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Control of Particle Re-Entrainment by Wetting the Exposed Surface of Dust Samples

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ABSTRACT

Experiments have been conducted in a wind tunnel to measure the emission factor of re-entrained particles from a dry or wetted dust sample with a smooth or rough surface. Effects of wind velocities and water contents in the sample on the emission factor also were investigated. The results show that re-entrainment of particles can be controlled efficiently in a certain period of time when the surface watering density is between 60 and 80 g/m^2 at a wind velocity from 7 to 15 m/sec for both smooth and rough surfaces. After the effective period is elapsed, which depends on wind speeds and environmental conditions, water will eventually evaporate, and re-entrainment starts to occur again. The experimental water evaporation rates at different wind speeds are in good agreement with theoretical values. After watering for 210, 130, and 110 min at average wind velocities of 0, 2, and 4 m/sec, respectively, the dust sample must be replenished with water to avoid dust re-entrainment.

INTRODUCTION

The application of water on soil surfaces to control total suspended particles (TSP) and particulate matter (PM) less than 10 μm (PM$_{10}$) is one of the most commonly used and cost-effective methods to prevent dust emission by binding particles together. Hesketh and Cross[1] indicated that the watering control efficiency was found to be ~50% for an unpaved roadway. Fitz and Bumiller[2] investigated the effectiveness of watering in controlling PM$_{10}$ emissions under high wind velocities. The results showed that the watering technology was effective at reducing PM$_{10}$ emissions, and the control efficiency was ~50–90% at the wind velocity of 18 m/sec for the pickup of soil at a landfill. Zimon[3] indicated that the existing water layer in particles would form a liquid bridge and reduce the distance between particles, resulting in increasing capillary forces to prevent dust re-entrainment.

IMPLICATIONS

A wind tunnel system was used to measure the emission factor of re-entrained particles from a test dust sample in the wind tunnel system. Experimental results showed that re-entrained particles can be controlled effectively when the water content reaches a critical value for a smooth or rough surface. Water evaporation decreases the water content below the critical values, which leads to dust re-entrainment when the effective control period is exceeded. The dust sample must be replenished with water to avoid dust re-entrainment.

The particle re-entrainment of the unpaved road could come from the native soil or the deposited dust. On natural surfaces, the particles will be emitted from surface crusts through abrasion by saltating grains. That is, when the wind velocity was slowly increased over the surface, the smaller or more exposed grains were entrained first by the air drag because of the influences of surface creep or saltation. As the wind velocity rose, the larger grains also were moved by the air drag. Houser and Nickling[4] used a series of wind tunnels on the clay-crusted surface to examine the importance of saltation abrasion in the emission of PM$_{10}$. The results showed that the abrasion efficiency (the ratio of the PM$_{10}$ emission rate to the saltation transport rate) was related to the crust strength, the amount of surface disturbance, and the velocity of the saltating grains. In addition, because of the strong cohesive forces associated with the deposited dust within the surface crusts resulting from the soil enrichment, organic matter, or soluble salts, the entrainment of PM$_{10}$ by aerodynamic forces was inherently difficult.[5–7] Of the many factors reducing particle entrainment by wind velocity, soil moisture was found to be one of the most important. Neuman and Nickling[8] concluded that most sands appeared to be extremely resistant to wind erosion at gravimetric moisture contents above ~0.2%. It is worthwhile to investigate the influence of soil moisture within the different soil types on the emission factor of re-entrained particles from the soil surface.

To improve the effectiveness of the watering control technology requires a detailed understanding of the effect of water content in the soil and the watering frequency for dust re-entrainment. In addition, both the wind velocity and surface conditions were found to play an important role in dust emission[9] and have to be investigated. Previous studies showed that a particle will roll and be re-entrained from the surface when the rotational moment of the particle caused by the wind velocity over the particle overcomes the moment caused by the adhesive force between the particle and surface.[10,11] Matsusaka and Masuda[12] concluded that most of the re-entrained particles were formed into aggregates, which were re-entrained more easily than the primary particle. Nicholson found that the resuspension rate, [13] which was defined as the fraction of particles removed from the surface in unit time, was related to the particle size, particle shape, and wind velocity. When the wind velocity increased, the resuspension rate also increased. Matsusaka and Masuda[12] found that the re-entrainment flux increased with time elapsed in an accelerated flow, while it decreased in a steady-state flow.

In this study, a wind tunnel system was used to measure the emission factor of the re-entrained particles from a test dust sample. The effect of wind velocity, surface condition, and water content within the sample on the emission factor was investigated. Because water will evaporate from the sample and reduce the control efficiency, the effective watering frequency also was determined at different wind velocities in the wind tunnel system.

METHODS

The wind tunnel system was used in this study to simulate the re-entrainment of particles from the sample surface at different wind velocities, shown in Figure 1a. The system includes a front HEPA filter, a honeycomb, a working platform, a back HEPA filter, and an exhaust fan. The outside air passes through the front HEPA filters before entering the contracted section. The filtered air then enters the honeycomb with a diameter of 30 cm, a length of 20 cm, and a tube diameter of 0.6 cm to smooth the flow. The airflow passes the test sample inside the working platform having a length of 60 cm and a diameter of 30 cm. Another HEPA filter is installed downstream of the working platform to prevent the suspended particles from entering the exhaust fan. The exhaust fan has a frequency inverter to control the rotational speed of the motor. The inverter can regulate the air linear acceleration rate to a prescribed maximum wind velocity. The linear acceleration

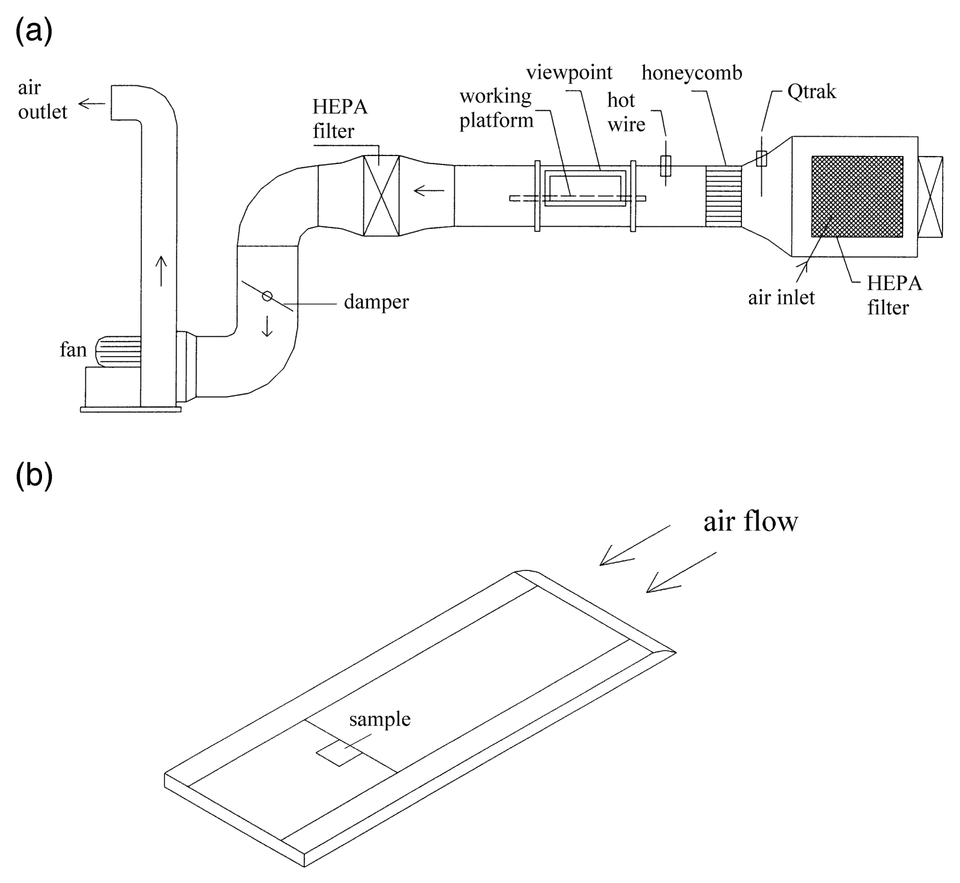

Figure 1. (a) The wind tunnel system. (b) The working platform for the test sample.

rate was fixed at 1.5 m/sec^2 to speed up the air velocity from the calm to the maximum wind velocity in this test. During the test, the air temperature was from 23 to 27 °C, and the relative humidity was between 55 and 70%.

Figure 1b shows the working platform for the test dust sample. A flat plate with a thickness of 0.3 cm constitutes the working platform. An aluminum cell with a cavity of 5 (length) × 5 (width) × 0.2 cm (depth) was used to contain the dust samples and was embedded in the flat plate. The test sample surface was flush with the top surface of the working platform to avoid edge effect. The front edge of the working platform was smoothed to prevent flow separation.

Test dust samples were collected using a vacuum cleaner from an unpaved road in the Nan Laio area in Hsin-chu, Taiwan. The collected dust samples were sealed and transported to the laboratory. An oven was used to dry the dust samples at 105 °C for 24 hr. The dried dust samples were sieved using standard No. 325 mesh to remove particles greater than 44 μm. The MOUDI (micro-orifice uniform deposit impactor, Model 100, MSP) was used to determine the initial and the re-entrained size distribution of the dust samples, which were dispersed by the dust feeder (Wright Dust Feeder, WDF-II, BGI). The results showed particles greater than 10 μm in aerodynamic diameter constituted the major fraction of the samples and were 71 and 92.3% of the total mass for the initial dust sample and the re-entrained particle, respectively.

Without Watering Control

The surface of the test sample is either smooth or rough. After the dry dust sample was put into the aluminum cell, the surface was flattened with a sharp knife edge. To obtain a rough surface, a stencil with a line gap of 1 cm and a line thickness of 0.1 cm was used to print a pattern on the test sample. In both cases, the aluminum cell containing the test sample was dried for 10 min and cooled for 5 min before being weighed. The test sample was re-entrained on the working platform in the wind tunnel system at different wind velocities. Re-entrainment occurs in the first 20 sec. After the re-entrainment test, the sample was dried, cooled, and weighed. The emission factor, E (kg/m^2-sec), can be calculated as

$$E = (W_2 - W_1)/AT \tag{1}$$

where W_1 (kg) and W_2 (kg) are the mass of the test sample before and after re-entrainment, respectively; A (m^2) is the surface area of the test sample; and T (sec) is the sampling time.

With Watering Control

An atomizer was used to wet the sample with a dry mass of W_1. The mass of the wetted sample (W_3, kg) was obtained before the re-entrainment test. After being re-entrained in the wind tunnel, the test sample was dried for 1 hr, cooled for 5 min, and weighed again (W_4, kg). The original water content within the test sample and the total mass of the re-entrained particles can be calculated as $W_3 - W_1$ and $W_4 - W_1$, respectively, at three maximum velocities, V, of 7, 11, and 15 m/sec. The average wind in the ambient will evaporate the water within the test sample. Thus, the water content within the test sample was determined during different sampling periods at three average wind velocities, V_0, of 0, 2, and 4 m/sec. After the water evaporated, the test sample was re-entrained again at a maximum wind velocity, V, of 7 m/sec during the different sampling periods.

Theoretical Considerations

Water will evaporate from the test sample and reduce the control efficiency. The evaporation rate, E_0 (kg/m^2-sec), of the test sample depends on the wind speed and many other factors and can be estimated by Penman's theory[14] as

$$\lambda E_0 = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma} \times CW_1(e_z^0 - e_z) \tag{2}$$

where $\lambda = 2.501 - 0.002361T$ (MJ/kg); W_1 is the wind function ($W_1 = 0.75 + 0.0185u_2$); $\gamma = C_pP/0.622\lambda$; Δ is the ratio between saturation vapor pressure and temperature; C is a constant of 6.43; R_n is the net radiation (J/m^2-sec); G is the heat flux (J/m^2-sec); C_p is the specific heat at constant pressure (J/kg °C); $e_z{}^0$ and e_z are the vapor pressure of the saturation and real condition (kPa); T is the temperature (K); and u_2 is the wind velocity (m/sec). In our experiment, all other factors were fixed at ambient condition but the average wind velocities were varied at 0, 2, and 4 m/sec.

RESULTS AND DISCUSSION

Effect of Surface Condition of the Dust Sample and Wind Speed on the Emission Factor

The wind speed and dust surface have important effects on the emission factor. Figure 2 shows the emission factor of the dry test sample with a smooth surface and a rough surface for the different wind velocities at an air acceleration rate of 1.5 m/sec.^{2} For the smooth surface, the curve shows that the emission factor increases as the wind velocity is increased. The minimum wind velocity for re-entrained particles is found to be 3–5 m/sec. As the wind velocity is increased from 7 to 15 m/sec, the emission factor is increased from $0.39 \times 10^{-4} \pm 0.03 \times 10^{-4}$ to $4.93 \times 10^{-4} \pm 0.39 \times 10^{-4}$ kg/m^2-sec (average ± standard deviation). Compared with the case of the smooth surface, the emission factor for the rough surface is increased from 4.83×10^{-4} to 30.27×10^{-4} kg/m^2-sec (average) when the wind velocity is increased from 7 to 15 m/sec. It is seen that the emission factor of the rough surface is much greater than that of the

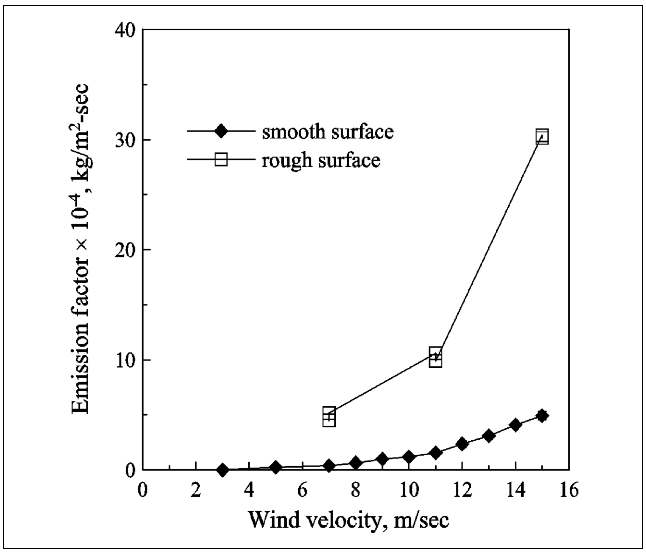

Figure 2. Emission factors for the dry test samples with smooth and rough surfaces.

smooth surface at the same wind velocity. The existence of the boundary layer effect on the rough elements increases the possibility of dust re-entrainment.

Effect of Water Content on the Emission Factor

It is important to know how much water per unit exposed surface area is needed to prevent dust re-entrainment. Figure 3 shows the effect of the water content in the dust sample on the emission factor for the smooth surface and the rough surface at three maximum wind velocities. For each water content, the test was conducted for 20 sec and water evaporation was found to be negligible. For a maximum wind velocity of 7 m/sec on a smooth surface, the curve shows that the emission factor decreases from ~5 × 10^{-4} kg/m^2-sec to nearly zero as the water content is increased from 10 to 60 g/m^2 (0.45–2.7% in [water/dry dust mass] × 100%). That is, there will be no particle re-entrainment when the water content is more than 60 g/m^2. The emission factor of the rough surface is greater than that of the smooth surface at the same water content and the same wind velocity. However, when the water content is increased to 60 g/m^2, the emission factor is also decreased to almost zero. A similar conclusion can be reached when the wind velocity is increased to 11 and 15 m/sec, as shown in Figure 3. In both cases, the experimental data show that the re-entrained particles can be controlled effectively, which may be caused by the massive formation of liquid film surrounding most particle surfaces when the water content ranges from 60 to 80 g/m^2 for the smooth or rough surface. A water content of 60–80 g/m^2 can be said to be the critical value to prevent dust re-entrainment.

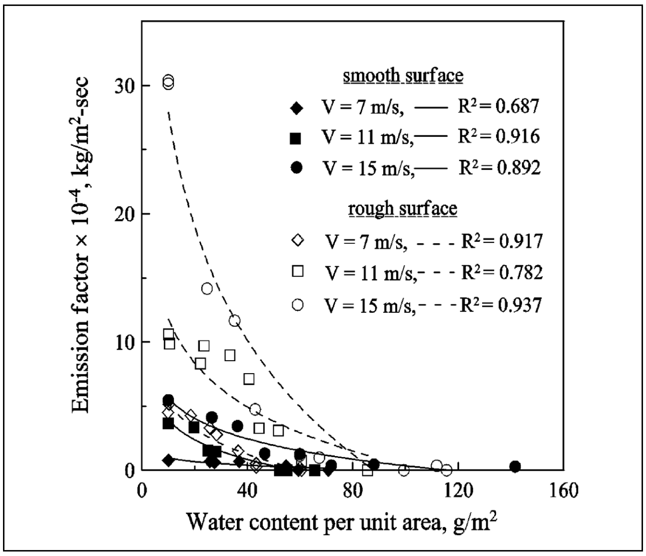

Figure 3. Effect of water content on emission factor at three wind velocities. (Lines represent logarithm fit to the data points.)

Water Evaporation Rate and Watering Frequency for Effective Dust Control

There is a period when the dust sample has enough water to prevent particle re-entrainment. As time goes by, the wind will evaporate the water. Figure 4 shows the relationship of the water content per unit area with the evaporation time at three wind velocities. It is seen that the water content within the sample decreases with increasing evaporation time even at the calm wind condition, 0 m/sec, as shown in Figure 4. The water content eventually reaches a constant minimum value of 18.8 g/m^2 when the evaporation time is greater than 240 min. The evaporation rates of the water content of the experimental data agree with the theoretical values calculated by Penman's theory, 3.09 g/m^2-min, except near the end of the evaporation when the sample is almost dry. The larger wind velocities, such as 2 and 4 m/sec, have a higher evaporation rate of water content than does the calm wind

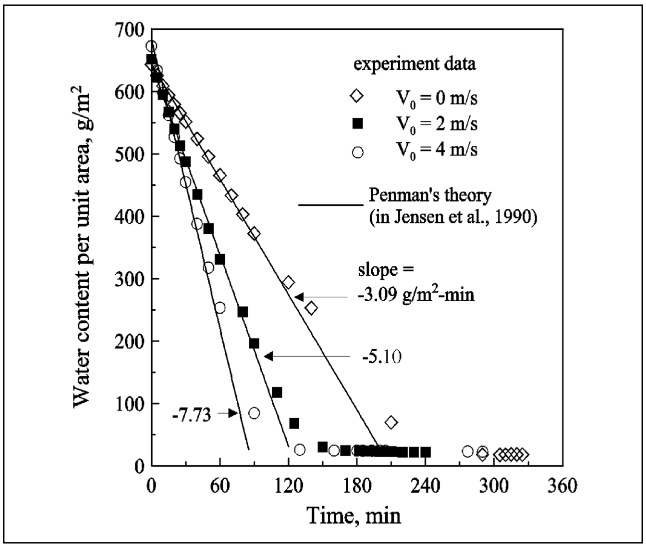

Figure 4. Relationship of the water content per unit area with different times for three average wind velocities.

condition. The evaporation rates of the water content also agree with those of Penman's theory for wind velocities of 2 and 4 m/sec and are calculated to be 5.10 and 7.73 g/m^2-min, respectively. The water content decreases to a constant minimum value of 23 g/m^2 when the evaporation times are greater than 150 and 110 min, respectively. The study has shown that the evaporation rate is slow by free convection at the calm wind condition and force convection caused by the blowing wind greatly increases the evaporation rate.

Figure 5 shows the relationship of the emission factor with evaporation time for three average wind velocities of 0, 2, and 4 m/sec at a maximum wind velocity of 7 m/sec when the initial water content is 30% (664 g/m^2). It is seen that there is no particle re-entrained from the sample surface as the elapsed time is less than 210, 130, and 110 min (i.e., the effective control period), for the average wind velocities of 0, 2, and 4 m/sec, respectively. When the effective control period is exceeded, water evaporation decreases the water content below the critical values of 60–80 g/m^2, which leads to dust re-entrainment. Figure 5 also shows that after 330, 200, and 160 min, the emission factors are equal to those of dry dust samples for average wind velocities of 0, 2, and 4 m/sec, respectively. That is, water must be replenished regularly depending on wind speed to avoid dust re-entrainment.

CONCLUSIONS

In this study, effects of wind velocities, surface conditions, and water contents of a dust sample on the emission factor of the re-entrained particle from the dust sample were investigated with or without watering control technology in the wind tunnel system. The results show that the emission factor of a rough surface is much greater than that of a smooth surface at the same wind velocity and water content. The re-entrained particles can be controlled effectively, which may be because of the formation of liquid film surrounding the most particle surfaces when the water content ranges from 60 to 80 g/m^2 at wind velocities from 7 to 15 m/sec for a smooth or rough surface.

After a period of re-entrainment, the dust sample must be replenished regularly because of the effect of water evaporation. The evaporation rates of experimental data are in good agreement with the theoretical values, which are found to be 3.09, 5.10, and 7.73 g/m^2-min for wind velocities of 0, 2, and 4 m/sec, respectively.

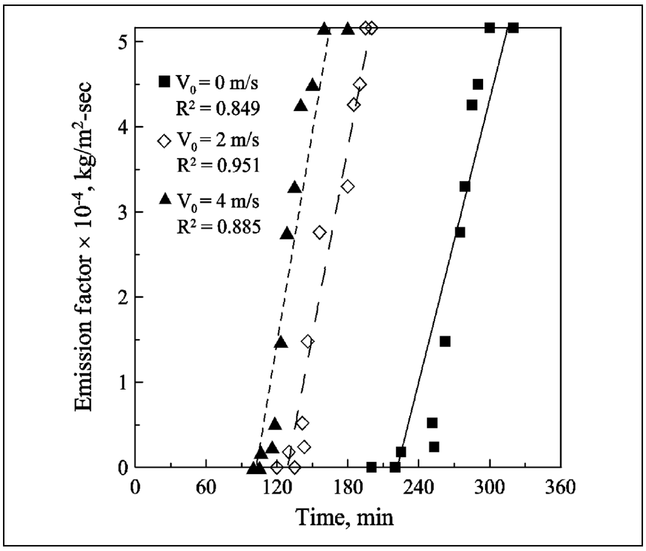

Figure 5. Relationship of the emission factor with evaporation time. (Lines represent linear fit to the data points.)

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