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3.0 PHYSICS OF WINDBLOWN PARTICLES

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3.1 Introduction

This report describes a laboratory facility proposed for the Space Station to investigate fundamental aspects of windblown particles. The experiments would take advantage of the unique environment afforded in Earth orbit and would be an extension of research currently being conducted on the geology and physics of windblown sediments on Earth, Mars, and Venus. The report reviews aeolian (wind) processes in the planetary context, gives the scientific rationale for specific experiments to be conducted, describes the experiment apparatus (the Carousel Wind Tunnel, or CWT), and presents a plan for implementing the proposed research program.

Introduction to aeolian processes

Many processes modify planetary surfaces, including volcanism, tectonism, and impact cratering. Surface weathering and erosion, as by aeolian or wind activity, are particularly important on planets having atmospheres. Thus, any planet or satellite having a dynamic atmosphere and a solid surface may be subject to aeolian processes. A survey of the Solar System (Table 1) shows that Earth, Mars, and Venus meet these criteria.

Table 3.1 Relevant properties of planetary objects potentially subject to aeolian processes

	Venus	Earth	Mars
Surface gravity (Earth = 1)	0.88	1	0.38
Surface gravity (cm s^{-2})	890	981	371
Atmosphere (main components)	CO_2	N_2,O_2	CO_2
Atmospheric pressure at surface (millibars)	90,000	1,000	7.5
Mean temperature at surface (°C)	480	22	-23

Wind has the potential for directly eroding material and redistributing it to other areas. Wind transports sediment via: *suspension* (mostly silt and clay particles, i.e., $\leq 60\ \mu m$), *saltation* (mostly sand size particles, 60 to 2000 μm in diameter), and *surface creep* (particles ≥ 2000 μm in diameter). Wind "threshold" curves derived from laboratory experiments (Fig. 3.1) define the minimum wind friction speed (Bagnold, 1941) to initiate movement of particles in different planetary environments. The ability of wind to attain threshold is primarily a function of particle characteristics (size, shape, density, etc.) and the properties of the atmosphere (density, viscosity, etc.). Thus, the low density atmosphere on Mars requires relatively high wind speeds to move particles, whereas relatively gentle winds can produce the same result on Venus.

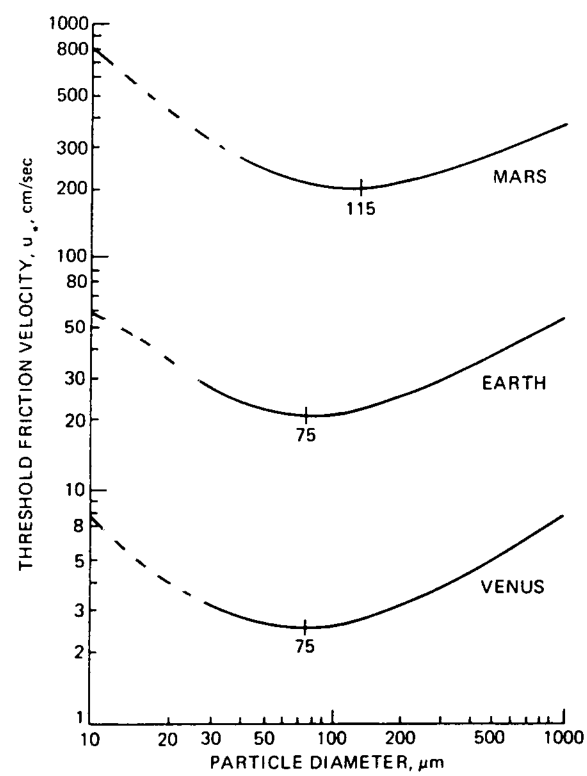

Figure 3.1: Comparison of threshold friction speed versus particle diameter for Mars, Earth, and Venus. The friction velocity is a function of the wind velocity profile above the surface; dashed lines are extrapolated (from Greeley and Iversen, 1985).

Aeolian processes are capable of redistributing enormous quantities of sediment over planetary surfaces, resulting in the formation of various landforms and deposition of windblown sediments that can be hundreds of meters thick. Any process capable of bringing about these changes is relevant to the geological evolution of the planet. Furthermore, because aeolian processes involve the interaction of the atmosphere and lithosphere, knowledge of aeolian activity leads to a better understanding of planetary meteorology and climate history. For example, the paucity of impact craters on the vast north-polar dunes of Mars would indicate the relative youth of the dunes; if the dunes presently are inactive, then they might reflect a recent change in climate, i.e., a decrease in winds of sufficient strength for sand movement and dune formation.

It is estimated for Earth that more than 500 x 10^6 metric tons of dust are transported annually by the wind (Peterson and Junge, 1971). Dust storms also reduce visibility on highways and are responsible for loss of life and property. Atmospheric dust, whether raised by winds or injected into the atmosphere by volcanic processes, also can have a significant effect on atmospheric temperature, as demonstrated on Mars via Mariner 9. 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.

Great quantities of silt and clay are transported in dust storms and eventually deposited (Goudie, 1983). Dust deposits are difficult to identify by remote sensing; yet, identification of such deposits is very important in interpreting some planetary surfaces. For example, substantial areas of Mars may be mantled by aeolian sediments and the analysis of Viking data and remote sensing measurements anticipated from the Mars Observer mission require detailed knowledge on the erosion, transportation, and deposition of particles by the wind.

Observations of active aeolian features provide direct information on atmospheric processes. Crater-related streaks on Mars are albedo patterns that show local surface wind directions. Repetitive imaging of crater-streaks shows that many of them appear, disappear, or change their position with time. Mapping the orientations of these features has been used to assess empirically the patterns of near-surface wind circulation (Thomas et al., 1981; and others). Knowing the details of how and why crater streaks form would provide additional insight into local meteorological conditions on Mars.

Although many advances have been made in the study of aeolian processes in the last decade, knowledge of how "dust" (particles $\leq$20 μm) becomes airborne remains enigmatic, especially for martian dust storms. The "threshold" curve (Fig. 3.1) shows that particles $\leq$80 μm in diameter become increasingly more difficult to move by the wind as particle size decreases. The main cause results from various interparticle forces (electrostatic charges, cohesion from moisture, etc.) which become increasingly important as particle size decreases (i.e., the ratio of surface area-to-mass increases, making surface effects more dominant).

From a "first-principles" perspective, particle movement will occur when the effects of aerodynamic lift (L), wind drag (D), and moment (M) exceed the particle weight (W) and interparticle force (Ip), as shown in Figure 3.2. For sand-size and larger grains (>60 μm), the Ip term is relatively unimportant and existing theory for the movement of large

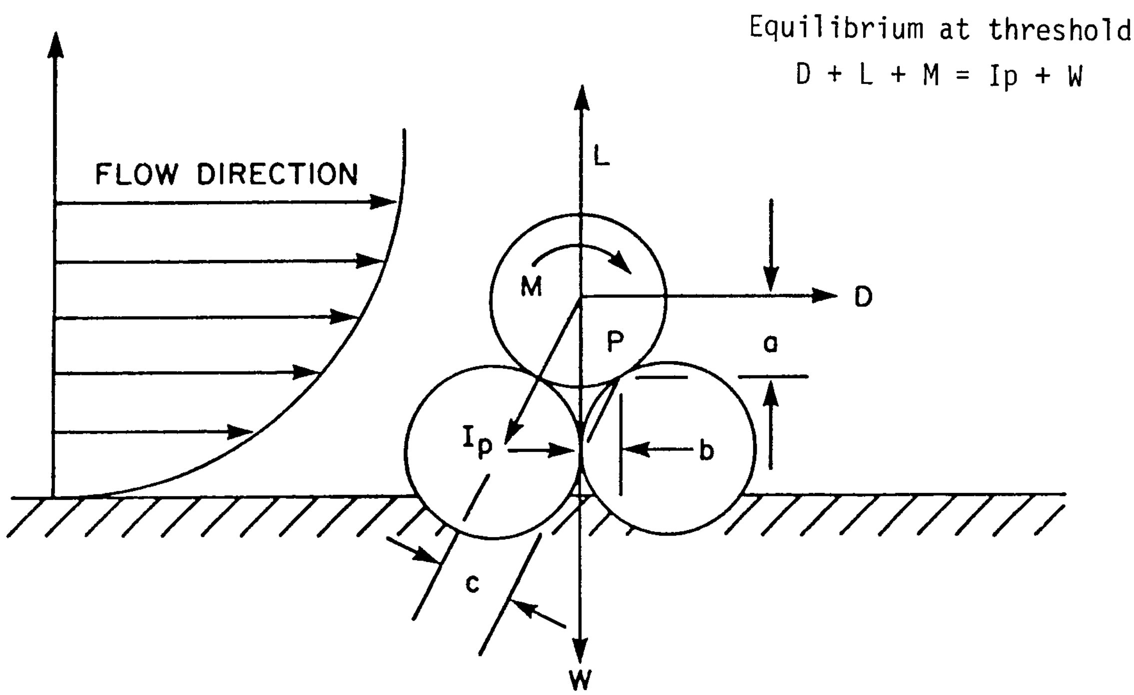

Figure 3.2. Diagram showing stylized wind velocity profile and the forces acting on a particle at rest; L = aerodynamic lift, D = wind drag, M = moment, W = particle weight, and Ip = interparticle force.

grains appears to be valid. Very few experiments, however, have been conducted with dust-size (≤ 20 μm) grains, nor has theory been developed because the problem is very complex. Dust particles a few microns in diameter are well beyond the "understood" range of the threshold curve (Fig. 3.1). Yet, it is this size of particle that constitutes dust storms and deposits on Earth and Mars.

The principal cause for the lack of knowledge on the physics of windblown dust is the unresolved interparticle force term. In effect, it is difficult to separate the weight (W) term from the interparticle force (Ip) term for experiments conducted on Earth, making the study of various Ip forces virtually impossible. However, in a weightless environment the "W" term is effectively removed in the equation, leaving only the interparticle force term. ***Consequently, one of the primary objectives of the proposed Space Station experiments is to study threshold conditions in the absence of gravity in***

order to study interparticle forces. Moreover, these and related experiments bear directly on other processes involving particles, including granular flow and solar nebula formation.

Approach for the study of aeolian processes

Aeolian processes incorporate elements of geology, meteorology, physics, and chemistry. A unified study, therefore, requires a multi-disciplinary approach using results from field studies on Earth, numerical analyses, laboratory simulations, and interpretation of spacecraft data. The *Planetary Aeolian Consortium* (Table 3.1) has used this approach to study aeolian processes on Earth, Mars, and Venus. Use of wind tunnels to investigate the physics of windblown grains under a wide range of planetary atmospheric conditions has provided critical information on the movement of particles by the wind, formation of sedimentary structures, and patterns of erosion and deposition associated with various landforms. The results from these studies not only have provided insight into the surface evolution of Mars (and Venus), but to Earth as well. Through this work, the consortium has established an international reputation for study of aeolian processes, particularly through the use of wind tunnels and other laboratory simulations.

Table 3.2 Planetary Aeolian Consortium

Investigator	Affiliation	Specialty
Greeley, R.	Arizona State University	Principal Investigator and Planetary Geologist
* Gillette, D.	NOAA	Meteorologist
Iversen, J.	Iowa State University	Aeronautical Engineer
+ Krinsley, D.	Arizona State University	Geologist
Leach, R.	ASU/Ames Research Center	Aeronautical Engineer
Marshall, J.	ASU/Ames Research Center	Geologist
* Nickling, W.	University of Guelph, Canada	Soil Physicist
Pollack, J.	Ames Reseach Center	Planetary Physicist
* Sorensen, M.	Aarhus University, Denmark	Statistician
Tsoar, H.	Ben-Gurion University, Israel	Geologist
+ Ward, W.	U.S. Geological Survey	Planetary Geologist
White, B.	Univ. of California/Davis	Mechanical Engineer
* Willetts, B.	University of Aberdeen, U.K.	Engineer

+ Not presently active in consortium
* Potential Space Station experimenter

In summary, aeolian processes play a significant role in the modification of the surfaces of Earth and Mars; some evidence suggests that Venus also may experience aeolian activity. Dust storms constitute a particularly important aspect of aeolian processes, both on Earth and on Mars. Yet, many of the fundamental aspects of dust movement by the wind remain unknown, primarily due to lack of knowledge of the interparticle force term in the threshold equation. The potential for conducting experiments on the Space Station under reduced gravity conditions, or in the absence of gravity, would enable the study of various interparticle forces which, in turn, would shed light on the very essence of the dust transport phenomenon.

3.2 Scientific Rationale

Introduction

The key to understanding problems associated with aeolian sediments 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 transportation of windblown grains. Beginning with research in the 1920s, 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.

Many aspects of aeolian processes have been investigated by the Planetary Aeolian Consortium, including particle threshold using both wind tunnels and theory (Greeley and Iversen, 1985; Greeley and Leach, 1978; Greeley and Marshall, 1985; Greeley et al., 1976, 1980a, 1983, 1984; Iversen and White 1982; Iversen et al., 1976a,b,c, 1986; Nickling, 1984; Nickling and Ecclestone, 1980, 1981; Pollack et al., 1976). Trajectories of individual particles in saltation have also been analyzed (White and Schulz, 1977; White et al., 1975), as have the mass sediment transport capacity of the wind (Greeley et al, 1980b; White, 1979, 1981; White et al., 1976) and the effects of erosion (Greeley et al., 1974a,b,c; Iversen and Greeley, 1984; Iversen and Jensen, 1981; Iversen et al., 1973, 1975a,b, 1976c), deposition (Iversen, 1980, 1981, 1982) and abrasion (Greeley and Iversen, 1985; Greeley et al., 1982). In these studies, the understanding of the physical processes involved in aeolian transport have been substantially advanced by varying the particle density (100 to 11300 kg/m^3), atmospheric pressure (0.005 to 35 bars) and particle diameter (40 to 10000 μm) appropriate for different planetary environments, but we have been constrained by Earth's gravity.

Gravity is one of the most critical parameters in the analysis of sediment movement; however, there are no feasible means for isolating and assessing the effect of low gravity during experiments conducted on Earth. Experiments on the Space Station not only would enable gravity to be assessed as a parameter, but through its control and elimination in some experiments, other critical parameters, such as interparticle forces, could be evaluated.

Static threshold experiments

Static threshold defines the minimum wind speed (or friction speed, u_{*t}, a parameter related to the *surface shear stress* exerted by the wind) required to initiate particle motion over a bed of stationary grains and is the fundamental parameter controlling aeolian processes. The prediction of threshold wind speed involves determination of the forces acting on the resting particles, including aerodynamic lift and drag, weight, and interparticle force. As discussed in Section 1, elimination of the particle weight term in the threshold force equation would enable a more accurate measurement of interparticle force, which is in question both in magnitude and origin. Threshold experiments conducted at one "g" indicate that the interparticle force is at least 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 for particles 30 to 100 μm in diameter. Feasibility experiments conducted in the NASA microgravity facility provide some clues to the magnitude of the interparticle force term (discussed in Section 3.3).

In addition to Van der Waal's force, other interparticle forces include cohesion due to moisture and electrostatic charges. Electrostatic charges are known to be significant in sand and dust storms on Earth (Mills, 1977) and are predicted to be important in martian aeolian processes (Greeley, 1979). The study of this and other interparticle forces as functions of wind speed and particle size, shape and composition would constitute an important aspect of experiments proposed for the facility.

The relevance of these experiments can be considered in the context of martian dust storms. Despite more than a decade of study, the mechanics for raising fine dust on Mars to form the frequent global storms remain a mystery. Because extremely high winds *appear* to be required for static threshold of grains on Mars (Fig. 3.1)--and because such winds are either absent or rare--various *ad hoc* mechanisms have been proposed for dust-raising, as reviewed recently (Greeley, 1986). These mechanisms include injection into the airstream by outgassing of CO_2 (Johnson, 1975), or H_2O (Hueginen et al., 1979), and entrainment by dust devils.

While some of these mechanisms may occur on Mars (such as the recent discovery of dust devils by Thomas and Gierasch, 1985), their relative importance in dust storm generation is at present unknown. Observations of dust storm frequency and intensity on Mars may also imply that the threshold curve for Mars, derived from wind tunnel experiments, is in error or cannot be extrapolated to consider very small particles.

The smallest particles that have been tested in a low-density atmosphere are 38 μm in diameter which is considerably larger than the particle size range (~2-3 μm) thought to exist on Mars (Pollack et al., 1977). Extrapolation of the derived curve for particle diameters more than an order of magnitude smaller is rather tenuous, particularly since interparticle forces which are not thoroughly understood are thought to increase significantly with decreasing particle size.

The steepening of the wind-tunnel-derived martian threshold curve with decreasing atmospheric pressure (Fig. 3.3) also suggests that other factors may be affecting fluid threshold that are not taken into account in this bivariate relationship. For example, it is known that the electrical conductivity of carbon dioxide is highest at approximately 6 mb pressure, which is equivalent to the average pressure on Mars. This could mean that charge transfer among particles and between particles and the surface is enhanced, possibly resulting in greater cohesion for the bed as a whole, thereby increasing the fluid threshold.

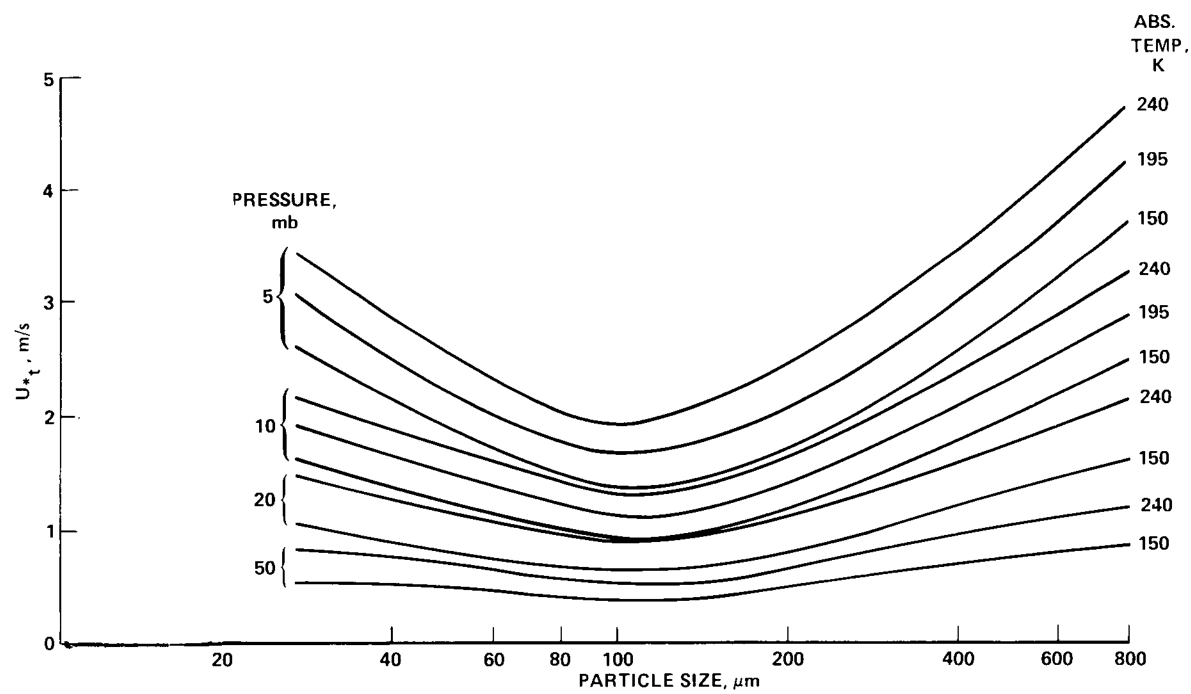

Figure 3.3. Threshold curves (wind friction velocities) for particle movement on Mars derived from experiments, showing increase in slope for winds with decrease in atmospheric pressure.

Alternatively, on Mars the higher electrical conductivity of the atmosphere could allow the charges on the grains to "leak away", and thus decrease the particle cohesion and the threshold wind speed. In the proposed Space Station experiments, these interparticle forces could be measured directly in the absence of gravity to determine their effects on threshold conditions.

The physics of saltation

The saltation process is a complex phenomenon, aspects of which are stochastic in character (Anderson and Hallett, 1986; Sorensen, 1985). The particles in motion within a saltation layer usually exhibit a large range of particle sizes, governed by some statistical distribution. The particle trajectories vary through a large range of values of trajectory height, length, and speed. The turbulence within the boundary layer is particularly important for small (dust) particles and also can be described statistically. The stochastic nature of the saltation process is primarily responsible for the problems encountered in measuring and predicting parameters such as mass transport rates.

Although the threshold process in the apparatus proposed for experiments on the Space Station closely simulates the process on Earth and Mars, the saltation dynamics are somewhat different. Particle trajectories will have a similar but somewhat different shape in the experiment apparatus from those on a planetary surface because of the absence of external gravitational attraction. However, the basic physics of the saltation process remain the same, and the opportunity to observe particle motion is much enhanced compared to Earth because, at the low values of threshold achievable in zero-gravity, the particle speeds will also be low. Thus, not only should it be possible to study the trajectories of small-particles affected by turbulence to a degree heretofore unattainable, but the stochastic nature of trajectory distribution should also become much clearer. The effects of particle impact on threshold and on particle injection during saltation at speeds above threshold are currently of much interest (Haff, 1983; Werner and Haff, 1986; and Iversen et al., 1986) and could be studied more closely than in Earth-bound wind tunnels because of much lower particle speeds.

Other applications

The wind tunnel apparatus proposed for the aeolian experiments possibly could be used for other experiments dealing with particles. For example, *granular flow* is important in many planetary processes (landslides, ash-flow emplacement, etc.) and insight into such flows could be gained via low-g experiments. In addition, some aspects of solar nebula formation involving particle interaction should be assessed in a turbulent gas flow, low-gravity environment, as would be afforded in the proposed apparatus.

Granular flow. The flow of granular material is important in many fields, including geology, industry and agriculture. The word "flow" is used for all rapid movement of granular materials characterized by high shear rates. The least complicated case is the flow of identical spherical grains with no interparticle forces and a negligible interstitial fluid. Research on granular flow began with the study of granular static deformation by Coulomb (1776) and Reynolds (1885). The flow of very dilute dispersions of particles which do not interact with each other was studied by Einstein (1906). R.A. Bagnold (1941) studied the flow of interacting particles.

There has been a rapid expansion of study of granular flow over the past decade. Modern models include: (1) continuum mechanics models based upon the theory of mixtures (e.g., Goodman and Cowin, 1971), (2) kinetic theory of gases models in which the grains are treated as analogous to the molecules of a dense gas (Ogawa, 1978). Extensions of this type of model are currently receiving considerable theoretical attention, (3) discrete particle simulations using the computer to follow individual particles (e.g., Cundall and Strack, 1979), and (4) turbulence models in which the fluctuating velocities of the grains are treated as the fluctuating fluid velocities of a turbulent flow (Jenkins and Savage, 1981).

In all these models, the value and direction of the gravitational acceleration are important factors. Experiments have been performed in which the direction of g varied with respect to the granular flow, as for example, those cases involving variable slope. The value of g has been changed for low strain-rate testing, such as in the high-g centrifuge testing of Earth structures. Bagnold's (1954) work, "Experiments on a Gravity-Free Dispersion of Large Solid Spheres in a Newtonian Fluid Under Shear" was not actually "gravity-free" but instead used neutrally-bouyant spheres in water, all at one-g.

The work proposed here represents perhaps the first granular shear flow experimentation to be done at variable gravity. Such experiments could: (1) aid in the fundamental understanding of granular flow, (2) help validate various theoretical models, (3) have direct application to certain low-g processes such as landslides or sediment sheet flows on the Moon, and other small bodies, (4) aid in the understanding of adhesion and coagulation of flux particles undergoing shear, and (5) provide qualitative information on grain-flow mechanics and dispersive stresses at the limit of low gravity and low gas pressure.

Solar nebula formation. From the broadest perspective, the apparatus proposed for aeolian simulation could also be used for fundamental experiments in particle dynamics. Particles could be placed in a flowing atmosphere which can be at a continuous or variable rate. With appropriate scaling, this condition may be analogous to some parts of an evolving solar nebula. The existence and the importance of turbulence and mass flow within solar nebula formation models are well-documented; other, non-equilibrium particle-gas flow dynamics could be envisioned in the controlled environment offered by the experiment apparatus. These experiments could involve variations in gravity and the effects of turbulence which can be induced (and adequately compared) by differential flow in the apparatus. Wind tunnel experiments of this type may provide answers to a number of fundamental dust-gas interaction questions, some of which are:

- *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)?*
- *Do grains aggregate in a steady mass flow turbulent-free-environment over time?*
- *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 include dust-gas flow experiments with the application of an ionizing atmosphere. This could be induced in the experiment 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 grains with mixed characteristics (i.e., spheres and laths; clays and silica; organics and graphites) were introduced.

3.3 Carousel Wind Tunnel (CWT) Design

Introduction

Boundary-layer wind tunnels appropriate for investigations of aeolian processes typically exceed 10 m in length. Size limitations on the Space Station led to the consideration of other wind tunnels that would be compact and suitable for the proposed experiments. Based on these factors, a "carousel" wind tunnel was designed which consists of two concentric rotating drums (Figs. 3.4 and 3.5) containing the test section. Differential rates of rotation of the two drums provide a wind velocity with respect to either drum surface. Rotation of the outer drum provides a "pseudo" gravity ("pseudo" in the sense that a gravity force acts on the particle while it is resting on the outer drum surface). In order to test the concept, a model Carousel Wind Tunnel (CWT) was constructed and calibrated. Tests were run in the laboratory to assess the flow-field characteristics and on-board the NASA microgravity aircraft (KC-135) to evaluate the CWT operation in a reduced-gravity environment.

Bench-testing of the CWT

Flow field experiments were run to assess the boundary layer properties that are critical for the proposed experiments. Because CWT is a new design for wind tunnels, there is no previous, direct experience upon which to draw. However, for the more general case for turbulent flow between rotating cylinders, Taylor (1935) proposed that nearly potential (inviscid) flow should occur and noted that the boundary layer should be governed by Prandtl's mixing-length theory. In the CWT it is important that the mixing-length theory govern the boundary-layer flow adjacent to the curved surfaces, because the

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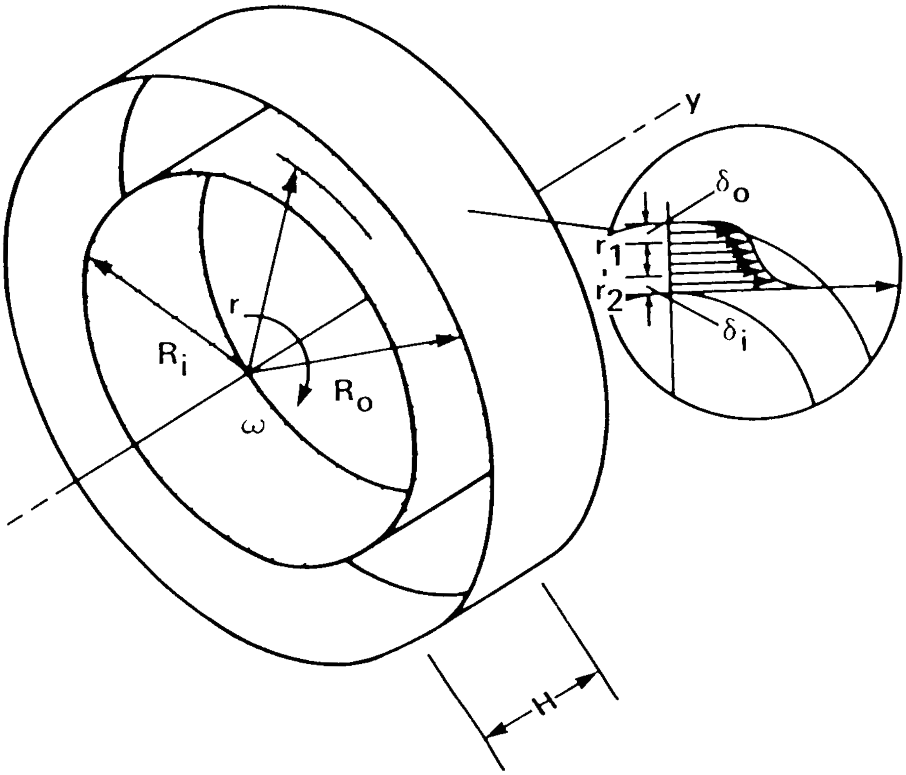


Figure 3.4. Geometry and flow characteristics of Carousel Wind Tunnel (R_i = radius of inner drum, r = radial distance from drum axis, R_o = radius of outer drum, ω = angular velocity, r_1 = radial distance to interface between the central and outer layers, r_2 = radial distance to the interface between the inner and central layers, δ_o = outer boundary layer and δ_i = inner boundary layer, H = width of apparatus.

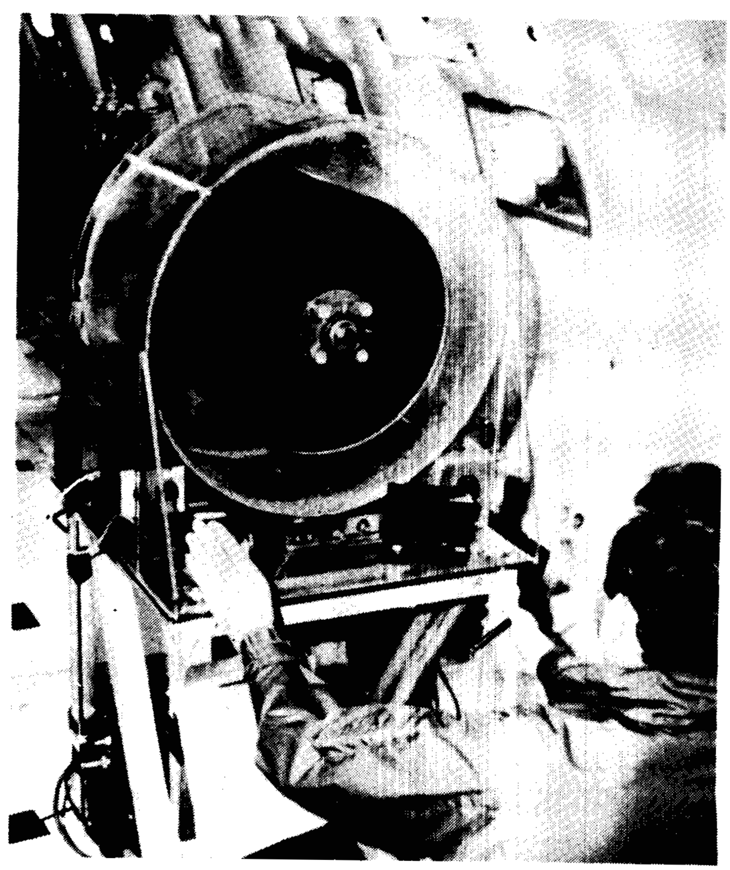


Figure 3.5. View of the model Carousel Wind Tunnel on-board the NASA KC-135 aircraft.

same theory governs the flow over a plane surface and would be comparable to natural conditions and to conditions in conventional wind tunnels. Experiments were performed in the CWT to determine if these assumptions are correct and if Taylor's hypothesis is valid. First, the following equations for the flow can be derived for an inner rotating cylinder:

inner layer (Prandtl boundary layer)

$$U = R_i\omega - u_{*i}\,\{2.5 \ln [(r - R_i)u_{*i}/\upsilon] + 5.5\}$$

$$\text{for } R_i/R_o + (\upsilon/u_{*i}R_o)e^{0.4R_i\omega/u_{*i}}$$

$$\leq r/R_o \leq r_2/R_o$$

central layer (potential inviscid layer)

$$U = KR_i\omega R_o/r$$

$$\text{for } r_2/R_o \leq r/R_o \leq r_1/R_o$$

outer layer (Prandtl boundary layer)

$$U = u_{*o}\,\{5.5 + 2.5 \ln [(1 - r/R_o)\,R_o\,u_{*o}/\upsilon]\}$$

$$\text{for } r_1/R_o \leq r/R_o$$

$$\leq 1 - 0.1108/(R_o\,u_{*o}/\upsilon)$$

in which U = the tangential wind velocity, R_i = radius of inner drum, ω = angular velocity of the drum, u_{*i} = inner layer friction speed (where the friction speed is defined as the (wall shear stress)$^{1/2}$/air density), r = radial distance from the drum axis, υ = kinematic viscosity, R_o = radius of outer drum, K = constant, r_2 = radial distance to the interface between the inner and central layers, r_1 = radial distance to the interface between the central and outer layers, and u_{*o} = outer layer friction speed.

In general, the velocity magnitude within CWT can be written as:

$$U/R_o\omega = F\{r/R_o,\ y/R_o,\ R_i/R_o,\ H/R_o,\ Z_o/R_o,\ R_o^2\omega/\upsilon\}$$

In this equation, y is the lateral (axial) coordinate, H is as defined in Figure 3.4, and the surface roughness of the drum is indicated by the equivalent roughness height z_o.

For general flow between two cylinders, zones of flow instability often occur in the test region. These have been investigated extensively at low Reynolds numbers ($R_o^2\omega/\upsilon$) and for low-height test sections $(R_o-R_i)/R_o$ (Coles, 1965; Fasel and Booz, 1984; Andereck et al., 1986). However, these problems may not be significant in CWT because the test section height R_o-R_i is large and the experiments are run at large Reynolds numbers.

Although preliminary experiments suggest that this assumption is valid, additional experiments need to be conducted to evaluate the flow characteristics for the full range of conditions in the anticipated experiments.

The nondimensional wind speed, $u/\omega r$, inside the CWT is a function of nondimensional radial distance r/R. The inset of Figure 3.4 represents the flow in the test section of the CWT. The wind velocity profile adjacent to the surface is representative of a turbulent boundary layer velocity profile over a smooth surface under natural conditions and in a normal wind tunnel. Experiments were conducted with CWT and turbulence intensities were measured. The results were found to be well within the range of acceptable levels for turbulent boundary layer flow in conventional wind tunnels. Experiments were conducted to assess the characteristics of the wind velocity profile (Fig. 3.6). Results show similar vertical profiles, providing further evidence that the CWT properly simulates the conventional turbulent boundary layer flow appropriate for conducting particle threshold experiments. Comparison of theoretical predictions with observed test data shows good agreement, suggesting that Taylor's hypothesis is correct and that surface friction speeds can be predicted *a priori* . There is, however, a slight discrepancy between theory and calibration at the top of the test section (near the inner drum, Fig. 3.6). This is attributed partly to secondary flows in the wind tunnel which are not taken into account in the theory. Secondary flows contain a component normal to the main flow direction and, for flows over a concave surface, can take the form of a vortex flow, called a Taylor-vortex system. To eliminate or minimize the influence of the vortex flow, anti-vortex vanes were installed in the CWT. Subsequent flow-field experiments show that the vanes greatly reduced the secondary flows. The proposed Space Station CWT is larger than the model CWT which would reduce further the secondary flows because of the larger radius of curvature.

In summary, experiments with the model CWT show that boundary layer flow is developed and is similar to flows in conventional wind tunnels that are used to investigate the physics of windblown particles. Thus, the CWT design concept appears to be valid so far as flow characteristics are concerned.

NASA microgravity facility experiments

In order to assess the performance of the CWT in a weightless environment, experiments were conducted in the NASA microgravity facility on board a specially-modified KC-135 aircraft. This plane flies on a parabolic trajectory to provide 20 to 30 seconds of low gravity; it first climbs to 10,000 m, then descends to 8,000 m, attaining an airspeed of >800 km/hr, and then climbs sharply upward at 45° to initiate the parabolic trajectory (Fig. 3.7). The radial acceleration (number of g's) of the aircraft increases to 1.8

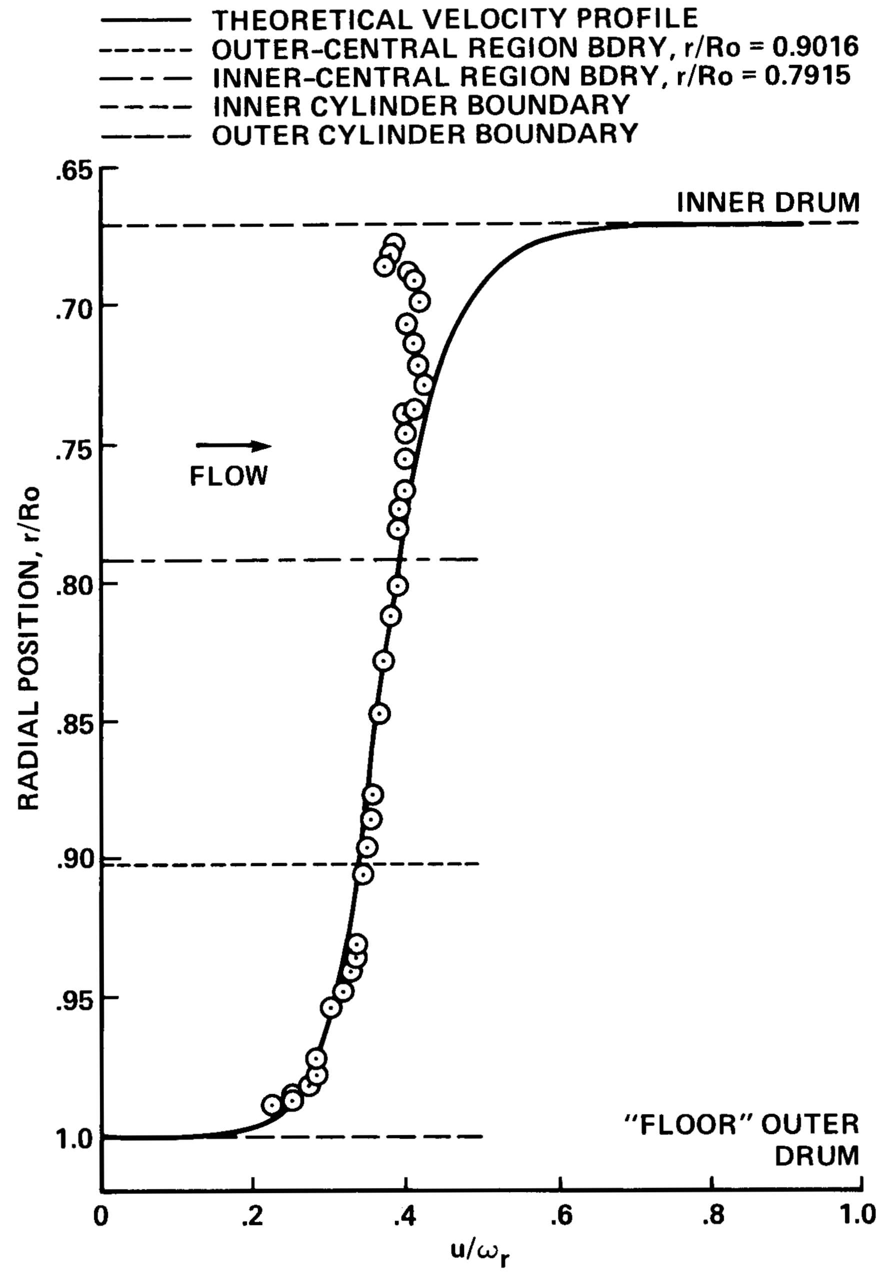


Figure 3.6. Wind velocity profile measurements (data points) made in the CWT compared with theoretical curve, showing close agreement near the floor where experiments would be conducted (R_i = 356 mm, R_o = 531 mm, ω = 515 rpm).

during the steepest part of the climb; as the aircraft pitches over the top of the trajectory, the aircraft radial acceleration decreases to a predetermined level and can be held constant (±2%) for the duration of the trajectory (Fig. 3.7). At the end of the maneuver, the sequence is repeated in a roller-coaster fashion.

Two flights have been flown with the CWT. Feasibility threshold experiments were conducted using 700 and 1080 μm in diameter particles. Particles were placed in the test section and the inner drum rotated to create airflow below threshold velocity at 1 g. The aircraft was then flown on a steadily-reducing g trajectory until particle threshold occurred. By varying the CWT airflow speed for subsequent maneuvers, data were collected for a

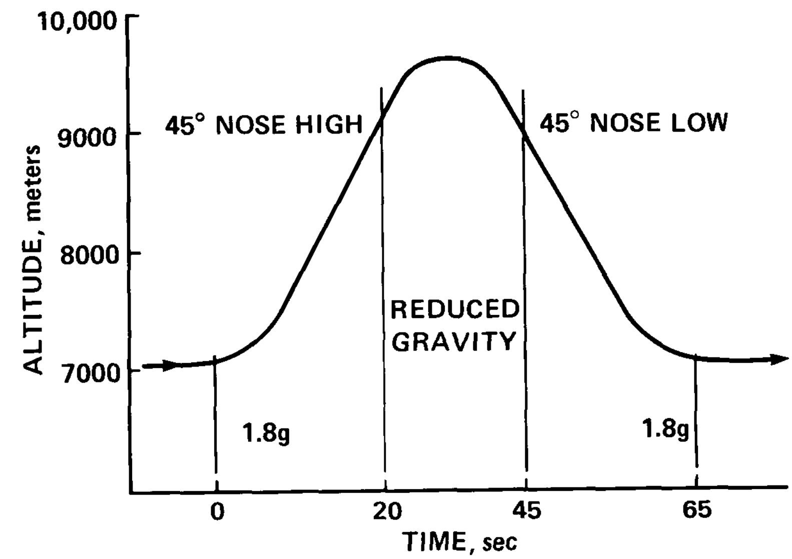


Figure 3.7. Diagram showing the flightpath of the KC-135 aircraft during a micro-gravity maneuver.

wide range of g-levels. These data are shown in Figure 3.8 along with theory as obtained from the following equation:

$$u^2{*_t} = 0.0166\, \rho_p g D_p/\rho \left[1 + \frac{0.006/2.5}{\rho_p g D_p^{2.5}}\right] \div \left[1.928 R_*^{0.092} - 1\right]$$

The data correlate well with the gravity term for values of g less than unity. The friction velocity is $u*_t$ at which particle movement begins, ρ_p is particle density, g is gravity, D_p is particle diameter, ρ is atmospheric density and $R*$ is the friction Reynolds number, defined as $\rho D_p u*_t/\mu$, in which μ is the coefficient of absolute viscosity.

Figure 3.9 displays $g\rho_p D_p$ as a function of ρu^2*. The extrapolation of these curves to $g\rho_p D_p$ equals zero and indicates the relative magnitude of the interparticle force term since equation (1) may be rewritten as:

$$\tau = \rho u^2{*_t} = f(R*_t)\, [\rho g D_p + K I_p/D_p^2]$$

where τ is the surface shear stress, $f(R*_t)$ is a function that depends only on $R*_t$ (not I_p), and K is a constant. Thus, if g equals zero, the interparticle force may be obtained. If the interparticle force were zero, the curves in Figures 3.8 and 3.9 should go through the

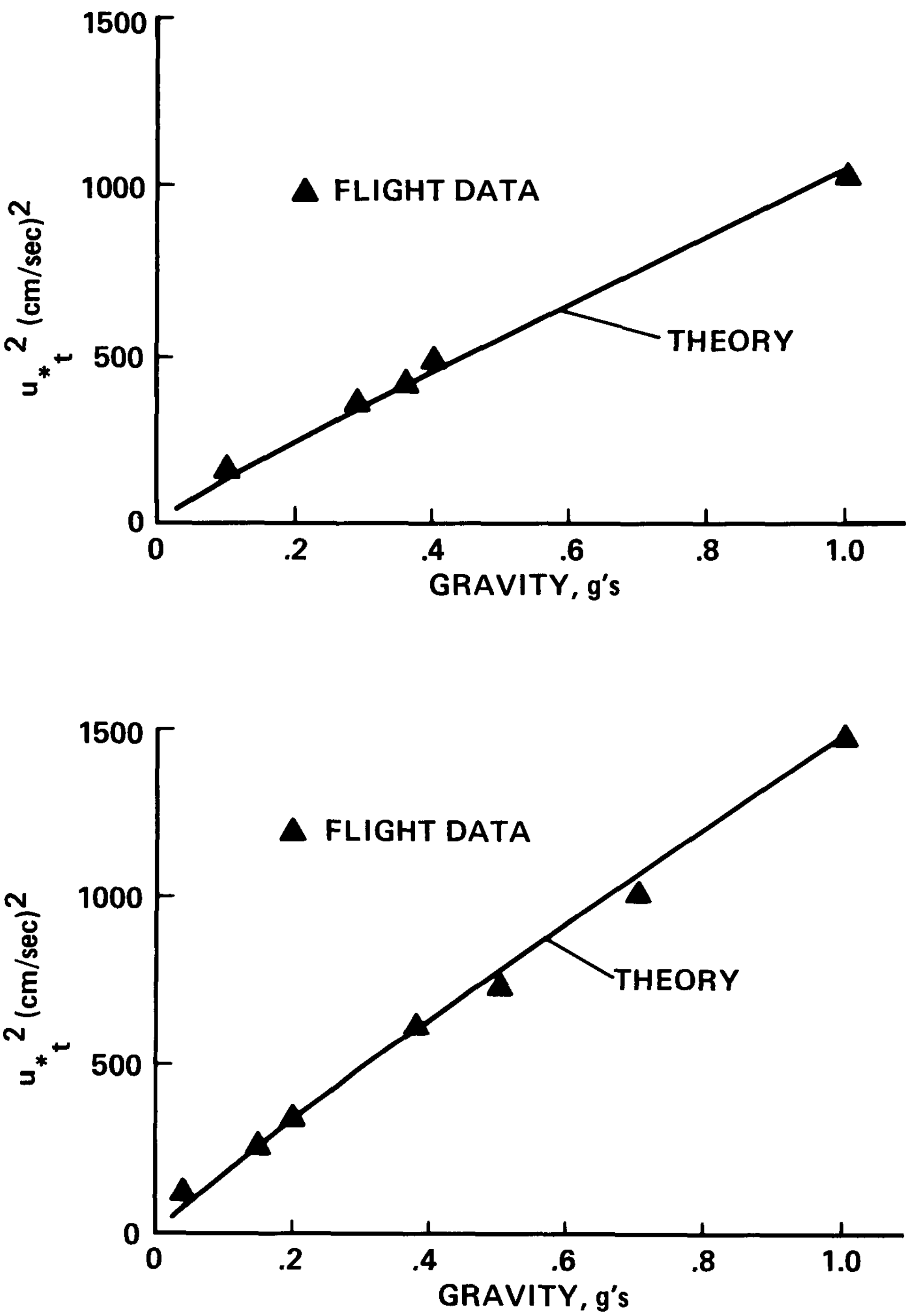


Figure 3.8. CWT experiments performed on the KC-135 aircraft showing threshold for particles as a function of gravity, for 700 μm in diameter (top) and 1080 μm in diameter (bottom) particles, compared to predictions based on theory. These results demonstrate that the CWT can be used for conducting threshold experiments.

origin. However, the curves for the 700 and 1080 micron particles are slightly above the origin showing the presence of I_p, even for these large grains. Smaller particles will magnify this effect and by cross plotting the offset versus particle size, the interparticle force as a function of particle size may be obtained.

These experiments show that the CWT can be used to investigate both gravity as a parameter in threshold experiments and the interparticle force. It must be noted, however, that the experiments conducted on the KC-135 are extremely limited and only allow testing of concepts. The very limited low- and zero-g flight duration and the high turbulence on the flights prohibit experiments with small (dust) particles, which constitute the primary experiment objectives for the Space Station.

3.4 Carousel Wind Tunnel Design for Space Station

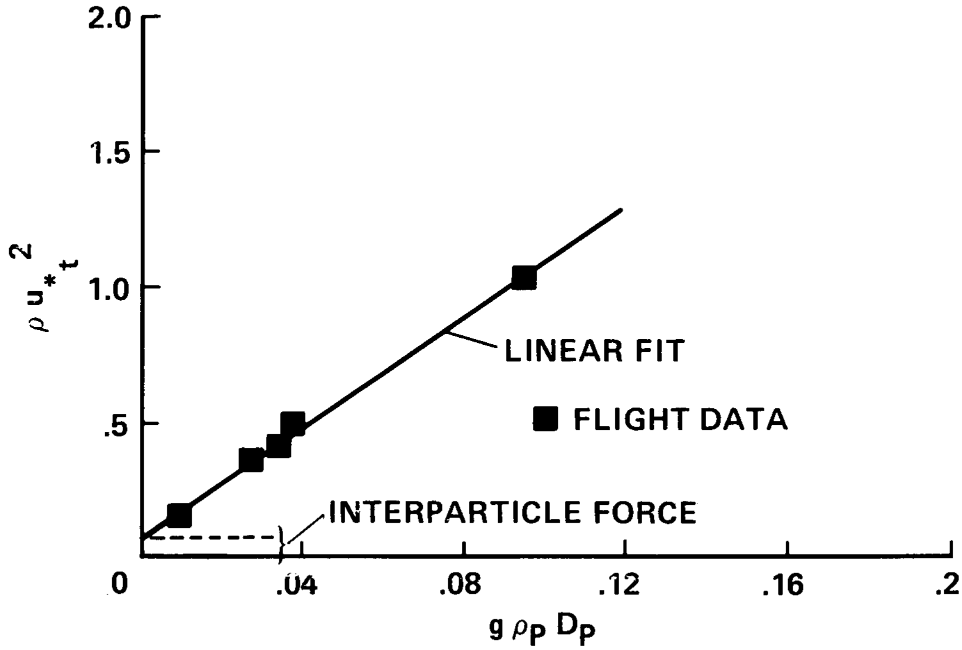
Introduction

The Carousel Wind Tunnel and associated equipment are designed to occupy a standard double laboratory rack (~1 m wide) on the Space Station (Fig. 3.10) and to operate at a range of atmospheric pressures to simulate Earth and Mars. The operation would be automated to require minimal crew attention, other than initiation of the experiments or to repair possible malfunctions. Power would be required for several small electric motors, a video camera system and lights, and a micro-computer control system. Data would be stored on a tape medium and observations would be made via video camera for broadcast to Earth. Low atmospheric pressure in CWT for martian simulations would be accomodated via lines running outside the laboratory module and controlled through automated valves. Some particles from the experiment may be returned to Earth for analysis.

Design concepts

Artificial Gravity. Artificial gravity for threshold experiments would be obtained by rotating the outer drum of the CWT, with particles placed on the inside of the outer drum surface. For an outer drum radius of 0.5 m, the equivalent of one Earth gravity can be obtained with an angular speed of approximately 1600 rpm. For an artificial gravity of 0.1 g, the rotational rate needed is only approximately 500 rpm; thus a reasonable range of gravity values can be obtained with the CWT.

Particle handling. Test particles and cleaning materials would be stored in sealed bins located at the rear of the tunnel. Each bin would be connected to the tunnel through tubes controlled by solenoid valves, with material transferred by a pneumatic system. Loading and unloading of test particles and cleaning would be automatic from either on-board or ground command. Material from any bin can be loaded into the tunnel, transferred to another bin, or mixed together.



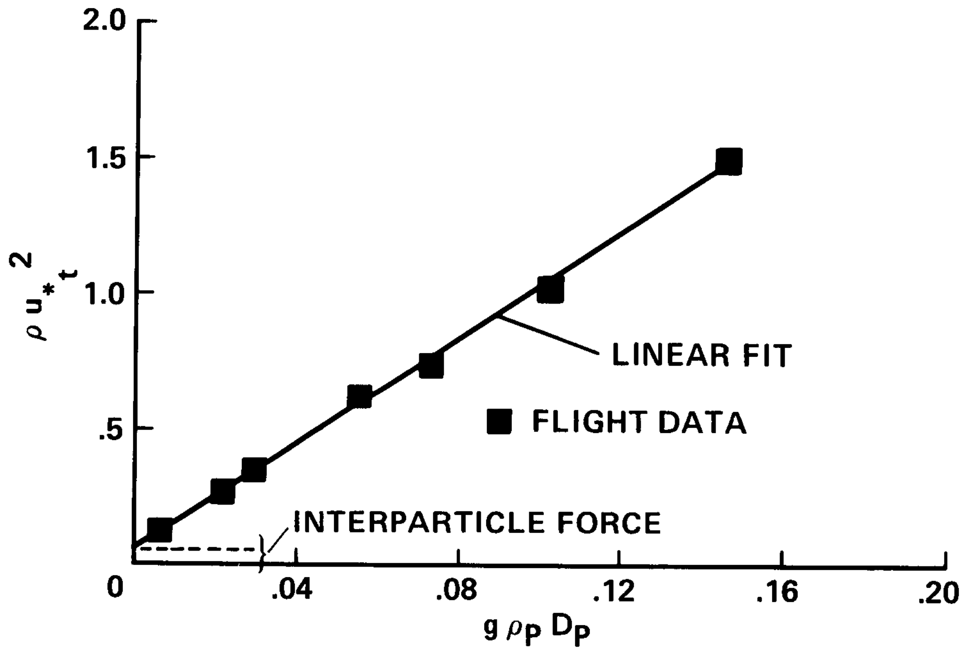


Figure 3.9. CWT experiments from 700 μm (top) and 1080 μm (bottom) particles conducted on-board the KC-135 aircraft showing linear fit through data. The curve does not pass through the zero-intercept due to the presence of interparticle forces. With decreasing particle size, the interparticle force effect is expected to increase significantly.

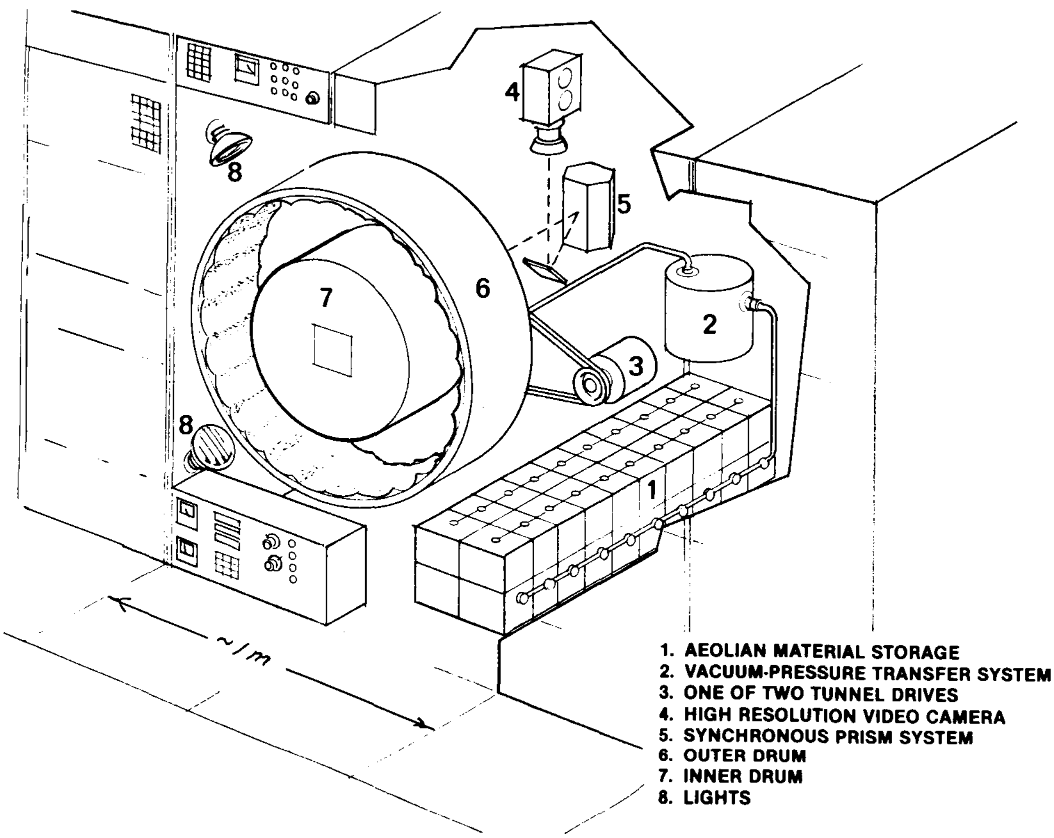


Figure 3.10. Conceptual diagram showing major components of the Carousel Wind Tunnel on-board the Space Station.

At the start of a test, particles would be injected into the test section and the inner drum rotated to distribute the particles uniformly in the test section. The threshold experiment then would be conducted, data taken using the instruments described below, and visual observations made via the video system. At the completion of the test, the particles would be automatically vacuumed from the test section. Between experiments, static charges in the CWT would be neutralized using anti-static cleaning material inserted into the tunnel in the same manner as the test particles.

Threshold detection. Determination of threshold wind speeds for particles under low gravity conditions and in the absence of gravity constitutes a key series of experiments. Threshold (initiation of particle motion) would be detected by: (1) a laser interferometer, (2) a static charge detector, and (3) a piezoelectric impact detector. The laser interferometer directs a laser beam across the test section onto photo-detectors. As the particles begin to move they interrupt the beam, causing an attenuation of the signal. A similar device currently is used (Greeley et al., 1981) and a new, more efficient device, based on the same principle but using a laser "sheet", is being developed by W. Nickling. This new design has the potential to monitor automatically the take-off velocities and sizes of particles entrained from the surface while providing a direct measure of the particle flux rate throughout the experiments.

The static charge detector consists of a pair of conductors that become electrically charged by the impact of particles. This device also has been used in conventional wind tunnels (Greeley, 1979); it can be used to detect particle motion and to monitor the level of static charge of the particles.

The third device uses a piezoelectric crystal. Particle movement is detected by the charge produced by the crystal when it is impacted by a particle. The signal from the crystal is conditioned to provide momentum information on moving particles. Three prototype instruments have been built. The first prototype measured the momentum flux of particle impacts perpendicular to the floor and parallel to the wind direction. Details of the instrument and results of saltation experiments are given by Gillette and Stockton (1986). A second instrument measures impacts on the floor and does not project into the stream of particles, thus providing a non-interfering method of measuring particle momentum flux to the floor. A third version, presently under development, is designed for outdoor experimentation and measures momentum flux parallel to the ground. It is felt that the second instrument would be suitable for use in the CWT and would provide a non-interfering, particle-movement measuring system, complementary to laser systems, that does not rely on optical methods.

Interparticle force determination. One of the most important parameters to be investigated is the interparticle force. This force is not only responsible for the high velocity winds required to initiate the movement of fine-grained materials, such as dust, but also tends to cause particle agglomeration. Because of the difficulties in working with fine particles and the measurement of interparticle forces on Earth, there is little previous experience to rely upon in the development of the experiments proposed here. However, several approaches can be explored.

First, the total interparticle force can be determined by analysis of the threshold velocity. By plotting the value of the wind-surface-friction force versus the gravitational term, the interparticle force can be determined from the non-zero y-intercept. By plotting these values for a range of particle sizes, the interparticle force can be determined as a function of particle size, as shown in the feasibility experiments flown on the KC-135. In the proposed Space Station experiments, this sequence would be repeated for particles of small size (1 to 100 μm) and of different compositions.

One of the most important parameters to be monitored and controlled is the interparticle force attributed to electrostatic charges. Operationally, electrostatic charges accumulated on the CWT drums will be neutralized between runs; however, because some of the experiments will be of long duration the particles and drums will accumulate charges during the runs. The charge would be monitored using an electrometer and could be removed if desired by generating positive and negative ions to neutralize the charges on the particles and the drum. The long-term effects of electrostatic charges could include particle agglomeration, which could alter threshold by orders of magnitude.

The interparticle force is a function of many parameters such as electrostatic charges, internal charge imbalances (as found in clay crystals), Van der Waal's forces, particle moisture content, and particle size, texture and size distributions for mixtures of grains. This will complicate the analysis of the matrix of threshold experiments to be conducted. However, by careful selection and/or preparation of the material samples, each of the major contributors to the total interparticle force may be individually identified and measured. For example, an electrically conducting material, such as copper spheres or copper powder, may be used to eliminate particle surface electrostatic charges by "grounding" the material to an electron-drainage source along the inner and outer walls of the CWT. Then, by repeating the experiment without the "grounding" effect, the influence of electrostatic surface-charges may be directly measured.

In a similar fashion, by varying test condition and test materials or properties of similar materials, the affect of internal charge imbalance, cohesive forces and Van der Waal's forces each may be measured independently and separately. For the internal charge imbalance, clays of different internal charge structure could be tested along with earth-based laboratory analysis of the internal charge imbalance (each sample) thus, directly measuring the effect of internal charge imbalance.

3.5 Proposed Plan for Development

Introduction

The research proposed here for the Space Station would be implemented by:

1. Establishment of a user group;
2. Continued testing of the CWT concept and development of a Space Station prototype, and fabrication of a flight-qualified model;
3. Instrument development and design for automation, and
4. Coordination of this program with other research in aeolian processes.

Establishment of a User Group

The research program outlined here resulted from discussions within a consortium of investigators who are engaged in the study of planetary aeolian processes (Table 3.1). The primary focus of the consortium has been on laboratory experiments (although field studies and development of theory have also been important elements) and the experiments proposed for the Space Station are a natural extension of this research to take advantage of an environment not previously accessible, but which is critically important for many aspects of aeolian processes.

Most of the investigators involved in the proposed Space Station effort (Table 3.1) already have formal and informal collaborative projects. We envision a more formal CWT user group to be formed as part of the program development. As the concepts and experiments evolve, the composition of the user group may change, especially to give new and young investigators the opportunity to conduct experiments.

KC-135 microgravity program

Preliminary experiments conducted on the KC-135 aircraft have been invaluable in testing the CWT concept and have already produced new scientific results, as discussed in Section 3. Experiments with the model CWT would continue to help refine techniques, to assess problems in particle handling, and to aid in defining areas for automation.

The next phase in the development of the research program would be the fabrication of a prototype CWT that would be a full-size model proposed for the Space Station to allow 1:1 testing of various components. As instruments and techniques for automation are developed, they would be tested using the prototype, both on the ground and on the KC-135 aircraft. As with the current CWT, "science" results can be anticipated from some of the experiments conducted with the prototype model.

Instrument development

Development of instruments and techniques for automation are key elements in the research program. The complexity of instrument development ranges from relatively simple adaptation of existing items (such as the laser threshold detection system) to the development of entirely new concepts.

Because crew time would be extremely limited on the Space Station, we would plan to automate as much of the apparatus as is reasonable and cost-effective. Although at this stage of the study, relatively little attention has been given to this issue, we consider that many aspects of the experiment could be automated.

Testing of instruments and automation procedures would be carried out both in the laboratory and on the KC-135 aircraft.

Space Station CWT

Experiments with the prototype would enable the design of the final CWT and the last phase of the implementation plan would be fabrication of a flight-qualified CWT. The fabrication could be by an aerospace company, NASA-Ames Research Center, or through a university. NASA-Ames has provided engineering and fabrication in the past for apparatus used by the Planetary Aeolian Consortium and has experience in providing space-flight components. Similarly, a university could be responsible for some flight-qualified apparatus.

Related research activities

All of the proposed investigators have active research programs in aeolian processes. Most of the group either have wind-tunnel facilities, or access to wind tunnels as an integral part of their program. Depending upon the investigators, the terrestrial work is funded by NOAA, the Department of Agriculture, the Natural Sciences and Engineering Research Council of Canada, or the Danish Academy of Sciences, whereas the planetary studies are supported by NASA. Results from these studies would continue to provide refinement of the proposed Space Station work. In all cases the investigators recognize the potential benefits to their own research through experiments that could be flown in the new environment afforded by the Space Station.

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