Surface Roughness Effects on a Mach 6 Turbulent Boundary Layer

D. E. Berg*
Sandia Laboratories, Albuquerque, N.M.

Abstract

NEW data on the effect of surface roughness on the velocity defect and skin friction coefficient for a Mach 6 turbulent boundary layer are presented. All of the available compressible and incompressible data collapse when viewed as functions of the nondimensional equivalent sand-grain roughness height, but the correlation normally used to determine the equivalent sand-grain roughness is shown to be inappropriate for the current work.

Contents

The experiment was conducted in Leg II of the Graduate Aeronautical Laboratories, California Institute of Technology hypersonic wind tunnel. For this work, the two-dimensional, flexible nozzle was configured as a half nozzle with a freestream Mach number of 6. Surface roughness consisting of two-dimensional, transverse square bar elements with a wavelength-to-height ratio of 4 was introduced on the flat nozzle wall 64 cm downstream of the throat. Three roughness heights k were used, corresponding to $k/\delta = 0.015$, 0.029, and 0.058 where δ is the smooth wall boundary-layer thickness at the start of roughness. The present measurements were obtained in a region 25-67 cm downstream of the start of surface roughness, sufficiently far downstream to establish a fully developed equilibrium turbulent boundary layer on the wall. Nominal tunnel operating conditions for this experiment were $M_\infty = 6.0$, stagnation temperature $= 428$K, and stagnation pressure $= 1572$ KPa, which resulted in a freestream Reynolds number of 1.6×10^5/cm. The tunnel wall temperature was adiabatic.

Skin friction was measured with a balance and detailed pitot pressure and total temperature boundary-layer surveys were obtained. The resultant velocity profile data were then cast into an "equivalent incompressible" form through the application of a modified Van Driest I transformation in which curve fits of the actual temperature-velocity relation were used. Following this transformation, the velocity profile data were correlated using the incompressible form of the rough-wall law of the wall to determine the skin friction coefficient and the nondimensional velocity defect, $\Delta u/u_\tau\ (= \Delta u \sqrt{\rho_w/\tau_w})$. The details of the data reduction and the transformation and correlation procedures may be found in Ref. 1.

Compressible and incompressible velocity defect data are plotted in Fig. 1 as functions of

$$k_s^+ = k_s \sqrt{\frac{\tau_w}{\rho_w}} \Big/ \nu_w$$

where k_s is the height of Nikuradse's sand-grain roughness required to produce the same velocity defect in the "fully rough regime" ($k_s^+ > 70$). The use of k_s^+ as the abscissa effects the collapse of the data into a single, well-defined curve.

If the available skin friction data are plotted vs k_s+, they too collapse into a single, well-defined curve, as shown in Fig. 2. With the correlations of Figs. 1 and 2, the effect of surface roughness for a given flow (compressible or incompressible) may readily be determined once k_s/k is known.

Dirling[2] has developed a low-speed effective roughness correlation which is presented in Fig. 3 where λ is the effective wavelength-to-height ratio of the roughness and k is the actual roughness height. This correlation is often used to determine the effective roughness of a surface for compressible as well as incompressible flows. Also shown in Fig. 3 is the value of k_s/k determined for the present work. The Dirling correlation value of 3.9 for $\lambda = 4$ is three times the value of 1.3 found in this work, a very poor approximation. Although this correlation has been successfully applied to

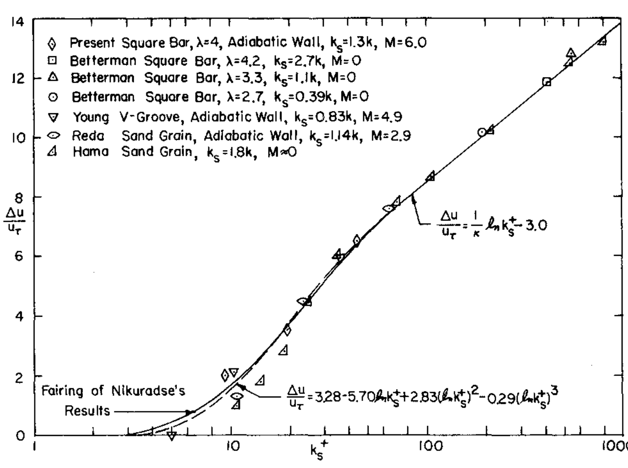

Fig. 1 Rough wall velocity defect correlation.

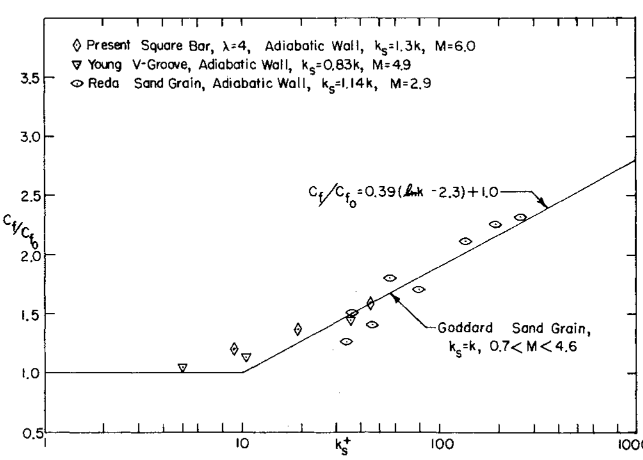

Fig. 2 Rough wall skin friction ratio correlation.

Presented as Paper 78-1159 at the AIAA 11th Fluid and Plasma Dynamics Conference, Seattle, Wash., July 10-12, 1978; synoptic received March 8, 1979. Full paper available from AIAA Library, 555 W. 57th Street, New York, N.Y. 10019. Price: Microfiche, $2.00; hard copy, $5.00. **Order must be accompanied by remittance.**

Index categories: Boundary Layers and Convective Heat Transfer—Turbulent; Supersonic and Hypersonic Flow.

*Member of Technical Staff, Experimental Aerodynamics Division. Member AIAA.

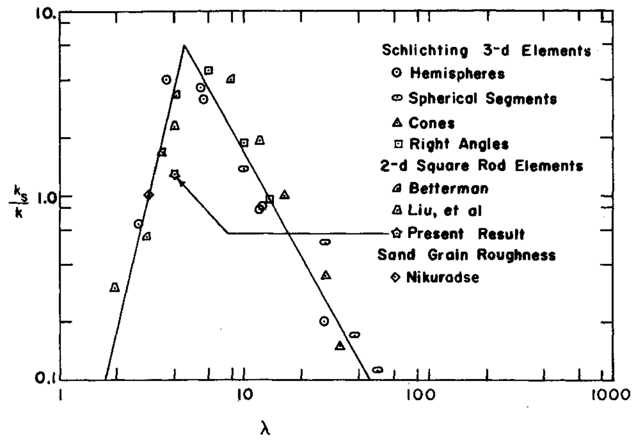

Fig. 3 Low-speed effective roughness correlation (from Ref. 2).

some roughnesses in compressible flow, it does not work for the presented distributed roughness, and it obviously cannot be indiscriminately used for all roughnesses in compressible flow.

Skin friction and velocity defect data were obtained for a distributed surface roughness at a Mach number of 6. The available surface roughness data can be correlated as a function of nondimensional equivalent sand-grain roughness height, but the available correlations for equivalent roughness heights are not applicable to the current type of roughness in compressible flow. Additional work is required to determine the equivalent roughness correlation applicable in the compressible regime.

Acknowledgment

This work was supported by the U.S. Department of Energy and the U.S. Army Research Office.

References

[1] Berg, D.E., "Surface Roughness Effects on the Hypersonic Turbulent Boundary Layer," Ph.D. Thesis, California Institute of Technology, 1977; also, SAND77-0587, Sandia Laboratories, Albuquerque, N. Mex., Sept. 1977.

[2] Dirling Jr., R.B., "A Method for Computing Rough Wall Heat Transfer Rates on Reentry Nosetips," AIAA Paper 73-763, Palm Springs, Calif., July 1973.