DETERMINATION OF SURFACE SHEAR STRESS WITH THE NAPHTHALENE SUBLIMATION TECHNIQUE

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Introduction

Aeolian entrainment and transport are functions of surface shear stress and particle characteristics. Measuring surface shear stress is difficult, however, where logarithmic wind profiles are not found, such as regions around large roughness elements. Presented here is an outline of a method whereby shear stress can be mapped on the surface around an object. The technique involves the sublimation of naphthalene ($C_{10}H_8$) which is a function of surface shear stress and surface temperature.

The naphthalene sublimation technique is based on the assumption that the transfer of momentum, heat and mass are analogous. This assumption is known as the Reynolds analogy (see Kays and Crawford, 1980; Schlichting, 1979). If the Reynolds analogy can be shown to be correct for a given situation, then knowledge of the diffusion of one property allows the determination of the others. The naphthalene sublimation technique was developed for heat transfer studies (see Eckert, 1976) and can be readily applied to the determination of shear stress.

Analytical Framework

The naphthalene mass transfer coefficient, C_{mt}, is defined as

(1) $C_{mt} = q_{ns} / \rho_{ns}$

where q_{ns} is the mass transfer flux of naphthalene from the surface and ρ_{ns} is the density of naphthalene at the surface. Goldstein, et al. (1985) outline a procedure for determinining C_{mt} for naphthalene sublimation experiments.

A value of the heat transfer coefficient allows the calculation of the surface shear stress, τ_s. The Stanton number, St, is a dimensionless term defined as (Schlichting, 1979, p. 708)

(2) $St = C_{mt} / (\rho_a c_p U_\infty)$

where ρ_a is the atmospheric density, c_p is the specific heat of naphthalene and U_∞ is the freestream velocity. The local coefficient of skin friction, c_f, is also dimensionless and is defined as (Schlichting, 1979, p. 143)

(3) $c_f = \tau_s / (0.5 \rho_a U_\infty^2)$.

If the Reynolds analogy is acceptable, then St can also be expressed as (Schlichting, 1979, p. 708)

(4) $St = 0.5 c_f$

Combining Equations (2), (3) and (4) and solving for τ_s yields

(5) $\tau_s = (C_{mt} U_\infty) / c_p$

Shear stress is often expressed in terms of the friction velocity, u_*, which is defined as

(6) $u_* = (\tau_s \rho_a)^{0.5}$

Data Acquisition

The naphthalene sublimation technique requires information on the change in surface elevation, surface temperature of the naphthalene and freestream velocity during a wind tunnel run. The measurement surface is obtained by casting naphthalene in an aluminum mold. Surface heights are determined for points on a grid network before and after a wind tunnel run using a linear variable differential transducer mounted on an X,Y positioning device.

Surface temperature is monitored with a thermocouple embedded in the naphthalene with its tip near the surface. Average temperature during the wind tunnel run is used in the analysis.

The naphthalene sublimation technique was tested in the Arizona State University Planetary Geology Wind Tunnel. The tests involved eight wind tunnel runs during which the average sublimation depth (of twenty points) on the naphthalene surface was determined and the wind profile was measured during each run using a boundary layer rake.

The friction velocity was determined both from the naphthalene sublimation technique as described above and the wind profile. The profile data were reduced following a procedure outlined by Lettau (1957) to determine the aerodynamic roughness length, z_o, which was used in the logarithmic wind profile equation (Greeley and Iversen, 1985, p. 42)

(7) $u_* = (0.4\, u_z) / (\ln(z/z_o))$

where u_z is the wind speed at height z

Figure 1 shows the relationship between the two techniques for determining u_*. The naphthalene sublimation technique calculates u_* values one order of magnitude lower than the wind profile technique. This discrepency can be caused by a number of factors. The most likely are 1.) the wind profile is determined on the masonite wind tunnel floor while the naphthalene has a smoother surface, 2.) residue from silicon spray (used in the naphthalene casting) may reduce the sublimation rate, and 3.) the naphthalene surface temperature cannot be measured with a thermocouple; temperature just below the surface is measured.

The linear relationship between the friction velocity values calculated with the two methods (correlation coefficient = 0.99) allows the naphthalene sublimation data to be adjusted (by linear regression) to realistic values for the wind tunnel floor.

Conclusion

The naphthalene sublimation technique as outlined here is a reasonably accurate method for determining surface shear stress. Its most useful application is in determining the spatial variation of shear stress around objects where numerous point values are needed.

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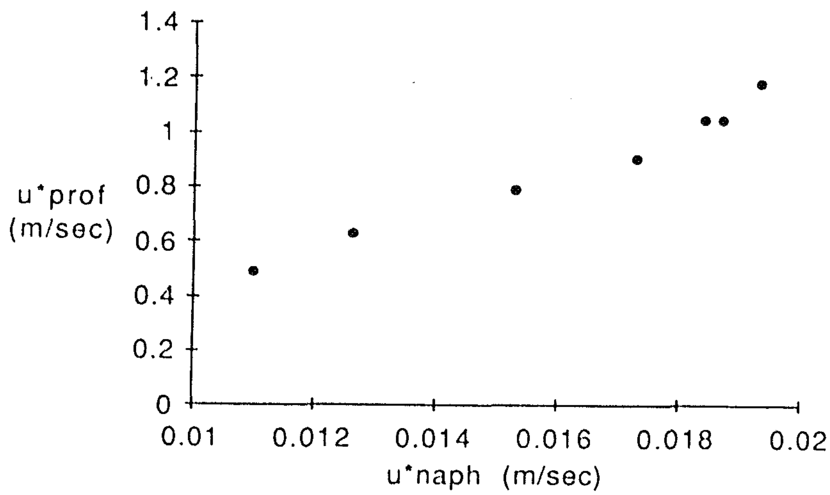

Figure 1. Friction velocity determined from naphthalene sublimation ($u_{*\,naph}$) and wind profile ($u_{*\,prof}$) during the same wind tunnel run.