3.0 SEDIMENT-TRANSPORT (WIND) EXPERIMENTS IN ZERO-GRAVITY

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3.1 Introduction

Aeolian processes involve the movement of particles by the wind and include dust storms, sand storms, and erosion by the wind. At least Earth, Mars, and Venus are affected by winds and understanding the physics of aeolian processes is essential to the interpretation of the current and past modification of the surfaces of these planets.

On Earth, it is estimated that more than 500 x 10^6 metric tons of dust are transported annually by the wind. Dust storms reduce visibility on highways and are responsible for loss of life and property through many accidents each year. Atmospheric dust, whether raised by winds or injected into the atmosphere by volcanic processes, can also have a significant effect on temperature. Thus, windborne particles can have a direct effect on the climate. In addition, windblown sands cause abrasion and erosion of natural and manufactured objects and encroach upon cultivated areas, turning productive land to desert--a process termed *desertification*. The problem of desertification is enormous and is recognized on all inhabited continents of Earth. Agricultural land damaged by wind erosion in the United States alone varies from 400 to 6,000 km^2 per year.

The key to understanding problems associated with windblown sediments, including those aspects of desertification dealing with wind processes, is knowledge of the physics of windblown particles. Many parameters, such as grain size and wind speed, must be considered in assessing the entrainment and transport of windblown grains. Beginning with research in the 1930's, numerous investigators have used wind tunnels to analyze particle entrainment. Wind tunnels have the advantage that individual parameters can be closely controlled and isolated for study and analysis. Gravity is one of the most critical parameters in the analysis of windblown sediment movement; however, there is no effective means for isolating and assessing its effect during experiments conducted on Earth. Hence, a space station would afford an opportunity to conduct experiments in zero-gravity and variable-gravity environments. Such experiments would enable not only this parameter to be assessed, but through its elimination as a factor in the experiments, other critical parameters could be evaluated as well.

Approach

We propose to fabricate an experimental facility that can simulate the movement of particles by the wind, or in other turbulent-fluid environments. We could use a "phased" approach in which experiments would be flown initially on board the KC-135 aircraft for "proof of concept" and to assess potential problems, as may occur in handling particles and in recording appropriate data. The second step might be to fly an experiment on board Shuttle, followed by a fully operational facility on Space Station.

The wind tunnel proposed (termed the *Carousel Wind Tunnel,* or CWT) consists of two concentric rotating drums. The space between the two drums comprises the test section. Differential rates of rotation of the two drums provide a wind velocity with respect to either drum surface. A zero-gravity environment results in a space station laboratory by rotation of only the inner drum. Rotation of the outer drum provides a "pseudo gravity" for particles resting on the inner surface of the outer drum. In order to test the concept of the design, 1/3 and 1/5 scale model CWTs have been constructed and calibrated. Calibrations show that a Prandtl logarithmic boundary layer exists adjacent to the inner surface of the outer drum, a necessary requirement for the simulation of an aeolian saltation layer on a planetary surface. An interesting and quite satisfying characteristic of the CWT is that the so-called "fetch-length" (after initial start-up time) is infinite.

3.2 Experiments

We envision several types of experiments to be conducted, as described below.

Threshold Experiments

Threshold defines the minimum wind speed (or friction speed u_{*t}) required to initiate particle motion and is a fundamental factor in aeolian processes. The prediction of threshold speed involves assessment of the forces acting on the resting particles, including aerodynamics lift and drag, weight, cohesive force between particles, and perhaps force due to impact from another already moving particle. Elimination of the particle weight in the threshold force equation—as in a weightless environment—would enable more accurate assessment of the cohesion and aerodynamic forces. In particular, the cohesive force is currently much in question as to its magnitude and origin. Threshold experiments conducted at one g in a range of atmospheric densities indicates that the cohesive force is at least approximately proportional to the particle diameter, as predicted by the Van der Waal's force, although the coefficient of proportionality is much smaller than the Van der Waal's coefficient, at least for particles between 30 and 100 microns in diameter.

Is the source of the cohesive force primarily electrostatic? If so, the CWT would be a good tool for studying this phenomenon because of three factors: (1) the cohesive force is the only retarding force on the particle in the zero-g environment, (2) the electrostatic forces could be altered by using particles of differing electrical properties (i.e., conducting and non-conducting particles, clays of differing mineralogy, etc.), and (3) providing electric potential difference between the outer and inner drum surfaces (drum surface electrical conduction property can also be changed). It will be necessary to establish an appropriate matrix of experimental conditions before final space laboratory CWT design.

Ripple Experiments

The CWT may be used to performed critical experiments that will provide insight into the relationship between the saltation path length and surface bedform structures such as ripples, waves, dunes, etc. The CWT can provide controllable saltation path lengths by adjusting the rotation rate of the outer drum of the CWT. Thus, saltating particles relative to an observer positioned on the outer drum moving with it, may be made to have positive, negative or neutral (a purely electrical) jumps. Experiments then may be performed where the only variable in the saltation process could be the path length or jump length of the particle (i.e., the D_p, ρ_p, p, g, ρ are held constant while u_* is adjustable by fixing different rates of outer drum rotation). Hence, a direct assessment of saltation path length of wave lengths of surface structures (i.e., ripples, etc.) could be made.

Varying the position at which a particle lands with respect to the position from which it lifted off will provide the only direct method of finding the relationship between path length and ripple frequency. Researchers have not resolved this problem since Cornish first considered bed formation in 1903.

A second application of the controllable path length would be the study of the physics of particle interactions with the surface. This may be accomplished by varying the impact angle of the saltating particle which thus enables direct control of particle velocity with respect to the bed, i.e., control of both magnitude and direction of individual particle momenta. This is directly applicable to the understanding of initiation of particle motion by impact, i.e., how momentum is transferred between an incoming particle and stationary material on the surface. This latter aspect is important for understanding how particles and rock surfaces become abraded during transport and for determining the real ~ coefficient of restitution between colliding particles in the natural environment.

Saltation Induced Emission of Fine Particles vs. Direct Suspension of Fine Particles

Fine particles that are suspended by the turbulent motions of the air may be defined as particles whose setting velocity is some small fraction of the scale of vertical turbulence (alternately fluid friction velocity, u_*). These particles are emitted by direct suspension (Owen and Gillette, personal communication, 1985) or by the sandblasting effect of saltation. The proportion of the flux by sandblasting to direct suspension is unknown and is probably a function of the state of sediment in the soil. For example, a soil composed of loose particles, all of which would go into suspension for a given wind, would have fine particle emissions dominated by direct suspension. For the more usual (for earth) case of a soil composed of a mixture of particles the suspendable fraction having higher threshold velocities and the saltation-sized-particles having a lower threshold velocity we would suspect that both sandblasting and direct suspension would be producing particles. The fraction of particles produced by sandblasting to those produced by direct suspension is not known, however.

The above ratio can be determined, however for a given soil by changing gravitation so that the entire soil mixture goes into direct suspension (low g) or that it displays saltation mode for coarser particles and direct suspension is possible for finer particles (higher g).

The ratio of sandblasted to direct suspended particles is the ratio of concentration of suspended particles for the saltation run reduced by the concentration of particles of the same size for direct suspension divided by the same concentration.

i.e.

$$\frac{\text{particle mass produced by sandblasting}}{\text{particle mass produced by direct suspension}} = \frac{\text{c (saltation)} - \text{c (direct suspension)}}{\text{c (direct suspension)}}$$

where c (saltation) is the concentration of suspended particles in the saltation experiment and c (direct suspension) is the concentration of particles of the same size interval as suspended particles produced in the saltation experiment.

The experiment should use a wide variety of soil types. The practical use of such experiments would come in the prediction of flux of suspended particles. If the suspended particle flux can be shown to be dominantly produced by sandblasting, then relationships of suspended particle flux to saltation flux can be developed. Applications could come in agriculture (long term loss of soil nutrients), acid rain (production of suspended alkaline particles), planetary geology (martian dust storms), and possibly other fields.

Solar Nebula Formation

From the broadest perspective, the Carousel Wind Tunnel in zero-g provides a baseline for fundamental experiments in particle dynamics. This situation can best be perceived with the notion that at zero-g, particle-surface interaction is negligible (apart from "interparticle" attraction effects for particles physically located on or near a drum surface). Thus, particles within the central (experimentally well-characterized) portion of the wind tunnel can be placed in a flowing atmosphere which can be at a continuous or variable rate. With appropriate scaling this condition may be analogous to portions of an evolving solar nebula. The existence and the importance of turbulence and mass flow within solar nebula formation models are well-documented (Morfill, 1983; Kornacki and Wood, 1984); other, non-equilibrium particle-gas flow dynamics could be envisioned in the controlled environment offered by CWT. These experiments could involve variations in micro-g and the effects of turbulence which can be induced (and adequately compared) by differential rotation speeds of the carousel drums. Carousel Wind Tunnel experiments of this type may provide clues to a number of fundamental dust-gas interaction questions and include:

a. What grain characteristics (size, shape, charge, composition) influence grain growth (or aggregate dispersal) in a given flowing atmosphere (e.g., O-rich, He-rich, C-rich)?

b. Do grains aggregate in a steady mass flow (turbulent-free) environment over time?

c. At the onset of turbulence, or at particular levels of turbulence, will interparticle attractions predominate? If so, for what particle size range?

Additional refinements may be included in a series of dust-gas flow experiments with the application of an ionizing atmosphere. This could be induced throughout the experimental apparatus or within a given phase (a rough analogy to the latter case would be an ionized atmosphere/dust flow in the ecliptic of an evolving solar nebula). These experiments may be especially fruitful if mixed grain characteristics (e.g., spheres and laths; clays and silica; organics and graphites) were introduced to a given run.

A simple, IOC level experiment might be performed to test the survivability of certain grains in flowing atmospheres by placing well-characterized aggregates (e.g., refractory condensates made by Nuth or others) in the Carousel Wind Tunnel at zero-g. These aggregates would be in a suitably scaled atmosphere in the CWT and with drum rotation, grain (or gas) motion to desired volatiles may be obtained. The CWT can then be sampled at appropriate time intervals to determine whether these open fluffy refractory aggregates remained or were disaggregated.

Requirements:

- Zero-g (±1%) for periods of approx. 24 hours
- CWT atmosphere intake and outlets
- Operator intervention (by remote sample collector) every 3 hours
- Optical and/or laser monitoring of grain characteristics (nephelometry) on continued, automated basis

3.3 Instrumentation

In order to assess experiment results, it is necessary to measure particle velocities and fluxes. The nature of particle movement at threshold can be evaluated by the use of a laser monitoring system. The present single-beam system used by Nickling (1984, 1985) can be modified for CWT and could be adapted for tests on the KC-135. The system uses a 5 mW He-Ne laser, high response photo-diode, filtering circuits and a high speed pulse counter/microprocessor. This monitoring technique overcomes many of the problems of visually detecting the initial movement of isolated grains over a relatively large surface area. In addition, the system characterizes the change in particle motion from fluid to dynamic threshold. The point of full saltation flow is also indicated when the beam becomes continuously broken.

In its present form, the threshold monitoring system requires continuous input of velocity data from which shear velocity is calculated. If velocity probes are not used in the Carousel Wind Tunnel, drum velocity or g level (KC-135 tests) could be used as input data and shear velocity calculated indirectly. This system can be improved by using a thin, wide sheet of laser light rather than a single reflected beam. At present, the recorded total grain count is really a measure of grain activity and not an absolute measure of the number of grain movements, since a single grain can break more than one beam. A sheet of light produced by appropriate lenses could be placed horizontally over the surface or vertically as a curtain in front of the sample bed. Using this method an individual spike would be recorded for each grain passage unless two or more grains passed through the beam simultaneously.

A velocimeter probe would also be extremely useful especially in the grain trajectory tests. This could be done using traditional probes or by some modification of the threshold monitoring system. For example, the width of the "spike" produced when a grain passes through the laser beam is a function of the grain velocity (and particle diameter). By using a pulse analyser, the time required for the grains to pass through the beam can be compiled and individual grain velocities calculated. This would require some assumptions in the grain diameter and the beam widths.

The development of any threshold monitoring system is contingent upon the final design of the Carousel Wind Tunnel. Of primary importance will be whether or not the sides of the wind tunnel will revolve with the outer drum. This will probably have ramifications for any other instrumentation that might be used in the tests.

As was shown in the presentation of Gillette and Owen (this volume), a flat plate sensor using the piezoelectric principle could be a useful tool in measuring mass flux, momentum flux, and kinetic energy flux of particles hitting the floor. This sensor has the advantage of not disturbing airflow in the carousel wind tunnel and not having optical surfaces which could become dirty. The measurements of relevant fluxes in the wind tunnel could serve as an important system to provide primary information or as confirmation of other measurements.

3.4 Summary and Conclusions

Interparticle Force

The CWT wind tunnel can be a significant tool for the determination of the nature and magnitude of interparticle forces at threshold of motion. By altering particle and drum surface electrical properties and/or by applying electric potential difference across the inner and outer drums, it should be possible to separate electrostatic effects from other forces of cohesion.

Grain Threshold Criteria

The researchers contributing to this summary represent a significant fraction of the world's experience at determining particle threshold and the techniques involved should be readily adaptable to the CWT.

Other Applications

As with many new kinds of research laboratory devices, the applications which present themselves in addition to the original purpose continue to increase. Besides particle trajectory and bedform analyses, new suggestions for research investigators include particle aggregation in zero- and sub-gravity environments, effect of suspension-saltation ratio on soil abrasion, and the effects of shear and shear-free turbulence on particle aggregation as applied to evolution of solar nebula.

Commonality with Particle Group Experiments

In addition to some common interests with particle group experimenters, the aeolian and particle groups should be able to share particle storage, particle insertion and transport techniques, instrumentation (such as photography, nephelometry, lighting equipment, electrical equipment), and cleaning equipment.