UNIVERSITY OF CALIFORNIA

DEPARTMENT OF MECHANICAL ENGINEERING

DAVIS, CALIFORNIA

NUMERICAL AND EXPERIMENTAL STUDIES OF PARTICLE FLOW
IN A HIGH-PRESSURE BOUNDARY-LAYER WIND TUNNEL

Semiannual Progress Report
January - June 1984

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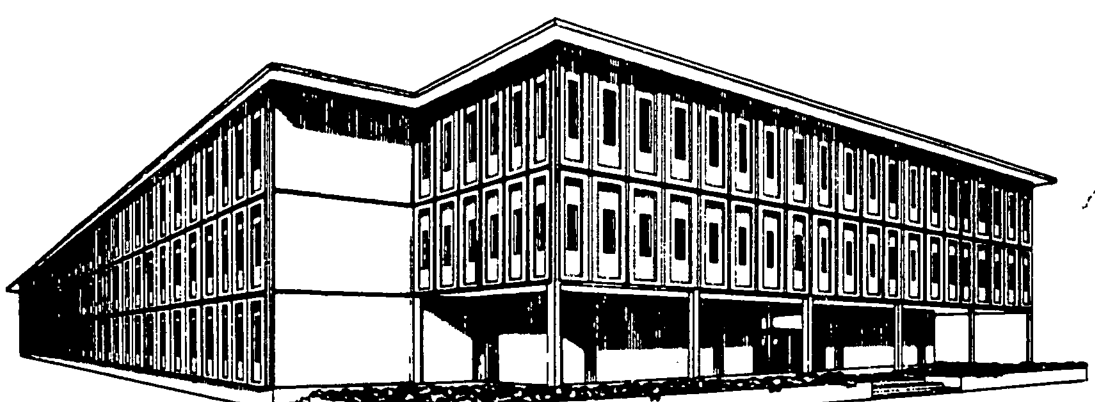

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NUMERICAL AND EXPERIMENTAL STUDIES OF PARTICLE FLOW IN A HIGH-PRESSURE BOUNDARY-LAYER WIND TUNNEL*

B. R. White, Principal Investigator

Department of Mechanical Engineering
University of California
Davis, CA 95616

Introduction

Aeolian processes were predicted for Venus by Ronca and Green (1970) from considerations of the surface environment. Subsequently, Sagan (1975), Hess (1975), Iversen et al. (1976 a and b), and Iversen and White (1982) predicted the minimum wind friction speeds required to entrain particles on Venus based principally on extrapolation from experiments performed under terrestrial conditions.

In 1975 the Soviet landers, Veneras 9 and 10, measured venusian wind speeds of 0.5 to 1 m/s (Florensky et al., 1977) at the height of the wind sensors (~ 1 m above the surface). More recent measurements of wind speeds obtained by the Pioneer-Venus atmospheric probe imply a surface wind speed of 1 to 2 m/s (Counselman et al., 1979). Although it is difficult to convert either of these measurements to surface wind friction speeds ($u_{\star}$) without detailed knowledge of the wind speed profile and surface roughness, these values are well within the range predicted as necessary for particle movement. Venera images of the

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surface show rock slabs, rock fragments several cm across, and fines (< 1 cm), which could all contribute material in the size range appropriate for aeolian activity. Further evidence of fine particles on the venusian surface is discussed by Garvin (1981) based on Venera and Pioneer Venus data, which suggest that particles 18 to 30 μm in diameter were raised as dust clouds by the landers and the probe. Thus, both requirements for aeolian processes -- small particles and winds of sufficient strength to move them -- appear to be met on Venus.

The approach in this study was to simulate the surface environment of Venus as closely as practicable and to conduct experiments to determine threshold wind speeds, particle flux, particle velocities, and the characteristics of various aeolian bedforms. In this progress report, the Venus Wind Tunnel (VWT) is described and the experimental procedures that were developed to make the high-pressure wind tunnel measurements are presented.

In terrestrial simulations of aeolian activity, it is possible to conduct experiments under pressures and temperatures found in natural environments. Because of the high pressures and temperatures, venusian simulations are difficult to achieve in this regard. Consequently, extrapolation of results to Venue potentially involves unknown factors. The experimental rationale was developed in the following way: The VWT enables the density of the venusian atmosphere to be reproduced. Density is the principal atmospheric property for governing saltation threshold, particle flux, and the ballistics of airborne particles (equivalent density maintains dynamic similarity of gas flow). When operated at or near Earth's ambient temperature, VWT achieves venusian atmospheric density at pressures of about 30 bar, or about one third less than those on Venus, although still maintaining dynamic similarity to Venus.

The Venus Wind Tunnel

The Venus Wind Tunnel is a closed-circuit, boundary-layer tunnel with an overall dimension of 6 m by 2.3 m. Flow is generated by a one-horsepower, D.C., variable-speed motor that drives an eight-bladed fan. The fan operates at a maximum speed of 1750 rpm, which generates freestream wind speeds as high as 4 m/s through the test section.

The shell of the tunnel is constructed of schedule 40 steel pipe that has been hydrostatically tested to a pressure of 67 bar. Ten curved tubes, each 5 cm in diameter, are located in the two corners of the tunnel downwind from the fan to prevent flow separation and to minimize turbulence and secondary flow. A large diameter (47 cm) settling chamber containing Hexcell honeycomb and four 180-mesh screens is located immediately upstream of the test section to dampen small-scale turbulence. A smoothly-curved bell mouth provides the transition from the settling chamber to the test section. A diffuser section downstream from the test section improves the efficiency of the flow through the tunnel. Located in the diffuser are electrical ports to provide 20 connectors for various instruments used in the tunnel. A replaceable screen between the diffuser and the fan assembly traps sand particles to prevent recirculation of the particles through the tunnel and damage to the fan.

The test section is 20 cm in diameter and 122 cm long. It is mounted on a wheeled-track assembly and has quick-couple clamps to enable easy access to the test section between experiments. Floor plates provide a level surface for experiments and are of several varieties depending upon the type of experiment. Four glass ports, each 7 cm in diameter, enable direct observation and photography of experiments in the test section.

The VWT operates with CO_2, N_2, or air, at pressures up to 40 bar. Although not duplicating the atmospheric temperature or pressure of the Venusian surface, by maintaining near-ambient (laboratory) temperatures the density of the Venusian atmosphere is duplicated at a pressure of 30 bar with CO_2. Although it would be desirable to duplicate the temperature and pressure on Venus, the cost of fabricating such a system is prohibitive. Thus, because the ratio of test particle-to-atmospheric density is the primary parameter of concern for most experiments dealing with the physics of windblown grains, the approach opted for was using gases at lower pressures and ambient temperature. Furthermore, under VWT conditions the kinematic viscosity of the gas is approximately one half that on Venus, thus doubling the unit Reynolds number, which is an advantage when simulating certain aspects of aeolian activity on Venus such as saltation and other processes in which Reynolds number is important.

Carbon dioxide is used for most of the experiments simulating Venus. It is stored as a liquid at 20 bar and 250 K and is brought to operating pressure (~30 bar) and temperature (~295 K) using a heat exchanger and is then vented as a gas into the VWT. Nitrogen is also used in some experiments. It is supplied from a compressed gas storage chamber at 160 bar, then regulated to a lower pressure and vented into the VWT. In addition, air at 1 bar is used in the VWT for experiments to compare Venusian simulations with aeolian processes on Earth.

Gas temperature is monitored with a Leeds and Northrup Model 935 Numatron thermocouple system and type J (iron-constantine) thermocouples. The output signal is linearized with a model 939 auxiliary instrument and recorded on a two-channel strip chart recorder.

Wind Tunnel Calibration and Data Reduction

In order to determine the characteristics of gas flow through the test section, a floor plate containing a field of 22 pressure-sensing ports and an 18-port boundary-layer rake were installed. Ports from both the floor plate and the rake were connected with tubing to a Model J Scanivalve that shunted pressure from each port to a Barocel differential pressure transducer. The latter provided a signal for recording the pressures on a strip chart. Both the transducer and the Scanivalve system were located downstream from the test section in the corner of the wind tunnel to avoid interference with flow through the test section.

A second differential pressure gauge (Setra Systems Model 239), having a pressure sensitive range of 0 to 2.0 mb, was positioned behind the two Hexcel honeycomb screens following the first corner of the wind tunnel downstream from the fan. The pressure gauge was connected to a total head probe and a static pressure probe giving a differential pressure equal to the dynamic pressure in the reference section. The velocity determined from this dynamic pressure was compared with the velocity obtained with the calibration plate in the test section for a wide range of atmospheric densities and wind velocities. This system was used to determine wind speed in the test section when the calibration plate was replaced with the floor plates used in experiments.

The first series of calibrations involved flow over a smooth metal plate. However, because surface roughness affects both the boundary layer characteristics and the nature of particle motion, a second series of calibrations was also obtained for various "rough" surfaces. In this second series of calibrations, sandpaper with 30 to 80 μm diameter "grit" was glued to the floor to represent an immobile sandy surface of particles in the size range appropriate for aeolian entrainment on Venus. These data agreed well with theoretical data from smooth and rough surfaces.

A third series of calibrations was conducted over a floor on which an aeolian texture was generated. Prior to calibration, loose, 90 μm sand was mixed with a small amount of opoxy powder and spread uniformly over the floor plate. The plate was placed in the tunnel, and the tunnel was brought to venusian atmospheric density. The windspeed was gradually increased until saltation began and was held at this velocity for about one minute. The tunnel was stopped, returned to ambient pressure, and the plate removed. This surface, modified by the saltating particles, was fixed by heating the plate in order to set the epoxy. A boundary layer rake was then installed and the plate returned to the tunnel where wind velocity profiles were obtained for a wide range of wind speeds in venusian simulations. This was repeated for 700 μm sand.

An important parameter required to relate the wind speed at the centerline of the tunnel, u_∞, to the wind friction speed, u_*, is c'_f, the local coefficient of friction, which is defined as

$$c'_f \equiv \frac{\tau_o}{q} \qquad (2)$$

where τ_o is the surface drag per unit area parallel to the wind direction (called the surface shear stress) and q is the dynamic pressure, defined as

$$q \equiv \frac{1}{2} \rho_a u_\infty^2 \qquad (3)$$

where ρ_a is the atmospheric density.* Hence,

$$c'_f = \frac{2\tau_o}{\rho_a u_\infty^2} . \qquad (4)$$

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*Density was determined from the relationship

$$\rho_a = \frac{P}{ZRT}$$

where Z is the compressibility factor, P is pressure in psi, T is absolute temperature, and R is the universal gas constant. For the wind tunnel tests the charts of Reid et al. (1977) were fitted with the empirical equation

$$Z = 1 - (P/2228)$$

which is valid for T = 10° to 20°C, and P = 0 to 600 psi.

It is difficult to measure the surface shear stress directly, and τ_0 is therefore usually determined by indirect methods. One method is to measure the boundary layer velocity profile and relate this to shear stress by means of an assumed theoretical velocity profile. The rate of change of velocity with the logarithm of the height above the surface is proportional to u_* and is called the drag velocity or friction velocity, which is defined as

$$u_* \equiv (\tau_0/\rho_a)^{0.5} \tag{5}$$

Because the lower portion of the velocity-log height curve for mature turbulent boundary layers is nearly a straight line, u_* is constant and can be determined graphically. Then from (2) and (5), c'_f can be rewritten as

$$c'_f = 2(u_*/u_\infty)^2 \tag{6}$$

In practice, a difficulty arises in determining the correct fit of the slope and, because the quantity u_*/u_∞ is squared, small uncertainties in the slopes can result in larger uncertainties in values of c'_f. This potential problem can be overcome by obtaining several velocity profiles over the same surface at different velocities. The equation for the linear portion for all these profiles is fitted by the equation

$$u_z = 5.75\ u_*\ \mathrm{Log}\ \frac{y}{z_0} \tag{7}$$

where u_z is the velocity at height y above the surface and z_0 is the zero velocity height. This equation is known as the "law-of-the-wall" or the "universal velocity distribution" equation for rough-wall flows (Schlichting, 1968). The constant 5.75 is equal to logarithm base e divided by von Karman's constant and has been verified by numerous experimental tests. For all profiles over the same surface for fully developed turbulent boundary layers, the intercept z_0 will be nearly identical because z_0 is related to Schlichting's (1968) equivalent sand surface roughness, K_s, by the constant 30,

$$z_o = K_s/30 \ . \tag{8}$$

Thus, an average value for z_o can be determined from log profile slopes adjusted to intercept the abscissa at this value, and a consistent value for c'_f obtained, which increases with increasing velocity under present conditions. This procedure was followed for nine different velocity profiles over the same surface for the 90 μm test and 13 profiles for the 700 μm test and was compared with values of c'_f determined by the interpolation formula from Schlichting (1968),

$$c'_f = (2.87 + 1.58 \text{ Log } \frac{x}{K_s})^{-2.5} \tag{9}$$

where x is the distance from the leading edge of the plate, and K_s is given by (7). The "best" fit of data as determined by several analyses is presented in Figure 1. This can be fitted by the equation:

$$c'_f = 0.0012 \ u_\infty + 0.0052 \tag{10}$$

between $u_\infty = 0.40$ and 1.8 m/s and is 0.0074 for velocities above 1.8 m/s. The comparable value for Equation (9) is $c'_f = 0.0060$ for $K_s = 0.075$ cm ($z_o = 0.0025$ cm) for the 90 μm sand at a station 92 cm from the front edge of the plate. For 700 μm sand, $c'_f = 0.0067$, $K_s = 0.12$ cm, and $z_o = 0.0040$ cm.

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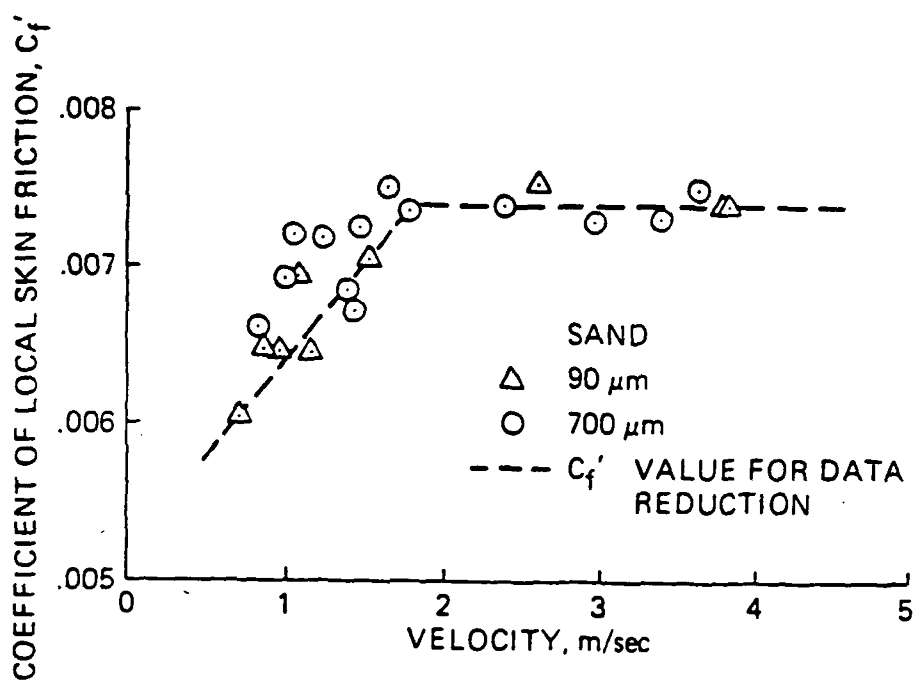

Figure 1 The experimentally-determined values of c'_f as a function of VWT velocity. Also displayed on the graph is the curve of Equation 9, which was used for surface shear stress determination.