CORROBORATION OF TITAN WIND TUNNEL EXPERIMENTS AND COMPUTATIONAL FLUID DYNAMICS MODELING OF TITAN SEDIMENT TRANSPORT.

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Introduction: The equatorial region of Titan, the largest satellite of Saturn, has extensive expanses of aeolian dunes revealed in synthetic aperture radar (SAR) images [1-4] and suggested to be composed of organics or organic-coated water ice [e.g. 5]. The dunes are among the youngest surface features and appear to be predominately longitudinal or linear [6,7]. Similar dunes have previously been observed on Earth, Mars, and Venus, and their presence on Titan indicates active processes of production, transport, and arrangement of sand sized particles. The morphology, extent and scale of the dunes are analogous to the Namib and Sahara sand seas on Earth [e.g., 8-10], with global areal coverage of ~12% and equatorial area coverage (as zonal average fraction) that can exceed 50% [11]. If the dunes are composed of organics, they are potentially the largest reservoir of hydrocarbons on Titan [11].

Understanding what wind regimes can mobilize particles to form and migrate these dunes is essential to understanding many questions for Titan such as seasonal versus epochal winds, particulate sources and sinks, sand fluxes, resurfacing processes, and aeolian sedimentation. Specifically, knowledge of the threshold wind speed—or the minimum wind speed at which particles are moved or redistributed by wind—is essential. The threshold wind speed, whether of rocky [12,13] or icy [14,15] particles, is necessary to model particle flux and dune or drift migration rates, as well as resurfacing processes such as aeolian sedimentation, abrasion, and cementation. This wind speed is usually empirically derived [16] as a complex function of the physical parameters and surface conditions [17]. Wind tunnel experiments are a well-controlled approach to determining threshold wind speeds [e.g. 18]. However, this approach requires carefully controlled boundary (wind tunnel) conditions for correct derivation of this value [16].

The Titan Wind Tunnel (TWT), a community resource for the planetary science community [19, 20], is uniquely able to simulate flow under high-pressure atmospheres such as on Titan [16]. Characterizing flow in the TWT is highly desireable to ensure accurate results, as the results cannot be reproduced in any other facility, but is likewise challenging due to the closed (pressurized) configuration of the facility, which limits internal instrumentation. Consequently, in this study, we pair empirical results from the TWT with a series of Computational Fluid Dynamics (CFD) simulations for corroboration of flow in the TWT.

Threshold Wind Speed and the Titan Wind Tunnel Experiments: In previous work, the Titan Wind Tunnel was used to reassess the saltation threshold wind speeds on Titan [21], where the threshold friction wind speed is defined as a function of A, a dimensionless proportionality parameter that is a function of the particle Reynolds number at threshold friction wind speed ($Re^*_t = u^*_t D_p/\nu$; D_p, particle diameter; ν, kinematic viscosity) and the interparticle forces ($I_p \equiv I_p(D_p)$), and also as a function of particle, fluid, and gravity characteristics:

$$u^*_t = A\left(Re^*_t, I_p\right)\sqrt{\frac{\rho_p - \rho}{\rho} g D_p} \approx A\left(Re^*_t, I_p\right)\sqrt{\frac{\rho_p}{\rho} g D_p} \quad (1)$$

where ρ_p and ρ are the particle and fluid densities and g is gravitational acceleration [21]. This previous study [21] determining saltation threshold wind speeds from Titan Wind Tunnel experiments inferred that kinematic viscosity—$\nu = \mu/\rho$; ratio of molecular or dynamic viscosity to fluid density—is the appropriate experimental similitude parameter [22, 23], rather than static pressure [17, 24, 25] or density [18] to match to Titan conditions. The Titan-specific experiments yield ~40-50% higher saltation threshold wind speeds than were predicted by prior models based on wind tunnel simulations for Earth, Mars, and Venus [20].

Computational Approach: For this numerical modeling of flow in the TWT, we employed the computational fluid dynamics (CFD) commercial code COMSOL Multiphysics 5.3a [26]. This code solves the Navier-Stokes equations using a finite element approach. The flow domain can be solved with either laminar, turbulent, or combined approaches and this study simulates both steady and time dependent flow, both with and without the particle tracing module with fluid-particle interactions. Mesh geometry is physics-controlled, allowing for additional resolution at the flow boundaries, and the 3-dimensional model approach allows precise reconstruction of wind tunnel dimensions, materials, and interior structures, such

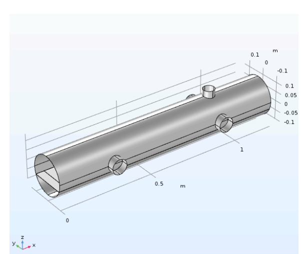

Fig. 1. The CFD flow domain for the TWT test section.

Table 1. Titan Conditions, Titan Wind Tunnel experimental conditions for similitude, and CFD simulation conditions.

Parameter	Titan	Titan Wind Tunnel	CFD Wind Tunnel Simulation
Atmospheric composition	(~95% N_2, ~5% CH_4)	(~79% N_2, ~20% O_2)	(95% N_2, 5% CH_4), (79% N_2, 20% O_2)
Static Pressure, P [Pa]	1.44×10^5	1.25×10^6	1.44×10^5, 1.25×10^6
Temperature, T [K]	94	293	94, 293
Molecular viscosity, μ[Pa s]	6.25×10^{-6}	1.85×10^{-5}	6.25×10^{-6}, 1.85×10^{-5}
Atmospheric Density, ρ[kg m^{-3}]	5.3	14.5	5.3, 14.5
Kinematic Viscosity,ν[m^{2}s^{-1}]	1.2×10^{-6}	1.2×10^{-6}	1.2×10^{-6}

as the test bed, pressure transducers, etc. Figure 1 shows the COMSOL computational domain constructed for the TWT test section, with the interior flat plate test section bed, side view ports, and top illumination port visible. The CFD simulation is set up as single phase isothermal (gas) flow. The turbulent flow is modeled with the Reynolds-averaged Navier Stokes (RANS) approach. Table 1 (after Burr et al. [21]) shows CFD simulation parameters. Simulations with the particle tracing capabilities computes the motion of particles in the background fluid driven by gravity, drag, and tracks trajectories [e.g. see 27]. In this preliminary modeling, particle-particle interactions are not yet tracked, nor is secondary particle release at boundary collisions or particle cohesion. Fluid flow boundaries are set to inlet (with several different velocity profiles suggested by experimental data), No-slip walls (particle momentum conserved), and outlet (free flow and particle escape).

Results and Discussion: Preliminary results indicate that the model output is indeed more sensitive to the particle/fluid density difference, as Burr et al. [21] suggest, under dense atmosphere conditions found on Titan (and Venus). Additionally, the boundary layer structures established within the CFD models suggests that the boundary layer structure traditionally assumed in empirical models may not be captured by relatively coarse wind tunnel instrumentation sampling.

Future work: As numerous prior authors have pointed out, both sediment and snow on Earth require significant distances to reach equilibrium saltation layers. For example, on Earth, attaining equilibrium requires 15 meters for sand and a friction velocity of 0.34-0.6 m/s, and up to several hundred meters for snow [e.g. 15, 28, 29]. The limited length-scale of the TWT Fig. 1) is most suitable for threshold measurements. With CFD approaches, we can extend these terrestrial results for equilibrium saltation to Titan. Additionally, particle-particle interaction modeling may allow consideration of particle adherence or "sticky" particles [e.g. 30], which may be significant for organic materials.

The CFD technique reduces the reliance on wind tunnel results, which can be expensive and time consuming, and are limited in the similarity parameter space that they can address. CFD allows us to consider more complex domains and geometries, a much wider range of particle sizes, shapes, and densities, and a virtually unlimited range of ambient and fluid properties. Overlapping and validation of the CFD and Wind Tunnel results allows greater confidence in extending our modeling in both terrestrial and extraterrestrial environmental conditions.

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