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Laboratory studies of aeolian sediment transport processes on planetary surfaces

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ABSTRACT

We review selected experimental saltation studies performed in laboratory wind tunnels and collision experiments performed in (splash-) laboratory facilities that allow detailed observations between impinging particles on a stationary bed. We also discuss progress in understanding aeolian transport in nonterrestrial environments. Saltation studies in terrestrial wind tunnels can be divided into two groups. The first group comprises studies using a short test bed, typically 1–4 m long, and focuses on the transitional behavior near the upwind roughness discontinuity where saltation starts. The other group focuses on studies using long test beds — typically 6 m or more — where the saturated saltation takes place under equilibrium conditions between wind flow and the underlying rough bed.

Splash studies using upscaled model experiments allow collision simulations with large spherical particles to be recorded with a high speed video camera. The findings indicate that the number of ejected particles per impact scales linearly with the impact velocity of the saltating particles. Studies of saturated saltation in several facilities using predominantly Particle Tracking Velocimetry or Laser Doppler Velocimetry indicate that the velocity of the (few) particles having high trajectories increases with increasing friction velocity. However, the speed of the majority of particles that do not reach much higher than Bagnold's focal point is virtually independent of Shields parameter — at least for low or intermediate u_*-values. In this case mass flux depends on friction velocity squared and not cubed as originally suggested by Bagnold. Over short beds particle velocity shows stronger dependence on friction velocity and profiles of particle velocity deviate from those obtained over long beds.

Measurements using horizontally segmented traps give average saltation jump-lengths near 60–70 mm and appear to be only weakly dependent on friction velocity, which is in agreement with some, but not all, older or recent wind tunnel observations. Similarly some measurements performed with uniform sand samples having grain diameters of the order of 0.25–0.40 mm indicate that ripple spacing depends on friction velocity in a similar way as particle jump length. The observations are thus in agreement with a recent ripple model that link the typical jump length to ripple spacing. A possible explanation for contradictory observations in some experiments may be that long observation sequences are required in order to assure that equilibrium exists between ripple geometry and wind flow.

Quantitative understanding of saltation characteristics on Mars still lacks important elements. Based upon image analysis and numerical predictions, aeolian ripples have been thought to consist of relatively large grains (diameter > 0.6 mm) and that saltation occurs at high wind speeds (>26 m/s) involving trajectories that are significantly longer than those on Earth (by a factor of 10–100). However, this is not supported by recent observations from the surface of Mars, which shows that active ripples in their geometry and composition have characteristics compatible with those of terrestrial ripples (Sullivan et al., 2008). Also the highest average wind speeds on Mars have been measured to be <20 m/s, with even turbulent gusts not exceeding 25 m/s.

Electrification is seen as a dominant factor in the transport dynamics of dust on Mars, affecting the structure, adhesive properties and detachment/entrainment mechanisms specifically through the formation of aggregates (Merrison et al., 2012). Conversely for terrestrial conditions electric fields typically observed are not intense enough to significantly affect sand transport rates while little is known in the case of extra-terrestrial environments.

1. Introduction

Almost a century of research on aeolian processes has led to an overall understanding of wind flow and sediment transport systems and

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their interaction. A substantial part of the advances of our understanding has come from meticulous studies in the most commonly used aeolian laboratory — the wind tunnel. In an aeolian context a breakthrough in wind tunnel testing came during the 1930s where R.A. Bagnold in a series of studies obtained the first physically based insight into aeolian dynamics as documented in articles in the *Proceedings of the Royal Society* (Bagnold, 1936, 1937, 1938) and later in his famous book *The Physics of Blown Sand and Desert Dunes* (Bagnold, 1941). After the Second World War new wind tunnels for aeolian research were built and the purpose of wind tunnel facilities broadened so that subjects other than pure aeolian dynamics were included. In Japan Kawamura (1951) studied sand movement in a wind tunnel at Tokyo University. In North America in late fall of 1947, a study of the mechanics of wind erosion was initiated at Kansas State College, Manhattan, KS, USA, using laboratory and field (portable) wind tunnels (Zingg and Chepil, 1950; Chepil, 1965). In Denmark, at the Danish Technical University, Jensen (1954) investigated the aerodynamics of shelter belts in order to optimize the protection of fields during periods with little or no vegetation. During the 1960s and 1970s laboratory wind tunnels became more abundant; and in 1976 the first planetary facility 'The Martian Surface Wind Tunnel' (MARSWIT; Greeley, 1977) was put into operation in Ames, California by NASA. Although the number of terrestrial wind tunnels has been more or less stagnant since then, new or modified facilities now enable not only wind speed but also environmental parameters such as temperature (cryogenic), humidity (McKenna Neuman and Scott, 1998; McKenna Neuman and Sanderson, 2008), and electrification (Rasmussen et al., 2009; Merrison, 2012) to be investigated. In the planetary context two closed-circuit facilities have also come into use at Aarhus University (Rasmussen et al., 2011).

Initially wind tunnel laboratory studies focused on steady state saturated transport, i.e., the transport of particles on granular beds composed of plentiful dry, unconsolidated grains of sedimentary or artificial (industrial) origin. Bagnold (1941) recognized the existence of a fluid threshold for initiation of saltation and another, lower impact threshold above which saltation, once started, could be sustained. Influences on threshold conditions from, e.g., varying gravity, particle and gas density and composition were investigated in aeolian wind tunnels as well as in the MARSWIT facility (e.g., Iversen, 1976; Greeley et al., 1980; Iversen and White, 1982), and later the role of bed slope was also investigated (Iversen and Rasmussen, 1994). Bagnold (1941) linked mass transport (q) to friction velocity (u_*) and suggested a cubic relation; subsequent modifications led to slightly different transport equations, e.g., Kawamura (1951), Lettau and Lettau (1978), and Owen (1964, 1980). Moreover, Bagnold (1941) observed that the feedback on the wind flow exerted by the saltating grains is equivalent to an increased friction (aerodynamic roughness length, z_0) of the bed; and from theoretical reasoning, Owen (1964) proposed that for a saltating bed z_0 increases with u_*^2 / g where g is gravitational acceleration. Experimental support of this came somewhat later (e.g., Rasmussen and Mikkelsen, 1991; Rasmussen et al., 1996). Bagnold also observed that the modification of the wind profile resulted in an almost constant velocity at some fixed height above the bed inside the region of intense saltation — the focal point.

As insight into saltation dynamics increased it became evident that a fundamental issue to solve was the physics involved in the collision process between impinging particles and the bed — expressed by the splash function (Unger and Haff, 1987). Although some information about the splash process (in the following referred to as the *splash*) initially came from high speed film recordings in wind tunnels (Willetts and Rice, 1986; Rice et al., 1996), another more valuable source of information was the experiments performed in special splash facilities equipped with high-speed cameras (Mitha et al., 1986; Beladjine et al., 2007). A formal name, the *splash law*, was introduced by Anderson et al. (1991) specifying the probability of number and velocity distributions for rebounding and ejected grains.

The terrestrial aeolian studies span a narrow fluid-dynamic range, and aeolian wind tunnels have undergone only small modification since the turn of the millennium. Planetary conditions, on the other hand, span an extremely broad range of dynamic conditions owing to varying pressure, temperature, and atmospheric composition — which impose large variation of density and viscosity and thus, indirectly, impose limitations on flow velocity, for instance. Parallel to this measuring, techniques and data analysis have advanced significantly and are the indirect cause for many recent advances within the aeolian field. Therefore the objectives of the present paper are to describe important developments in facilities and equipment and to highlight the contribution of laboratory experimentation to improve insight into aeolian dynamics and systems. We concentrate on active saltation of dry, loose, and unconsolidated materials; while aeolian systems where chemical bonding, cohesion, or adhesion plays an important role are beyond our experience. Initially in Section 2 we discuss the state of wind tunnels and the design of equilibrium air and sediment flows as well as the concept of steady-state saltation by also including new experimental data. Section 3 focuses on the splash laboratory where modern high-speed video recorders have replaced the old film techniques (e.g., Beladjine et al., 2007) and data analysis greatly improved using modern digital image analysis rather than cumbersome visual inspection. Section 4 focuses on the transport layer and results obtained using vertically stacked traps, laser techniques spanning simple laser illumination of cross sections, to advanced techniques such as Laser Doppler Velocimetry (LDV) and Particle Tracking Velocimetry (PTV). Section 5 presents important observations from planetary environments and discusses some aspects of laboratory experiments in a planetary context; while finally in Section 6 we discuss and conclude on important issues concerning laboratory-based simulation of aeolian systems. A list of symbols is given in Appendix A.

2. Steady-state air flow and saltation in wind tunnels

2.1. The terrestrial aeolian wind tunnel

A primary aim of an aeolian wind tunnel is to allow simulation of mechanics and transport of granular material ranging from dust to gravel size under the influence of wind flow in the atmospheric surface layer, i.e., the lowest part of the boundary layer between the surface of the Earth and the free flow in the overlaying atmosphere. Most wind tunnels are horizontal; but because in nature much sand transport takes place on sloping dune surfaces, at least one laboratory facility allows the slope of the bed to be varied within ±25° (Iversen and Rasmussen, 1994). Ideally wind tunnels should have as large a cross section as possible in order to let a turbulent boundary layer to form with eddies at scales that are common in nature. However, in reality space and power constraints for the fan limit how large the cross sections can be made at a reasonable cost. One may distinguish between large tunnels where the width (W) and the height (H) ≥ 1 m, medium-sized tunnels where 0.5 m ≤ W,H < 1 m, and small tunnels where W, H < 0.5 m. A selection of tunnels representing these classes is listed in Table 1.

Owen and Gillette (1985) investigated the constraints on the development of saltation imposed by a wind tunnel of limited height and concluded that the Froude number $Fr = U_\infty / (gH)$ (U_∞ being free stream velocity, g acceleration of gravity, and H tunnel height) should not be larger than 20. For a small 30-cm-high wind tunnel, this limits the free airstream velocity to ~8 m/s so that results from high friction velocity experiments may become dubious.

The turbulent spectrum in the tunnel must be as close as possible to that above a natural surface, but even for the largest tunnels a serious truncation of the low frequency end of the spectrum cannot be avoided. In contrast to this, the propagation of external disturbances into the wind tunnel is easier to remove by placing sets of screens and/or honeycombs at the entry to the working section. If the fan is placed downwind