag{5}$$

The Knudsen number Kn is defiled as 2 λ/d. where λ is the mean free path of air (λ≈66 nm, at the standard temperature and pressure conditions) [9]. C_D can be obtained from Reynolds number (Re), which is equal to 24/Re when Re is far less than the unity; $24\,(1+0.15\mathrm{Re}^{0.678})/\mathrm{Re}$ when Re is less than 1000; 0.44 when Re is over 1000) [12]. The aerodynamic torque (M_h) to generate the particle rolling movement is calculated as follows:

$$M_h = \frac{2\pi f_M \mu d^2}{C_c}v \tag{6}$$

where the coefficient of μ is air viscosity; f_M is the wall effect correction factor, assumed be to 0.94 based on a previous study [11]. Also, the lift force (F_L) is described as follows:

$$F_L = 1.61 d^2 v (\rho_{air}\mu)^{1/2}\frac{dv/dx}{|dv/dx|} \tag{7}$$

where dv/dx represents the velocity gradient near the particle surface and assumed to be about 24 /s for this study.

This study showed clear increases in PM data along with the convective transport in the second experiment with the

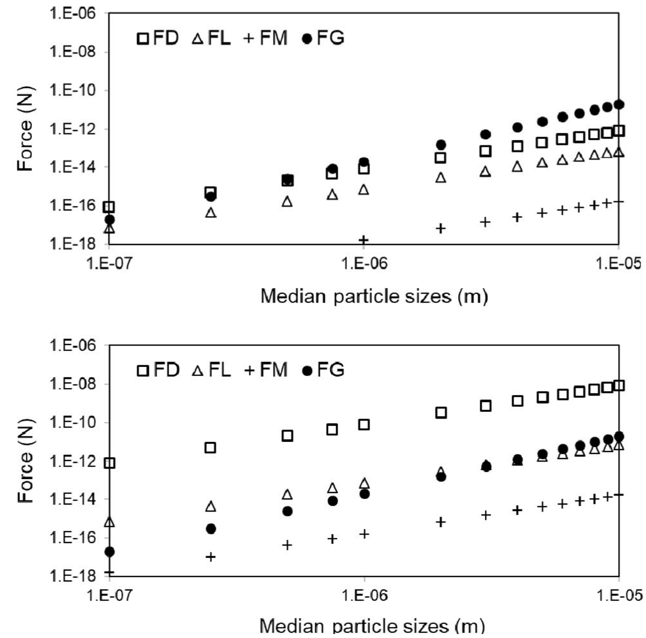

Fig. 4. Force magnitudes at a low (v = 0.02 m/s; top) and a high (v = 2 m/s; bottom) airflow velocity, respectively.

sprayed particles. The PM data trends seem to well correspond to human visualization or camera images (Fig. 3). Also, Fig. 4 exhibits the (log-scaled) magnitudes of the forces at a low (v = 0.02 m/s) and a high (v = 2 m/s) airflow velocity, according to particle sizes, in the plots at the top and the bottom plots, respectively. The horizontal axes of the plots show particle sizes while the vertical axes present the magnitudes of the forces. Each plot notes the increase of the forces as particle sizes increases, regardless of the airflow velocity. However, there is a difference in the dominance of the forces. For the low airflow velocity (the top plot of Fig. 4), the gravitational force is dominant at large particles, leading to settling and deposition. In contrast, for the high velocity (the bottom plot of Fig. 4), the drag force is dominant over the whole particle size range. These trends of the force dominance correspond to the experimental observation in the second test set with the sprayed particles.

With respect to the PM sensor, the reliability and the performance should be discussed. A previous study addressed collocation measurements between multiple SDS011 sensors. They found that the sensors showed generally proper correlation at typical conditions. Also, they provided high temporal resolutions. However, severe disadvantages were found as (1) unqualified performances at humid air conditions (2) occurrence of errors in measuring large particles or dense particles (3) noticeable differences between the sensors (4) thereby low reliability for the quantitative measurement PM data. The use of the sensors for experiments should be recommended under controlled humidity environments with low PM concentrations [7]. In addition, this study utilized the smartphone camera to capture the particle images, and found quantitative clues on the local particle movements and concentrations. Budde et al. [8] also supported the idea that a smartphone with a camera and flashlight can be used as a low-cost sensor. A strong advantage of the smartphone camera image is the ability to provide 2-D features. Surely, they suggested requirement of modifying the smartphone camera system to capture individual particle images. They proposed so-called FeinPhone, a phone-based fine dust measurement apparatus with a novel counting approach based on the light-scattering. This could provide a direct assessment of particle counting and sizes from camera images. The collected data shows good correlations with the coarse fraction of fine particles under realistic conditions. This is a promising type of extremely low-cost and convenient PM sensor with light-scattering sensor, using the internal camera and flash LED in a smartphone. A future test set accommodating the improvement of the sensors may contribute to the monitoring of the controlled environment as mentioned in a previous study [13].

Conclusion

This study prepared the test set that consists of a test chamber with a fan to generate airflow, a low-cost $PM_{2.5}$ sensor to measure particle concentrations and a smartphone to capture the images of the particle behaviors. Alumina mineral particles with a narrow range of diameters around 0.5 μm were utilized as the test particles and monitored suspension, convective transport by fan airflow and deposition of the particles. As a result, the particles had little motion from the stained glass when the glass with the particles was located at the distance of 45 cm from the fan of which airflow velocity was up to 2.7 m/s. The particles staying on the glass implies the gravitational and the adhesion forces as well as their relevant moments were dominant over the aerodynamic forces and moments. In contrast, the particles were favorably moved following the fan airflow when those were sprayed at the height of 40 cm from the bottom of the chamber. This reflects that the aerodynamic forces were dominant at a strong fan airflow. However, the gravitational force leading to particle deposition gradually becomes dominant as the particles were far from the fan where the airflow ceased. $PM_{2.5}$ and PM_{10} data obtained from SDS011 sensor appear to properly reflect the particle concentrations due to the presence of the reasonable temporal trends of the $PM_{2.5}$ concentrations. The light intensity of a smartphone produced somewhat overall spatiotemporal distribution patterns of the particle behaviors. In future, the image capture and analysis need further improvement.

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