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A wind tunnel study of the effect of density ratio on saltation threshold

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Abstract

An expression for aeolian saltation threshold – the minimum wind speed required to initially entrain sediment particles into saltation – is used in modeling aeolian processes and the formation of aeolian landforms on Earth and other planetary bodies. Previous experiments under high-fluid-density conditions in the Venus Wind Tunnel (VWT) concluded that this threshold is a function of the ratio of the density of the particle to the density of the entraining fluid (ρ_p/ρ). A curve for the dimensionless threshold parameter, *A*, as a function of (ρ_p/ρ), was derived [Iversen et al. 1987]. In this work, we revisit this curve of $A(\rho_p/\rho)$ using data from the Titan Wind Tunnel (TWT) [Burr et al., 2015b]. We use both previous and newly collected TWT data of freestream threshold wind speed spanning a range of density ratio conditions to derive friction wind speeds and then values for *A*. The TWT-derived data generally overly the VWT data used to derive the density ratio curve, although showing greater variability and an apparent offset to slightly higher values. We derive a new density ratio curve from the aggregated threshold data using the same format as the previous expression but with new values for the two exponential parameters. These TWT data provide additional constraints on the transitional portion of the density ratio curve between the low density ratio conditions of flume data and the high density ratio conditions of Mars Surface Wind Tunnel data.

Graphical abstract:

Highlights:

Keywords: density ratio; laboratory wind tunnel experiments; saltation threshold

Introduction

Evidence for the geophysical processes by which granular solids are entrained into transport across solid surfaces by flowing gas is pervasive across the Solar System. Such aeolian movement of sediment – whether by atmospheric, exospheric, or episodic (geysering, jetting) gas flow – has been documented on Earth, Mars, Venus, Titan, Triton, Enceladus, Pluto, and comets (Greeley and Iversen, 1985 and references therein; Sagan and Chyba, 1990; Weitz et al., 1994; Porco et al., 2006; A'Hearn et al., 2011; Lorenz and Zimbelman, 2014 and references therein; Burr et al., 2015b and references therein; Telfer et al., 2018). These processes differ as a function of different boundary conditions, including the sizes of the grains and the speed of the flowing gas (Bagnold, 1941), the densities of the granular solids and the flowing gas (Greeley et al., 1980; Iversen et al., 1987), the relative humidity of the gas and water content of the grains (McKenna Neuman and Sanderson, 2008; Yu et al., 2017), and other conditions (see, e.g., Rasmussen et al., 2015 and references therein).

One descriptor of aeolian processes is the minimum, or threshold, wind speed needed to entrain sediment. Values for threshold wind speed are fundamental to understanding and modeling all aspects of aeolian transport, including the onset of aeolian sediment movement (Bagnold, 1941), aeolian mass flux (White, 1979; White, 1981), minimum aeolian erosion potential (Sagan et al., 1977) and aeolian erosion effectiveness (Bridges et al., 2005). Thus, they impact our analysis and understanding of phenomena from a local scale, like ventification (Knight, 2008) and dune orientation (Rubin and Hunter, 1987), to the global scale, like the relative importance of various resurfacing processes (Bridges et al., 2012), all of which have important implications for past climate conditions and climate change (Bridges et al., 1999; Greeley et al., 2000; Golombek et al., 2006; Ewing et al., 2013).

The quantification of threshold wind speeds was laid on a foundation of terrestrial (ambient condition) wind tunnel research (Bagnold, 1941), which continues to advance our understanding through increasingly sophisticated instrumentation and experiments (Holstein-Rathlou et al., 2013; Bennett et al., 2015 and references therein; O'Brien and McKenna Neuman, 2016; Yu et al., 2017). Planetary wind tunnels, which simulate atmospheric density on planetary body surfaces (Merrison et al., 2009; Burr et al., 2015b; Swann and Ewing, 2016; Williams and Smith, 2017, and references therein), have enabled the exploration of the effects on aeolian transport of extraterrestrial boundary conditions. Early planetary wind tunnel work assumed that gravity similitude could be attained by variations in the density of the grains (e.g., Greeley et al., 1974), whereas the subsequent history of research into aeolian entrainment and transport processes indicates the need for careful matching of the similitude parameter according to the aeolian process under examination (Burr et al., 2015a; Burr et al., 2015b). Some degree of modeling based on wind tunnel results is necessary to account for gravitational and other differences (e.g., temperature) that have not been achieved in planetary wind tunnels (although see Marshall et al., 1991 for a study of aeolian attrition and accretion under Venusian temperatures and pressures).

The Planetary Aeolian Laboratory at the NASA Ames Research Center in Mountain View, CA, currently supports wind tunnel simulation of the air density at the surface of Mars in the Mars Surface Wind Tunnel (MARSWIT; Greeley et al., 1976; Greeley et al., 1980; Swann and Ewing, 2016; Williams and Smith, 2017). The facility also enabled simulation of the atmospheric density at the surface of Venus in the Venus Wind Tunnel (VWT; Iversen and White, 1982; Greeley et al., 1984; Marshall and Greeley, 1992). A refurbishment of that equipment led to the Titan Wind Tunnel (TWT; Burr et al., 2015b), which can be used to simulate aspects of the atmosphere, such as density or kinematic viscosity (Burr et al., 2015a), on the surface of Titan.

This simulation provides the means to investigate the effects of atmospheric density, pressure, or kinematic viscosity on threshold wind speeds. Threshold wind speeds vary as a function of grain size (Bagnold, 1941), where larger grains require strong winds due to greater mass (weight) and smaller grains require stronger winds due to interparticle forces (Greeley and Iversen, 1985). The result is a characteristic U-shaped curve for threshold velocity as a function of grain size with an intermediate grain size having the lowest threshold speed. Previous work in the MARSWIT and VWT yielded threshold curves for Mars and Venus (Greeley and Iversen, 1985). Based on the high-pressure VWT work, a threshold curve was also modeled for Titan, but not tested at that time against experimental data under Titan similitude conditions.

A synopsis of planetary wind tunnel studies shows the importance of testing model output against experimental results (Burr et al., 2015b). Modeling based on terrestrial threshold wind speeds to derive Martian threshold wind speeds was not consistent with later MARSWIT results (Greeley et al., 1976), and likewise, modeling of threshold for Venus surface conditions was not consistent with results from the VWT. To force consistency of the Venus threshold model with the VWT results, a term was included in the expression for threshold that accounts for the low ratio of grain to atmospheric density on Venus (Iversen et al., 1987). More recent modeling of saltation threshold on Titan could be made consistent with TWT results with the inclusion of this density ratio term (Burr et al., 2015a). This term is based on the assumed influence of grain impact on the bed, lowering the threshold curve that results from gas (or fluid) flow alone (Iversen et al., 1987). During the TWT experiments, thresholds were observed and wind speed data collected during increasing wind speed. Numerical modeling results indicate that the fluid threshold under both Venus and Titan conditions is lower than the impact threshold (Kok et al., 2012), so that the first saltation observed during increasing wind speeds likely occurs during conditions for which surface grains are mobilized by fluid drag, not by particle impacts as occurs on Earth and Mars. Thus, the physical justification for the density ratio term remains unclear. However, these prior data were collected under a single pressure and so with a limited range of density ratios, resulting from only the variability in the grain densities of ~3x.

To investigate further the effect of the density ratio term on threshold, we collected new data at a larger range of gas densities and thus a larger range of density ratio conditions than in previous recent work. These new data do now include the extrema of density ratio values previously published, in which a compilation of value for water and from terrestrial wind tunnels gave low and high extreme values, respectively (Iversen et al., 1987). Instead, we used the TWT to focus on the transitional region occupied by Venus and Titan conditions. We compared these new data to previously collected data from the VWT and to the VWT threshold curve, both without and with the density ratio term. The results of the work presented here raise questions about the sediment entrainment processes that occur at intermediate density ratios . . . .

Background

Derivation of expressions for planetary aeolian threshold

Expressions for threshold wind speeds were provided by Bagnold (1941), in which threshold is quantified as a friction speed (u_{*t}), a characteristic velocity that describes the magnitude of shear at the surface. Using a conceptualized force balance at the moment of entrainment, Bagnold derived the threshold friction speed as:

$$u_{*t} = A\sqrt{\frac{\rho_p - \rho}{\rho} g D_p} \quad (1)$$

where A is the dimensionless threshold parameter, ρ_p is the particle density, D_p is the mean particle diameter, and g is the gravitational acceleration. Bagnold suggested that A is dependent on the particle friction Reynolds number at threshold (Re_{*t}), defined as:

$$Re_{*t} = \frac{u_t^* D_p}{\nu} \quad (2)$$

where ν is the kinematic viscosity. However, by negating this dependence on Re_{*t}, the interparticle force, and the lift force, A was simplified to 0.1 for all grains with a diameter larger than 250 microns, based on terrestrial experimental data (Bagnold, 1941).

Later experiments under ambient (terrestrial) conditions in the Iowa State University (ISU) Wind Tunnel tested the validity of Bagnold's threshold equation (Eq 1) (Iversen et al., 1976a; Iversen et al., 1976b). Results indicated that A is not uniquely a function of Re_{*t} but also depends on interparticle force (parameterized by the exponent n in Table 1). This result led to a generic equation that describes the functional behavior of the dimensionless threshold parameter, A, in different flow regimes, where K is a constant having units of g cm^{-2} sec^{-2}. Experiments in the MARSWIT simulating aeolian processes in a low pressure environment yielded data that were inconsistent with the predictions based on mathematical extrapolation from ambient conditions (Greeley et al., 1976). Resolving the mathematical expression to the data led to defining different formulae for A for a given range of Re_{*t} (Table 1). The value of n has varied depending on whether it was set *a priori* to a presumed value or fit to data (Table 2). A value for n of 2.5 was derived from fitting the MARSWIT experimental data.

The literature suggests that the experiments under these low-fluid-density conditions were considered to involve fluid ("static") threshold (Greeley et al. 1977, p. 10), in which entrainment is only a function of fluid flow. However, numerical modeling has shown that under low-fluid-density conditions, impact threshold, in which impact by upwind grains contributes to entrainment, occurs at a lower wind speed than does fluid threshold (Kok, 2010). Threshold in the MARSWIT was defined as "the movement of particles over the entire bed" (Table 3). Such wide-spread movement was unlikely to have occurred simultaneously, as experiments and field data show that initial movement occurs as individual grains or small groups of grains (Bagnold, 1941; Nickling, 1988), and these initial grains would have impacted the downwind bed. Thus, the observation of threshold in the MARSWIT was likely a result of some (unobserved) impact by upwind grains.

Based on this refined threshold model derived from wind tunnel data for relatively low-density (Martian and terrestrial) conditions, a theoretical expression of threshold at high-density (Venusian) atmospheres was derived (Iversen and White, 1982). However, data from the VWT simulating entrainment under high pressure (Venusian) conditions (Greeley et al., 1984) were not consistent with this expression (Iversen et al., 1987). This inconsistency was ascribed to the effect of grain impact, which had not been accounted for in previous force-balance equations used to derive threshold under the (likely incorrect) presumption of fluid threshold. The model was corrected to the VWT data by introducing into the formula for A a density ratio term, $f(\rho_p/\rho)$, where ρ_p is the density of the particle and ρ is the density of the fluid (Equation 3).

The density ratio term

In previous work, determining formulae for A as a function of the density ratio involved compiling a threshold dataset over a range of density ratio conditions, including terrestrial conditions at ISU (Iversen et al., 1976b), under low pressure conditions at MARSWIT (Greeley et al., 1980), under high pressure conditions at the VWT (Greeley et al., 1984) and with water as the fluid (Graf, 1971). These threshold data were then filtered so that (1) $the\ grain\ diameter\ was\ larger\ than\ 200\ \mu m,$ eliminating dependence on interparticle forces (see Iversen et al., 1976b, Figure 2a), and (2) Re_{*t} was larger than 10, above which A becomes independent of the friction threshold Reynolds number (see Iversen et al., 1987, Figure 2).

The filtered data for A were plotted vs the density ratio, ρ_p/ρ, and fitted with a curve (Figure 1), for which A is a function of interparticle forces, Reynolds friction number, Re_{*t} and the density ratio function, $f(\rho_p/\rho)$. The derivation of the form of the curve in Iversen et al. (1987) omits some steps and contains a typo in first exponential parameter; a full derivation is provided by Nield (2018). The result of the derivation is the expression

$$A^2 = \frac{K}{h(Re_{*t})+f(\rho_p/\rho)} \qquad (3),$$

consistent with the generic form shown in Table 1. The shape of the curve (Figure 1) shows that the expression for A is sigmoidal and thus has the form $1/(1+e^{-x})$, which can be rewritten at:

$$A^2 = \frac{\alpha}{1+\beta(1-e^{\left(-\gamma(\rho_p/\rho-1)^{\lambda}\right)})} \qquad (4)$$

where α, β, γ, and λ are constants.

The numerator, α, represents the upper limit of the sigmoidal function for A, i.e., when the density ratio term, $f(\rho_p/\rho)$, approaches 1. Its value of 0.2 was derived by Iversen et al. (1987) using experimental measurements (Chepil, 1958; Coleman, 1967) and has been supported by more recent flume experiments (Bridge and Bennett, 1992; Elhakeem and Imran, 2012;

Tregnaghi et al., 2012). The lower limit of 0.11 was derived under terrestrial conditions (Bagnold, 1941; Iversen et al., 1976b). Substituting in these coefficients for the upper and lower limits of the sigmoidal function yields

$$A = {}^{0.2}\Big/\sqrt{1 + 2.3(1 - e^{-0.0078\,({}^{\rho_p}/_{\rho}\,-1)^{0.86}})} \qquad (5).$$

See Nield (2018) for a full derivation of Equation 5.

Although its derivation was impelled by data under intermediate density ratio (i.e., Venus Wind Tunnel) conditions, this continuous expression was intended to correct the previous formulations so as to align with experimental results at all density ratio conditions. At density ratios > 1000, as for atmospheric conditions on Earth or Mars, the density ratio term ($f(\rho_p/\rho)$ = EXP($-0.0078((\rho_p/\rho)-1)^{0.86}$)) goes to zero and the value for *A* of 0.11 as derived by Bagnold (1941) for terrestrial conditions is recovered. At intermediate density ratios, as on Venus (or Titan), this term increases and the expression for *A* correspondingly increases. As the density ratio approaches 1, as experienced in fluvial environments on Earth, the *A* value approaches 0.2.

Testing the expression for *A*

The TWT (Figure 2) (Burr et al., 2015b), provides an opportunity to quantify threshold wind speeds under Titan analogue conditions. Those data, like the data from the VWT, fall in the intermediate density ratio space that is transitional between fluvial (water) and aeolian conditions on Earth. Our methodology (Figure 3) was to collect freestream TWT data at threshold conditions for different density ratios, reduce them to friction wind speeds, filter them to eliminate the effects of particle friction Reynolds number and interparticle forces following Iversen et al (1987), and to compare them to the published density ratio curve.

Threshold Data Collection using the Titan Wind Tunnel

The similitude boundary condition used for these threshold experiments was kinematic viscosity (Burr et al. 2015a). This choice contrasts with that of VWT work, for which the parameter was density, but was made to provide the correct ratio of lift and drag forces and to simulate the viscous sublayer thicknesses. The surface atmospheric pressure on Titan is ~1.4 bar, but, given the difference in temperature between the surface of Titan and the Titan Wind Tunnel, higher pressures were necessary in order to recreate the kinematic viscosity conditions of Titan's atmosphere in the wind tunnel for current (Table 4) and past climates. For these density ratio experiments, the TWT pressure varied from 1 to 20 bars in order to achieve a greater range of density ratio conditions.

The experimental materials cover a range of densities and grain diameters, providing data that span the transitional portion of the threshold curve and overlapping the parameter space for the density ratio from previous experiments. For all data collection experiments, the experimental sediments were placed in the test section where they were smoothed into a bed of a constant thickness (1 cm). As discussed below, a roughness height of $z_0 = D_p/30$ was used for all experiments. After the bed was laid down, a ruler was placed so as to be viewable through the downwind observation port and briefly videographed for scale. The ruler was removed, and the tunnel was sealed and pressurized. The bed was then pre-conditioned by increasing the fan speed until ~50% of the bed surface was briefly observed to be in motion, in order to provide a more natural texture to the bed and remove any perched grains.

Videography was collected with an Edgertronic SC1 high speed video camera positioned outside the tunnel at the downwind side observation portal of the tunnel (Figure 4). The camera frame rate was set to 500 frames per minute (approximately 8 frames per second) with a field of view of 3.6 cm by 2 cm (1280 pixels by 720 pixels). The camera was focused on the bed under the pitot tube in the center of the tunnel, which was illuminated by two snake lights.

During each experiment, a high-pressure transducer measured the differential pressure between a static pitot tube that sensed the ambient pressure in the wind tunnel and a stagnation pitot tube that sensed the total pressure, that is, the sum of the ambient pressure and the dynamic pressure due to the air flow. The measure of this differential pressure was continuously output and recorded as voltage while a person visually observed the bed.

Threshold data were collected in August 2016. Following the procedure developed in previous work (Burr et al. 2015a), the fan motor speed was incrementally increased through each stage of motion (Table 5) as perceived by the observer, who recorded the time of its occurrence. For comparison, data were also collected during decreasing fan motor speeds and are provided in Supplemental Materials, although not used in this work. Three different researchers (DMB, NTB, EVN) served as observers, and no observer bias was detectable in the data.

Data Reduction

Data reduction entailed first matching the times recorded by the observer for threshold to the corresponding voltage data from the transducer. These voltages were then converted into dynamic pressures using manufacturer calibration curves for a range of pressures. The resultant dynamic pressures, in turn, were converted to wind speeds at threshold, *u,* by

$$u = \left(2\frac{P_{dyn}}{\rho}\right)^{1/2}, \qquad (6)$$

where P_{dyn} is the dynamic pressure of the gas (air).

Reducing threshold freestream values to threshold friction values involved solving the Law of the Wall equation for threshold friction speed. The law of the wall (also known as the Prandtl-von Kármán equation) states that the rate of increase of fluid velocity (u) with the logarithm of the height is proportional to the slope or rate of change of the velocity distribution curve

$$u_\infty = \frac{u*}{\kappa} ln\frac{\delta}{z_0} \qquad (7)$$

where u_∞ is freestream velocity, δ is the boundary layer thickness, κ is the von Kármán constant (0.41) and z_0 is the roughness height, the elevation above the bed where the wind speed is zero due to friction (Bagnold, 1941). Rearranging the equation to solve for the friction wind speed yields:

$$u_* = \frac{u_\infty \kappa}{ln\frac{\delta}{z_0}}, \tag{8}$$

Thus, in addition to the freestream wind speed, the freestream height, δ, and the roughness height, z_0, were required. The freestream heights were derived from boundary layer profiles (BLPs) and the roughness heights were derived as the Nikuradse roughness (Nikuradse, 1933) from the rule of $z_0 = D_p/30$ (White, 2006). This approximation, for conditions of $Re_t > 60$, was supported by repeated BLP data collection and analysis. However, the BLPs were not taken with sediment movement (due to concern over clogging of the pitot), which would sap momentum from the flow, increasing the roughness height. Thus, BLPs without sediment movement yield minimum values as roughness heights for the experimental conditions with sediment movement (Bauer et al., 2004). Because of this error introduced by the difference in conditions between those of the BLPs and those of the experiments, the approximation of $z_0 = D_p/30$ was considered more reliable.

Collecting BLPs to derive the boundary layer thickness entailed the construction of fixed roughness beds by gluing sieved sediment onto cardstock paper. To encompass and sample the relevant experimental grain sizes while maintaining operational efficiency, five sediments were used – 180-212 µm glass beads, 180-212 µm quartz sand, 400-600 µm glass beads, 500-600 µm quartz sand, and 833-1000 µm quartzofeldspathic sand. These fixed-sediment beds were placed in the wind tunnel, the tunnel was pressurized, and the fan speed was held constant while a stepping motor moved the pitot tube through a sequence of positions within the boundary layer. The pitot tube traversed 25 positions, logarithmically spaced, from 1 mm to 48 mm above the fixed bed. Each position was held for 10 seconds while the transducer attached to the pitot tube collected voltages. At the end of each traverse, the pitot was returned in the bed, the fan speed was increased by ~10% or 25%, and another boundary layer profile was collected. The procedure was repeated for a variety of fan motor speeds and atmospheric pressures for each of the three beds.

The voltages from the transducer were averaged for each of the 25 pitot tube positions and, as for the experimental threshold data, converted to dynamic pressures using manufacturer calibration curves. These dynamic pressures were converted to freestream wind speeds according to Eq. 6. The resultant plot of these wind speeds at each pitot height yielded the boundary layer profile. Boundary layer thicknesses were designated on these profiles as the locations at which the curves became vertical (Figure 6). For all five BLPs, the boundary layer height was 2.3 cm, without any detectable trend in value. Consequently, we used δ=2.3 cm for reducing all experimental data.

The raw data collection sheets, experimental data reduction spreadsheets and BLP data reduction spreadsheets (with manufacturer calibration curves) and experimental videography are available on the Mendeley Data Repository associated with this article.

Data correction for pitot configuration effects

During the course of the work, we discovered that our original BLPs, collected in 2016, exhibited two straight-line segments below the boundary layer, instead of a single continuous linear segment as expected. Investigation suggested that this anomalous behavior was a result of the original (2016) pitot tube configuration (Figure 5a), in which the static port was located downstream of the pitot stanchion and oriented vertically, so as to produce a speed-up of air flow. Following some research, we developed a new pitot tube configuration for which the static pressure is measured via a small hole on the side of a tube located approximately at the same streamwise location as the stagnation pitot (Figure 5b). BLP data collected in 2018 with this new configuration show expected behavior without the previously observed segmentation and yield consistent boundary layer heights (Figure 6). We used the 2018 BLP data exclusively in our data reduction.

The experimental data from 2016 were also taken with the original (2016) pitot configuration and thus required correction for this inferred speed-up effect. We reduced the BLP data collected with both the original and new configurations, deriving u_∞ for both configurations. The correspondence of these BLP u_∞ values shows a strong linear relationship (Figure 7). The equation for this correspondence is $u_{\infty NEW} = 0.5973 u_{\infty OLD} + 0.1284\ m\ s^{-1}$ (R^2=0.9946). On the basis of this correspondence between the BLP u_∞ values derived with the original pitot configuration and with the new pitot configuration, we arithmetically adjusted the original experimental u_∞ values to corrected values.

Uncertainty analysis

Results

Out of 193 experiments (summarized in Table 6), we obtained a total of 174 values for $u*_t$. In the remaining experiments, ‘patches’ – the stage of motion used as threshold in this work – was not observed. Of these 174 experiments, 67 meet both conditions set by Iversen et al. (1987) for deriving the density ratio curve, namely, $Re*_t > 10$ and $D_p > 200$ μm (the fewer number of results provided in Nield, 2018, are superseded by this work).These new data are shown in conjunction with the threshold data from Iversen et al. (1987) and Burr et al. (2015a) to recreate their plot of dimensionless threshold parameter (A) as a function of particle friction Reynolds number ($Re*_t$). This plot (Figure 8) confirms that at $Re*_t > 10$, A is independent of $Re*_t$. The plot also shows significant spread in the data. Specifically, for $Re*_t$ between ~10 and a few hundred, the TWT data exhibit a wider spread than the VWT data. At lower values of $Re*_t$. variability is even greater.

To investigate our main question as to the effect of density ratio on threshold, these filtered TWT values for A are also plotted against density ratio (Figure 9). The results show that our data are generally consistent with the previous data, but have slightly greater variability and tend toward slightly higher values for A. A new equation for the density ratio curve that includes the TWT data is .. .

Discussion

Data variability

The variability of the data of A vs Re_{*t} (Figure 8) may be due to multiple causes. Variable definitions of threshold both among the aeolian data (e.g., Table 3) and between the data collected under gas (aeolian) conditions and liquid conditions (water and oil) might be a cause or a contributor to this variability. At the same time, the values of A from water-based experiments vary by a hundred percent at high Re_{*t} values. This high variability from non-aeolian experiments suggests that the variability in the TWT data might be realistic.

The VWT data exhibit an upturn at the lower end of their Re_{*t} values ($Re_{*t} <\sim 10$) (Figure 8). Upturns in values of A occur at lower values of Re_{*t} in data from both low-fluid-density MARSWIT conditions and from high-fluid-density water and oil. A priori, one would expect that the upturn for intermediate-fluid-density conditions would fall between those of low- and high-fluid density datasets, but that expectation is not borne out by the VWT data. The TWT data do not reveal such an upturn, perhaps due to an absence of data at low density ratios in our dataset under the current capabilities of the TWT that limit consistent achievement of high pressures.

Different hydrodynamic lengths of the VWT and TWT tunnel

Sufficient test section length is necessary in wind tunnel experiments to allow full development of the boundary layer and maturation of the sediment-fluid interactions. The VWT threshold experiments were performed under density similitude conditions, for which a pressure of 30 bar was necessary at terrestrial temperatures to achieve the same density for CO_2 gas as the Venusian atmosphere at 90 bar (Greeley et al., 1984). Higher pressures serve to hydrodynamically lengthen wind tunnels (ref), an approach that might have been applied to the VWT, although no hydrodynamic calibration data of the VWT have been uncovered by us in searching decades of records at the Planetary Aeolian Laboratory where the wind tunnel is housed. Calculations suggest that at the lower pressured used in these Titan analog experiments, the test section was not sufficient for full development of a turbulent boundary layer (Table 7). The lack of a fully developed turbulent boundary layer might have shifted our data to different – and more varied – values than for the VWT work, for which the tunnel was hydrodynamically longer.

Different relative kinematic viscosities in VWT and TWT work

As mentioned, above the similitude parameter for the VWT threshold experiments was fluid density, whereas for this and previous TWT threshold work, the similitude parameter is kinematic viscosity (Burr et al., 2015a). Matching the near-surface atmospheric density of Venus in the VWT gave a kinematic viscosity of one-half that of Venusian conditions (Greeley et al.

1984). We speculate that this difference in relative kinematic viscosity might account for some of the offset between the VWT and TWT data (Figures 8 and 9), although the physical reasoning for this effect is not clear.

Conclusions:

As the operation of aeolian processes becomes increasingly apparent throughout the Solar System, understanding the controlling physics under this wide range of boundary conditions likewise becomes increasingly important. The results of this investigation into the effect of the density ratio on grain entrainment are consistent with the previously derived curve for dimensionless threshold parameter vs density ratio, although more variable and slightly offset to higher values. Thus, we consider that these data confirm the previous work, although we also speculate whether the dimensions of the wind tunnel might, at these intermediate fluid densities, introduce unknown artifacts. This work highlights the uniquely valuable opportunity provided by planetary wind tunnels to explore and understand the pervasive aeolian processes in our planetary system and likely in others, while also reinforcing the idea that accurate simulation of planetary boundary conditions is both vital to achieving robust results (e.g., Burr et al. 2015b) and a continued challenge.

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