IUTAM Symposium on the Dynamics of Extreme Events Influenced by Climate Change (2013)

Wind-tunnel Experiment on Dust Atmosphere-surface exchange: Emission and Dry Deposition

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Abstract

A series of wind tunnel experiments are carried out to study dust atmosphere-surface exchange, including emission and dry deposition. The gradient method is employed to measure the dust emission rate. And the PDA (Particle Dynamics Analysis) technique is applied for the measurement of dust deposition velocity. The experimental results indicate that saltation bombardment is a predominantly reason for dust emission from sandy loam surface. And the emission rate scales with $u^4$ to $u^5$. Except for horizontal saltation flux, the sandblasting efficiency intimately affects dust emission rate and increases with the increasing friction velocity by following an exponential law. The dust deposition velocity increases with particle size, for particles bigger than 0.75μm. Besides wind friction velocity, the roughness elements on surface can significantly enhance dust dry deposition, especially for dust smaller than 4 μm.

Keywords: Wind-tunnel, dust emission, dust dry deposition, gradient method, PDA

1. Introduction

Dust atmosphere-surface exchange, including emission and deposition, is the key part of the global dust cycle which has important influence on the transfer of minerals and nutrients (Shao et al, 2011), soil formation (Reheis et al.,

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In this paper, we present a series of wind-tunnel experiments for dust emission and dry deposition. The emission rate, the quality of the dust moving upward across the level near the surface per unit time and unit area, is measured by using the gradient method over sandy loam surface under different wind. The influence from friction velocity, horizontal saltation flux to the dust emission rate is investigated and discussed, to reveal the main controlling factors for dust emission and to estimate dust emission rate quantitatively. Aside, the PDA (Particle Dynamics Analysis) technique is applied to measure dust deposition velocity defined as the ratio of deposition flux (downward) to dust concentration. Dust deposition velocities for particles with different size are then obtained.

2. Experiment configuration and measurement method

The experiments are carried out in a blow-down wind-tunnel of Lanzhou University, which is in total 55 m long, including a powerful fan system, a rectification section, a working section and a diffuser. The working section is about 22 m in length and with a cross section of 1.3 m (width) by 0.45 m (height). The wind tunnel is controlled by a computer and the wind speed can be adjusted between 3 and 40 ms⁻¹.

Fig. 1 illustrates the arrangement of the devices in the experiment for dust emission. Some roughness elements are set up in the front of the work section of the wind-tunnel to generate a turbulent boundary layer. Downstream of the roughness-element is the test surface. A sand trap is placed at the position with the distance 8 m from the front of the surface to measure the horizontal saltation flux. Two probes of Aerosol Spectrometer (AS) are fixed at 7 cm and 14 cm height to measure the local dust concentration. A thermal anemometry probe is fixed on an adjustable frame to measure wind speed at different heights.

The gradient method is employed to measure the quantity of dust emit from the surface to the atmosphere. As shown in Fig. 1, the dust concentration \( c \) for two different height \( z_1 = 7 \) cm and \( z_2 = 14 \) cm are measured by AS. The dust emission rate, i.e. the dust upward flux \( F_e \), could be estimated as

\[
F_e = K_e \cdot \frac{c(z_2) - c(z_1)}{z_2 - z_1}
\]
where $K_p$ is dust eddy diffusivity which is approximated to eddy viscosity for fine particles. For a neutral atmospheric surface layer, $K_p$ is normally expressed as

$$K_p = k u_* (z_2 - z_1)/2$$

(2)

$k$ is von Karman constant ($\approx 0.4$).

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The main difference of the experiments from dust emission to dust deposition is a dust feeder is placed at the beginning of the working section and injects dust into the tunnel through a tubular manifold, which consisted of two rows of six outlets with even spacing of 20 cm and (see left hand side of Fig. 2). The manifold is adjusted, and the bottom and the top rows are at approximately 20 cm and 40 cm above the top of the surface. The measurement devices, such as the PDA and AS, are located near the end of the working section. The arrangement of the probes of these devices is illustrated in the right hand side of Fig. 2. The sampling point of the AS is 15 cm behind the measuring point of the PDA to avoid the influence of the air-pump on the flow at this point. All probes are fixed on adjustable frames to allow measurements at different heights, and the distance between the measurement area and the dust outlet is about 10 m to ensure sufficient development of the turbulence boundary layer and dust concentration profiles. To avoid the possible emission of the small surface particles, the sand and original sandy loam surface are wetted and then air-dried before the experiment, so that a crust forms to suppress the motion of surface particles during the measurement.

The deposition velocity $w_d$ is estimated by the following expression

$$w_d = \frac{\sum_{i=1}^{N} \left( D_{pi}^{3} \cdot w_{pi} \cdot \Delta t_i \right)}{\sum_{i=1}^{N} \left( D_{pi}^{3} \cdot \Delta t_i \right)} - \tilde{w}_p + w_i$$

(3)

where $D_{pi}$, $\Delta t_i$ and $w_{pi}$ are respectively the diameter, transit time and vertical velocity of particle $i$ which passes the measuring point, and $N$ is the total number of these passing particles during the observation time. Considering the possible effect of the mean vertical airflow, the average particle vertical velocity under unbiased sampling, $\tilde{w}_p$, is subtracted and then the theoretic gravitational settling velocity $w_i$ is added back. The value of $\tilde{w}_p$ can be estimated from the measurement data of the PDA, by using an iterative method to eliminate the effect of actually biased sampling of the PDA. The gravitational settling velocity is calculated by
\[ W_t = \frac{C_c \rho_p D_p^2}{18 \mu} \cdot g \]  

where \( \mu \) is the air dynamic viscosity, \( D_p \) is the particle diameter, \( g \) is gravitational acceleration, \( \rho_p \) is the density of the particles and \( C_c \) is the Cunningham correction factor.

### 3. Results and discussion

#### Dust emission

As the particles with the diameter of \(~100 \ \mu m\) are easy to be moved by fluid drag (Kok et al., 2012), the lifting particles hop along the surface and form the process known as saltation. The impact of these saltating particles on the sandy loam surface can mobilize particles of a wide range of size. The ejected particle with big size (e.g. from 50 \( \mu m \) to 200\( \mu m \)) will also bombard the surface and form the continuous saltation cloud. Simultaneously, the small dust particles are continuously emitted from the surface and transfer upwards due to air turbulence.

![Fig. 3: Size distribution of sandy loam](image1)

![Fig. 4: Measurements of dust emission on the sandy loam surface. (a) Wind profiles. The symbols are experimental data measured by Thermal Anemometer. The curves are wind profiles fitted to the logarithmical law. (b) The curve of horizontal saltation flux against wind friction velocity.](image2)

The horizontal wind speeds for different heights over sandy loam surface are measured by the Thermal Anemometer and the results are shown as the symbols in the Fig. 4a. By fitting the experimental data to the logarithmical law, the parameters of the wind field, such as the friction velocity \( u^* \) and the roughness length \( z_0 \) are shown in the label of Fig. 4a. The horizontal saltation fluxes measured by the sand trap are shown in Fig. 4b, for different wind friction velocities. As shown, the horizontal saltation flux scales with \( u^*^3 \) and satisfies the expression proposed by

\[ Q_s = A u_*^3 (1-u^*_2/u^*_1)(1+u^*_2/u^*_1) \]  

(Kawamura, 1951)

\[ A = 57.78563 \]  

\[ u^*_0 = 0.17492 \ \text{ms}^{-1} \]
Kawamure (1951). Additional, the threshold friction velocity \( u_* \) can be obtained as 0.175 ms\(^{-1}\) by fitting the measurements to Kawamure’s expression, which is consist with the observation from the experiments.

\[
F_e = a u_* (1 - u_*^2 / u_*^2) (1 + u_*^2 / u_*^2)
\]

\[
a = 361471.58587 \\
b = 4.70853 \\
u_* = 0.17492 \text{ ms}^{-1}
\]

Fig. 5: The relationship between emission rate and friction velocity

The relationship between the dust emission rate \( F_e \) and the wind friction velocity \( u_* \) are further illustrated as Fig. 5. For the amount of emitted dust is predominantly caused by the saltation bombardment, an expression similar to horizontal saltation flux mentioned above is employed to describe the relationship between \( F_e \) and \( u_* \). As the results shown, the dust emission rate scales with \( u_*^4 \) to \( u_*^5 \), which is similar to the opinion of Shao (2001) (scales with \( u_*^4 \)). The experimental results indicate that there would be other factor existing to affect the dust emission process and also depend on the friction velocity. According to the studies of Gillette (1979) and Rajot et al. (2003), that factor defined as the sandblasting efficiency could be described as the ratio of dust emission rate to friction velocity. Fig. 6 illustrates the curve of sandblasting efficiency (i.e. \( F_e/Q_s \)) against friction velocity. The order of the measured sandblasting efficiency for sandy loam surface is \( 10^{-4} \) to \( 10^{-3} \) m\(^{-1}\). As the experimental results shown, the sandblasting efficiency increases with the increasing friction velocity, following an exponential law. The values of the parameters, such as \( A_0, A_1 \) and \( A_2 \), should be determined by the characteristic of the surface.

\[
F_e/Q_s = A_0 \exp(A_1 u_*) + A_2
\]

\[
A_0 = 367.24307 \\
A_1 = 34.86832 \\
A_2 = 8.04906
\]

Fig. 6: The curve of sandblasting efficiency against wind friction velocity

**Dust deposition**

The characteristics of the sand surfaces is that they can be considered as flat surface superposed with some roughness elements (i.e. sand particles, clods or gravels). These roughness elements, although small in height, enhance turbulence near the surface and the collection efficiency of the surface.
Fig. 7: Measurements of dust deposition to the sand surface. (a) Wind profiles measured over the sand surface. The symbols are the mean horizontal speed of the particles which pass the measurement point and are used to represent the local horizontal air speed. The curves are wind profiles fitted to the logarithmical law. (b) Deposition velocity against particle size under different wind conditions over sand surface. The symbols are averaged results of \( w_d \) and the error bars represent the variability of the results. The curves are the results predicted with the Slinn and Slinn scheme (1980) with the parameter RH = 0% and the height of measuring point is 15 mm.

The wind profiles over the sand surface are shown in Fig. 7a for three different fan speeds. As shown, the profiles obey the logarithmical law very well. The friction velocity increases with fan speed. But the roughness length decreases with fan speed and friction velocity. This increase in friction velocity and decrease in roughness length indicate that intensified turbulence intrudes into the layer adjacent to the surface and reduces the thickness of the laminar layer, and then should enhance the dust deposition process.

The observed deposition velocities are shown as the symbols in Fig. 7b. As can be seen, deposition velocity is small for low friction velocity and increases with friction velocity. This is most obviously for particles in the size range of 4 to 22.5 \( \mu \text{m} \), because turbulent impaction is effective for this particle size range and is sensitive to friction velocity. The measured deposition velocities for small particles (about 0.75 \( \mu \text{m} \), as shown in the lower right corner of Fig. 7b) under higher friction velocity are negative. This may be caused by the re-suspension of the deposited particles.

The Slinn and Slinn (1980) scheme originally proposed for water surfaces can also be applied to sand surfaces but without dust particle growth caused by high humidity of the surface. The predications of Slinn and Slinn (1980) scheme are shown as the lines in Fig. 7b. It appears that the scheme can well predict the deposition velocity for the particles larger than 22.5 \( \mu \text{m} \), but small particles, especially for particles smaller than 4 \( \mu \text{m} \). It should caused by the neglect of the effect for roughness elements (sand particles) collection which is sensitive for small particles.

4. Conclusions

The surface like sandy loam which has wide size distribution can form the saltation of big particles under enough strong wind flow. The saltating particles bombard the surface and cause the small particles emit from surface. The dust emission rate is sensitive to friction velocity and scales with \( u^4 \) to \( u^5 \). Except for horizontal saltation flux, the sandblasting efficiency is also an important factor for dust emission process. For a certain surface (sandy loam), the sandblasting efficiency increases with the increasing friction velocity by following an exponential law.

Dust deposition occurs with the absence of dust emission source on surface. The measurements indicate that deposition velocity for the particle bigger than 0.75 \( \mu \text{m} \) increases with particle size and friction velocity. The roughness elements on surface can significantly enhance dust dry deposition, especially for dust smaller than 4 \( \mu \text{m} \).

Acknowledgements

This work is supported by the Innovative Research Groups of the National Natural Science Foundation of China (11121202), and the National Natural Science Foundation of China (11172118, 41371034, 91325203) and the DFG.
(Deutsche Forschungsgemeinschaft) project “A Wind-tunnel Study on Dust-deposition Mechanisms and Validation of Dust-deposition Schemes”.

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