A WIND TUNNEL STUDY OF THE EFFECT OF PRESSURE ON SALTATION THRESHOLD

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Introduction: Aeolian activity occurs under a wide range of atmospheric pressures in the Solar System. Dunes have been observed on Earth (average surface pressure of 1 bar), Mars (6 mbar), Venus (92 bar), and Titan (1.5 bar) [1, 2], and suggested for some icy bodies [2]. The formation of dunes requires the movement of sand in saltation. The initiation of the saltation process may occur at at fluid or impact threshold wind speeds. Fluid threshold refers to the minimum wind speed necessary to initiate saltation [3]. Impact threshold refers to the minimum wind speed at which saltation can be sustained by splash-induced impact [3]. The ratio of impact to fluid threshold is modeled to be proportional to atmospheric density, with model values <1 operative on Earth and Mars and >1 on Venus and Titan [4, 5].

The wind speed commonly used to quantify threshold is friction wind speed (u_*), defined relative to the shear stress exerted by the wind and is independent of height within the boundary layer. The threshold friction wind speed (u_{*t}) is quantified as

$$u_{*t} = A\left(Re_{*t}, I_p\right)\left(\left(\rho_p / \rho\right) g D_p\right)^{1/2} \text{, (Eq. 1)}$$

where A is a dimensionless threshold parameter dependent on both the particle Reynolds number at threshold friction wind speed [$Re_{*t} = u_{*t} D_p / \upsilon$] and the interparticle forces [$I_p = I_p f\left(D_p\right)$], υ is the kinematic viscosity of the gas, ρ_p and ρ are the particle and gas densities, g is gravity, and D_p is the median grain diameter. At this threshold of motion, the aerodynamic drag and the lift force, along with any contribution from impact, overcome the force of gravity and the interparticle force to initiate movement of the grain [2, 3].

Since Bagnold's seminal work on the physics of air blown sand [3], researchers have been deriving equations to model threshold speed and using wind tunnel data to parameterize their models. Iversen and his colleagues were instrumental in developing a model that can be applied to other planetary bodies over a range of pressures from 5 mb to 30 bar [6, 7, 8]. This empirically-derived model is based on the presumption that in their wind tunnel experiments the authors observed fluid entrainment at low pressures and impact entrainment at high pressures, which justified their inclusion of a density ratio term at higher pressures [8]. However, recent computational models by Kok [4] and Kok et al. [5] indicate that this relationship is inverted, and, on planetary bodies with thicker atmospheres, fluid en-

trainment is dominant over impact entrainment. A recent mismatch between the empirically-derived model and high-pressure wind tunnel data collected under Titan analog conditions [9] highlights the importance of resolving this contradiction between the empirically-derived and computational models.

Hypotheses: Due to their decades of use by the aeolian planetary community, the null hypothesis of our study is that the empirically-derived equations [7, 8] are correct in presuming that fluid entrainment is predominantly observed at lower pressures and at higher pressures impact entrainment is observed. In light of the new computational models [4,5], our alternative hypothesis is that the presumption behind the empirically-derived equations [7, 8] is incorrect and that instead fluid threshold is increasingly observed at higher pressures. To test these hypotheses, we conducted experiments in the Titan Wind Tunnel (TWT) [10].

Data Collection: Our experimental matrix includes materials covering a wide range of densities and grain diameters. This range enables us to compare new results with past experiments and to provide sufficient data coverage to rigorously define the threshold curve of grain size vs friction wind speed.

During data collection, the movement of the grains was viewed at the downwind observation port. Two snake lights provided illumination of the bed, and a high-speed video (HSV) camera with a micro lens captured movement at threshold at 1400 frames per second (fps). A Canon DSLR camera was positioned next to the observer to document, at 30 fps, the appearance of the bed at all the stages of grain motion. This videography, along with associated metadata, will be archived at the Planetary Data System Atmospheres Node for easy accessibility [11].

During each experiment, the fan speed was incrementally increased until threshold, defined as continuous grain motion over 50% of the bed, was perceived by the observer. At this moment, the HSV camera captured 2 seconds of grain motion. Each experiment was repeated three times at a single pressure and replicated for a range of select pressures between 1 and 20 bar. The surface pressure on Titan in ~1.5 bar, but these experiments were run at higher pressures in order to recreate the kinematic viscosity conditions of Titan's atmosphere for current and past climates.

Data Reduction Methods: The videos captured by the high-speed camera are being evaluated in order to quantify the proportion of grains entrained by impact

vs fluid processes. We have developed both visual and computer-based methods for this evaluation. In the visual method, the frames are being extracted from the video using MATLAB. Two independent researchers watch the high-speed videos frame-by-frame and record the number of grain ejections by impact (e.g., Fig. 1) and by fluid processes. If other categories of entrainment (e.g., reptation before ejection) are observed, we record data for those categories as well.

A computer-based approach is also employed. This computer program loops over all the frames and tracks the grains between successive images to identify i) if they have been entrained and ii) the conditions of entrainment (fluid or impact threshold). This method is limited to larger grains (>500 μm), but it is faster and less subjective than the visual method. The computational results are verified visually.

Data Analysis Methods: The output from all videos covering a range of pressures are organized into a table for each material composition and diameter. We record the fluid and impact threshold counts and calculate the ratio of fluid to impact threshold for each pressure. Table 1 is a partial example of one of these tables. More complete data from both analysis methods will be presented at the conference.

Table 1: Preliminary data of entrainment counts by type for walnut shells (707-833 μm) under two different atmospheric pressures; data from visual analysis.

Pressure (bar)	Fluid Entrainment Counts (F)	Impact Entrainment Counts (I)	Ratio (F/I)
3	3	12	0.25
20	4	12	0.33

In addition, we will compare our empirical results to the output from the computational model [4, 5]. This model keeps track of the fraction of particles that are ejected by impacts vs. entrained by the flow, enabling direct comparison with our empirical results. This comparison will provide a test of the model validity for our experimental conditions.

Implications: If the ratio of fluid to impact entrainment counts decreases as a function of pressure, as predicted by the empirical model [7, 8], then the null hypothesis would be supported. This result would in turn support the continued use of these established empirically-based threshold models. If the ratio of fluid to impact entrainment counts increases as a function of pressure, as predicted by the computational model [4, 5], then the alternative hypothesis would be supported. Such a finding would suggest the use of a density ratio term at lower pressures instead of higher pressures, contrary to the implementation of the empirical model [7]. Our preliminary results support this alternative

hypothesis; additional data will be presented during the conference. If future work continues to support the alternative hypothesis, the empirical model [7, 8] would need to be re-evaluated, and the model coefficients modified. Either results will lead to a better understanding of threshold on all planetary bodies with an atmosphere capable of moving granular material.

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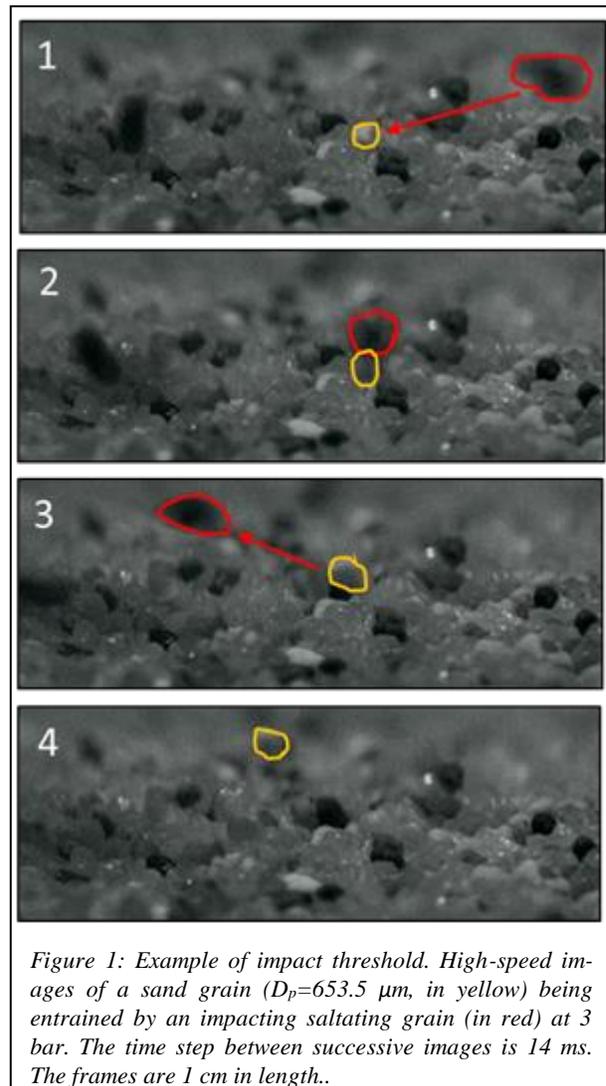

Figure 1: Example of impact threshold. High-speed images of a sand grain (D_p=653.5 μm, in yellow) being entrained by an impacting saltating grain (in red) at 3 bar. The time step between successive images is 14 ms. The frames are 1 cm in length..