Dynamics of particles in aeolian saltation

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ABSTRACT: Saltation has been studied for particles of diameter D_p=320 µm. We present wind tunnel measurements of particle speeds at different heights above the bed and at different values of the bed shear stress. To corroborate the measurements we propose an analytical expression for particle speed as a function of height and wind speed. There is reasonable agreement between model predictions and observations despite of several simplifications made in the analytical model. Furthermore comparison between observations of grain speed and air speed at the same height indicate that the absolute differences between the two is small near the bed, but then increases further away from the bed. Finally near the top of the saltation cloud grain speed again approaches air speed. This pattern appears to be similar for different bed shear stresses.

1 INTRODUCTION

In aeolian transport saltation is an important link by which momentum is transmitted from the air to the bed through grain impact, but momentum transfer, impact and subsequent entrainment take place in a very shallow layer at the air-bed interface with large velocity gradients. Consequently, experimental evidence on the impact-entrainment processes has been obtained from few and simplified studies of the splash (e.g. Willetts & Rice 1986, 1989, Mitha et al. 1986), from investigating the vertical intensity and distribution of the saltation cloud including the wind profile within the saltation layer (e.g. Williams 1964, Iversen & Rasmussen 1999, Liu & Dong 2004), and finally from theoretical reasoning and numerical modelling (Owen 1964, Sørensen 1985, Anderson & Haff 1988, 1991, McEwan & Willetts 1991, 1993, Shao & Li 1999, Spies & McEwan 2000).

Direct measurement of particle trajectory (e.g. White and Schultz 1977), Mitha et al. 1986) or particle speed (Rasmussen 2002, Dong et al. 2002) can be used to verify the (plausible) assumptions contained in such models, but data are sparse. The present paper reports from a series of wind tunnel measurements where the vertical variation of grain speed has been recorded using a Doppler method above beds of quarts grains of different diameter. It focuses on results of the horizontal component of grain velocity for one size class and for a range of friction speeds and also compares the experimental results to values predicted using a analytical model of saltation.

2 CHARACTERISTICS OF PARTICLES IN THE SALTATION LAYER

After the sand grains have left the surface they are accelerated by the wind. This process has been modeled by several authors. Here we will use an approximate model of the grain trajectories that is explained in detail in Sørensen (1991) and which gives results that are comparable to those of numerical models (e.g. Anderson & Haff 1991, McEwan & Willetts 1991). In order to derive the explicit expression given below for the mean horizontal grain speed as a function of height, further simplifications are made. The details can be found in Rasmussen and Sørensen (2005 in prep.). Here we will just briefly mention that it is assumed that the vertical component of the launch velocity is exponentially distributed with mean value λ^{-1}, and that the conditional expectation of the horizontal component of the launch velocity given that the vertical component has the value $v_{0,2}$ equals $\kappa v_{0,2}$. Here $\kappa = \cot(\theta)$, where θ is the mean launch angle of the grains. In accordance with results in White and Schulz (1977), Nalpanis (1985) and Sørensen (1985), θ is taken to be 50 degrees.

The model prediction of the mean horizontal speed of grains with a positive vertical velocity component (ascending grains) at height y is

$$\overline{U}_p^{\,up}(y) = U + 2\kappa\lambda^{-1}\tilde{y}K_2\left(2\sqrt{\tilde{y}}\right) + 2\sqrt{\tilde{y}}\left(\kappa v(y) - U\right)K_1\left(2\sqrt{\tilde{y}}\right), \tag{1}$$

where $\tilde{y} = y\lambda/(\alpha t_*)$ is a dimensionless height, U is the typical wind speed at the heights visited by the grains, t_* is a relaxation time for the grains that can be taken to be 0.236 sec for grains of size 320 µm, K_i is a modified Bessel function of the third kind, and $v(y)$ is the smallest value of the vertical component of the launch velocity for which a grain will reach the height y. This function is the solution to the equation $t_*[v(y) - v_f \ln(1 + v(y)/v_f)] = y$, where $v_f = g\, t_*$ is an approximate terminal fall velocity of the grains. Finally, α is a non-dimensional quantity given by $\alpha = v_f/(v_f + v(y))$. The typical wind speed U is taken to equal the wind speed u at height y except below one cm, where it is taken to be the wind speed at height one cm.

The model prediction of the mean horizontal speed of grains with a negative vertical velocity component at height y is

$$\overline{U}_p^{\,down}(y) = U + \frac{2\kappa e^{-a}}{\lambda\left(a^2+1\right)}\tilde{y}K_2\left(2\sqrt{\tilde{y}\left(a^2+1\right)}\right) + 2\sqrt{\frac{\tilde{y}}{\left(a^2+1\right)}}\left(\kappa v(y) - U\right)e^{-a}\,K_1\left(2\sqrt{\tilde{y}\left(a^2+1\right)}\right) \tag{2}$$

where the dimensionless quantity a is given by $a=\alpha/(\lambda v_f)$. The other quantities are as in eq. (1). Since the same number of grains goes up and down, the mean horizontal grain speed at height y is

$$\overline{U}_p(y) = \left(\overline{U}^{\,up}(y) + \overline{U}^{\,down}(y)\right)/2 \tag{3}$$

3 METHODS AND INSTRUMENTS

The wind tunnel at Aarhus University has a 15 m long working section with a cross section of 0.60 m by 0.90 m. A small bell mouth followed by turbulence spires and a 3 m long array of roughness blocks provides a turbulent boundary layer which is in fair equilibrium with the boundary layer influenced by ongoing saltation in the main part of the working section (Rasmussen & Iversen 1993). Sand is fed into the tunnel near the end of the roughness array and the speed of the air-flow can be varied between zero and approximately 20 m/s.

In the present experiment the bed was covered with a 2.5 cm layer of uniform sand with diameter D_p=320 µm. Before each run the surface was prerippled at a velocity similar to that of the following experiment. The profile of the wind speed (u) was measured using a pitot-static/electronic micromanometer so that the friction speed u_* bed shear stress could be calculated using the logarithmic wind law (e.g. Bagnold 1941). Grain speeds were measured with a 1-D integrated laser-optics system (Dantec Flowlite with a Flow Velocity Analyzer Signal Processor) configured with a 632.8 nm laser with beam separation of 38 mm and focal length of 300 mm. The laser was placed outside the tunnel 15 m downwind of the entry and data recorded through an optical window in the wall so that no disturbance of the flow occurred. Mostly the sensor was used to record the velocity component in the mean flow direction, i.e. parallel to the axis of the wind tunnel, but in a few runs the sensor was placed so that the vertical component of the grain velocity could be measured. Typically the duration of a run varied from 15-60 seconds depending on the measurement. Short runs were used at low heights while longer runs were used farther away from the bed where grain concentrations are low. Typically 1000-3000 grain speeds were sampled at the lowest level, but only about 20 were sampled at the highest. The processed data contains information about particle arrival time and transit time, and data were stored if the calculation of particle speed was validated by the software.

4 RESULTS AND DISCUSSION

4.1 *Transit time influences*

Early in the experiment it was realized that data for the horizontal grain velocity contained a fraction of negative velocities even at heights of 80 mm or more. Although negative speeds will occur occasionally (Bagnold 1941), it seems unlikely that such events will be relatively common at such heights, and therefore a few runs were made during which both the distributions of the u- and w-components of the grain speed were recorded (Fig. 1).

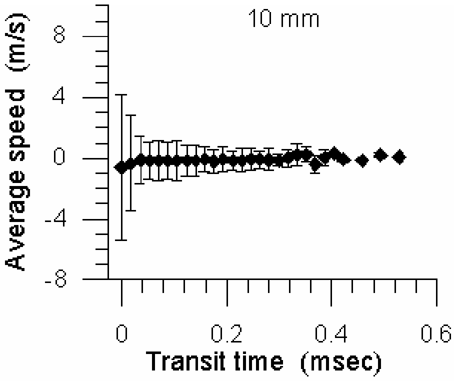

Figure 1. The distribution of the average vertical grain speed measured at 10 mm height as function of grain transit time (TT) in the control volume of the LDA-sensor. The standard deviation is shown with bars; no bars indicate single observations.

The figure clearly depict that when grains pass very quickly through (part of) the control volume, i.e. when the transit time (TT) is small, then the variation of the vertical speed is very large. For falling grains, i.e. grains with a negative w-component, its magnitude is limited by the terminal velocity of the grains. For 320 µm grains the terminal velocity is of the order of 3 m/s (Greeley & Iversen 1985). Thus the large negative velocities in Figure 1 must be due to measurement errors. The quarts grains used in the present study are large compared to particles normally seeded into the flow in LDA-anemometry for recording the (turbulent) wind. In addition they are non-spherical, have facets, and may spin (White & Schultz 1977). Therefore the large negative velocities in Figure 1 might well be caused by spin and grain facets. Experiments using other grain sizes and more measurement heights gave similar large variation with large negative values for the smallest TT-values. In the following analysis, we have therefore omitted data from the lowest 3 bins of TT-values, i.e. transit times less than 20 µs. This will only marginally influence the estimated average speed, but prevents using the number of particles as a direct measure of mass transport. However, at the lowest measurement height in particular, the percentage of validated samples is low - typically only 20-30 % of the number of attempted samples, which makes such use questionable anyway.

4.2. Grain speed

The distribution of the horizontal grain velocity (U_p) is presented at three different heights for two different friction speeds (Fig. 2). The selected heights represent conditions in the intense part of the saltation layer (5 mm), a bit above the most intensive part (20 mm), and far above the bed near the top of the boundary layer (80 mm), while the lower friction speed represents conditions close above saltation threshold and the higher value represents conditions at intense transport.

At the lowest height the distributions are left skew at both low and intense transport. At the uppermost level only large values of U_p are found at the low friction speed, while a wide range of U_p-values are found at intense transport. At the intermediate height the variation of U_p is large both at low and intense transport. Qualitatively the observed variation agrees with the perception that during the splash maybe only a single grain may receive a large part of the forward momentum of the impinging grain while several grains will receive some momentum and thus make low, short jumps. Only few grains jump as high as 80 mm, and almost none jump even higher where they can attain higher speed than at that level, which might the narrow distribution of high velocity grains at 80 mm. At the intermediate level the variation in speed is considerable because a large number of grains are on their way up and has not yet approached their final horizontal velocity while another large number of grains are descending with a considerably higher speed. The influence from increasing friction speed and hence particle energy and jump-height is demonstrated by the overall similarity between U_p(0.27 m/s; 5 mm) and U_p(0.87 m/s; 20 mm) as well as U_p(0.27 m/s; 20 mm) and U_p(0.87 m/s; 80 mm).

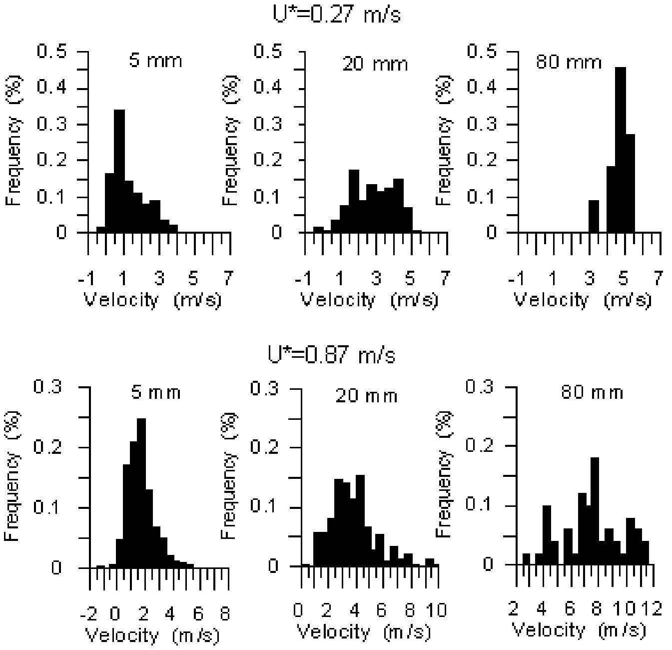

Figure 2. The distribution of the average horizontal velocity (U_p) at 5 mm, 20 mm, and 80 mm above the bed, and at friction velocities u_* = 0.27 m/s and 0.87 m/s.

For four different flow speeds the variation of the measured and predicted grain speed with height is depicted in Figure 3, where is also plotted the air speed through the upper part of the saltation layer. At low friction speed the few grains that jump highest are almost able to attain a horizontal speed similar to that of the flow, while at the higher friction speed there is a clear deficit in speed. At all friction speeds there is a large deficit in speed between particles and flow between 10 mm and 50 mm height.

For the predicted grain speed the value of lambda was chosen to obtain the best fit to the measured mean values. In this way the mean vertical launch speed was estimated to: 0.17 m/s for u_*=0.27 m/s and 0.40 m/s for the other friction speeds. There is excellent agreement between predicted and measured values indicating that the basic principles on which the analytical model is based are sound and also corroborating the measurements.

The data presented in the present experiment have been measured at 5 mm or more above the bed, basically because of technical problems and large measurement uncertainty. However, a few data sets have been recorded in the wind tunnel at about 1-2 mm above the bed and their velocity distribution is consistent with the data measured further away from the bed. In a recent paper (Dong et al. 2002) presented data measured with a Phase Doppler Analyzers, PDA system. Their data indicate that at or immediately above the bed the distribution of the horizontal particle speed is almost symmetrical around zero. Presently we are not able to detect whether there is a discrepancy between our observations and the results by Dong et al. (2002). However, we take the consistent behaviour of our data combined with the fact that our experimental data are in fair agreement with measured particle trajectories (White & Schultz 1976), numerical predictions (Anderson & Haff 1991) as well as analytical predictions (Sørensen 2004) as an indication that a forward velocity component exist at even low height above the bed. Finally the analysis shows that particle spin and influence from grain facets may significant influence results if not handled properly.

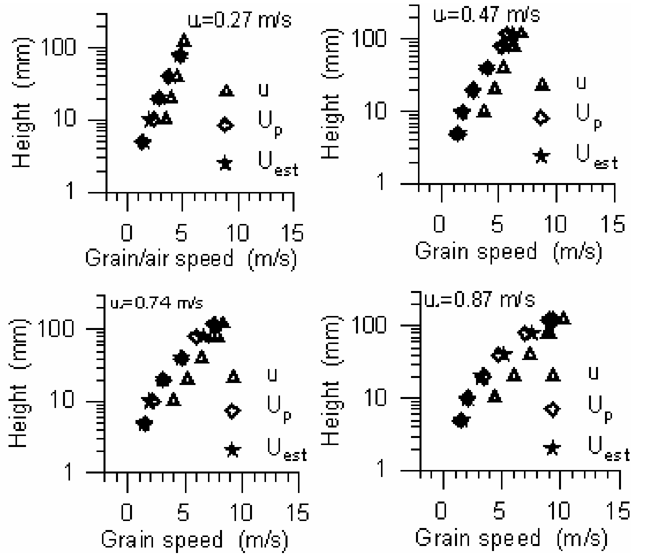

Figure 3. The variation of average horizontal grain velocity as function of height above the bed at a friction speed of u_*=0.27 m/s, 0.47 m/s, 0.74 m/s, and 0.87 m/s (u is wind speed, U_p is measured particle speed, and U_{est} is predicted particle speed).

5 CONCLUSIONS

Wind tunnel observations of grain speeds over a bed of uniform grains of diameter D_p = 320 µm m measured at different heights above the bed and at different friction speeds have been obtained by means of a laser Doppler sensor and shown to be in good agreement with predictions from an analytical model. In particular, an explicit formula for the mean horizontal grain speed as a function of height was presented. Both observations and models predictions show a small difference between air and grain speed low, respectively high in the saltation cloud, while a larger difference between these is predicted as well as observed in the intermediate parts. It was demonstrated that very considerable measurement errors may occur, if data from a laser Doppler sensor are not handled properly. In particular, unrealistic negative velocities can be caused by particle spin and grain facets.

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