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PIV measurements of two phase velocity fields in aeolian sediment transport using fluorescent tracer particles

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ABSTRACT

This paper presents a method to simultaneously determine the velocity fields of both phases in aeolian sediment transport by means of PIV with fluorescent tracer particles. The fluorescent particles were atomized micron-sized droplets of rhodamine B solution. Specific optical filters were employed to ensure that the fluorescent tracer particles and the sand particles were respectively imaged on two CCD (charge-coupled device) cameras during measurement. A cross-correlation algorithm and image processing were used to obtain vector plots. The experimental results show that the distributions of the averaged velocity u of the wind-sand flow in both phases were concave downward curves on a semi-logarithmic figure. The upper parts of the profiles of both phases fitted well with a logarithmic distribution. When sand particle sizes were smaller than or equal to 160 μm, the averaged velocity u of both phases decreased with increasing particle size. The difference between the horizontal velocities (i.e. relative velocity u_r) in both phases of the sand phase increased with increasing particle size and height. In the region where $h/\delta < 0.25$, the momentum transfer between both phases was the most intense, and the effect of the air viscosity on the sand motion played an important role in the transfer. In the region where $h/\delta > 0.85$, the horizontal velocity hysteresis between both phases in each group of samples tended to be constant. For a sand particle diameter of 80–200 μm, Re_r changed linearly with the square root of d_m at the top of the saltation layer.

1. Introduction

During the process of aeolian sediment transport, the local wind field determines not only the trajectory of the sediments but also the flux and spatial density distribution of the sediment transport. On the other hand, Bagnold [1] stated in 1941 that "the sand profoundly alters the state of the wind". Thus, once sand transport is initiated the wind field and the sand phase are coupled in the sediment transport process. In past experimental studies, air velocity measurements usually have been conducted with a Pitot tube and thermal anemometers in wind tunnels, and with cup anemometers in the field [2–4]. The experimental results include the time-averaged velocity measured at a small number of points. The solid-phase measurements were focused on the mass flux of the sand captured by a sand trap, such as the measurements of the transport rate and the mass density distribution [5]. In recent years, electronic grain impact sensors and optical mass flux sensors have been used to measure sand transport rates [6–8]. The correlation between air velocity profile and sand transport rate (or the mass density distribution) has been widely investigated. However, the correlation only represents the indirect interaction between the wind field and the sand particles. Comparatively the coupling relation of the two phase velocity fields will provide insight into the interactions between the two phases. In addition, the measuring instruments mentioned above should perform the flow intrusions in the measurements [9].

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As a non-intrusive optical technique, Particle Image Velocimetry (PIV) has wide applications for flow field measurements since using the technique can yield the full-field flow information. An indication of its usage and development can be gained from Adrian [10]. PIV has been used in recent years to perform two-phase flow measurements by combining it with image processing techniques based on the particle image size and intensity, for the case where the solid or the liquid particles are expected to be significantly larger than the artificial seed particles [11–13]. However, due to the limited gray scale range of the CCD detector system, it is hard to identify a single particle image from a recording laden with particle images. Conventional processing methods of separating the two phase particle images inevitably must cause the loss of image information. Moreover, the irregular shapes of the sand particles will increase the difficulty of successfully completing the image separating process.

It is well known that some specific chemicals can absorb the energy of laser light and then emit fluorescence while they are illuminated by the laser. The molecules of a given fluorescent species will be driven into the exited electronic state by laser excitation. During relaxation of molecules to their ground state, the species emit isotropic light spontaneously. Since the fluorescent intensity is proportional to the intensity of the incoming laser light, the local concentration of the dye, and the surrounding temperature, this property often is used to perform concentration and temperature measurements in flow, combustion and other applications [14,15]. Since a certain amount of energy loss occurs between the molecule's transition and light emission, the Stokes shift in the fluorescence spectrum exists (i.e. the wavelength of the lasing fluorescence is larger than that of the excitation light source). With an appropriate filter on the camera, fluorescence could be distinguished from the laser light. This character provides the basis for the two phase velocity measurement in wind-sand flow. In actual fact, using fluorescence to separate the phases has been applied to measure the air flow accompanying spray droplets [16].

Herein, fluorescence of the gas-phase tracers is induced through planar laser exposure. The fluorescent particles and sand particles were respectively imaged through the filter on two CCD cameras. Then, the velocity fields of two phases were obtained simultaneously by processing the captured images using the PIV technique.

2. Experimental methods and materials

2.1. Wind tunnel

All runs were conducted in a small wind tunnel at the Center of Environmental Mechanics, Xi'an Jiaotong University, China. It is an open type wind tunnel with a test section of $550\ \text{mm}^{\text{L}} \times 100\ \text{mm}^{\text{W}} \times 70\ \text{mm}^{\text{H}}$. A sketch of the wind tunnel is shown in Fig. 1.

2.2. Fluorescent tracer particles

Since each fluorescent species has a unique excitation spectrum, the peak value of the excitation spectrum should be as close as possible to the wavelength of the laser light. In our case, the double-pulse laser (Mini-Yag Laser, Newwave Corp.) emits green light with a wavelength of 532 nm. The species selected was the solvent of ethanol and rhodamine B [17]. Its absorption and emission spectra are shown in Fig. 2 (measured by Du et al. [18]). The absorption spectrum with a peak value of 542.75 nm ensures that the molecules transition by the adopted laser excitation. The maximal intensity of the fluorescence occurs at 565 nm, which means that the fluorescence mainly appears orange. The micro-droplets were produced by ultrasonic atomization with a size distribution between 1 and 3 μm.

There are two effects that should be considered in PIV experiments while using the fluorescent particles instead of usual seeding particles (e.g. olive oil). One is the light scattering intensity on the surfaces of the fluorescent particles, which would determine the imaging quality of the fluorescent particle image. The imaging quality in our study could meet the requirements of the evaluations of PIV recordings by adjusting laser intensity and image post-processing (see Section 3.2).

The other effect of using the fluorescent particles as seeding particles in PIV experiments is the velocity lag of the particles in airflow. An estimate for the velocity lag of a particle in a continuously accelerating fluid could be listed as [19].

$$U_S = U_P - U = d_P^2 \frac{(\rho_P - \rho)}{18\mu} a \tag{1}$$

where U_P, U are the velocities of the particle and the fluid. ρ_P, ρ are the densities of the particle and the fluid. μ is the dynamic viscosity of the fluid and d_P is the diameter of the particle. Finally a is the acceleration of the fluid.

Therefore, the velocity lag depends on the diameter and density of the seeding particles in same fluid flow. For different oil as seeding materials in gas flow, the diameters of their droplets need be in 0.5–10 μm [19]. In the experiment, the diameters of the fluorescent particles were just between 1 and 3 μm. The relative densities of the olive oil and the fluorescent solvent approximate to 0.91 and 0.80, respectively. It could be concluded that the fluorescent micro-droplets could work much well as tracer particles in airflow than olive-oil droplet with same size. Moreover the calibration experiment results of ABL flow without sand particles in the lower part of the wind tunnel were shown in Fig. 3. The ABL velocity profiles of airflow with fluorescent particles or oil droplets resulted from time-spatial averaging of the instantaneous velocity fields. Symbol h is the height from the bed surface and u denotes the mean streamwise velocity. The averaged velocity distributions along with height of airflow with both particles were much close, which means that the fluorescent microdrops could be function comparable to the olive-oil droplet. In addition, it could be found from Fig. 3b that the mean streamwise velocity profiles were well fitted with the logarithmic law. Therefore, the ABL flow at observation field in the wind tunnel had been fully developed and the thickness of the simulated ABL surface layer was about 20 mm.