(1). Some data[2,3,8] have been examined to determine whether a universal similarity exists for these profiles, but the results are inconclusive.

The results of this investigation imply that the Howarth transformation may be employed to reduce all fully developed jet velocity data to a common scale if a spreading constant that is a function of the Mach number is employed. It is possible this constant is simply related to the ratio of nozzle static and total enthalpies.

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Some Effects of Surface Roughness on the Turbulent Boundary Layer

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It is well known that the turbulent boundary layer is sensitive to surface roughness.[1] The increase in skin friction due to various types of surface roughness is reviewed concisely in Ref. 2. This note describes the results of measurements of the effects of a special type of surface roughness peculiar to woven-wire porous materials on some overall characteristics of the turbulent boundary layer such as skin friction and boundary-layer growth, as well as on the detailed structure of the boundary layer such as the velocity and shear stress distributions throughout the boundary layer. This type of porous materials frequently is used in investigations of mass-transfer cooling and many recent engineering applications.

In fabricating the porous material, the weaving and calendaring processes resulted in the formation of regular triangular depressions in its surface of about 0.005 in. to the side and approximately of the same depth. A sheet of the material was rolled into a 2-in.-o.d. circular cylinder and fitted with a suitable nosepiece and afterbody. The assembly, with its axis parallel to the tunnel air stream, was mounted in the 1- × 2-ft low-speed wind tunnel of the Heat Transfer Laboratory. The model, apparatus, and nomenclature are described in detail in Ref. 3. Velocity profiles were measured at various axial locations, from which the boundary layer thickness, displacement thickness, and momentum thickness were determined. By extrapolating these thicknesses to zero, the effective starting point of the boundary layer was

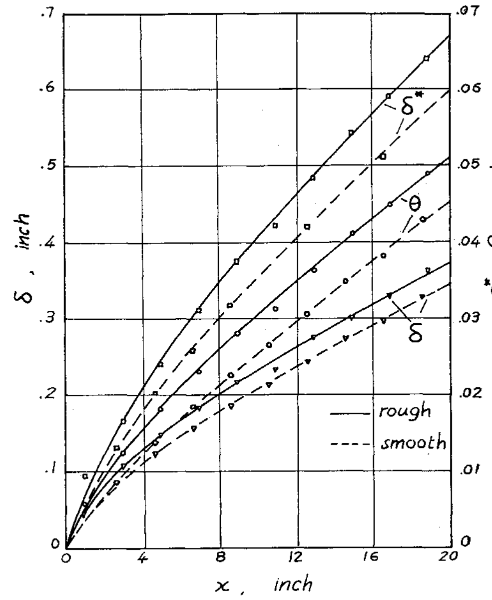

Fig. 1 Boundary layer growth.

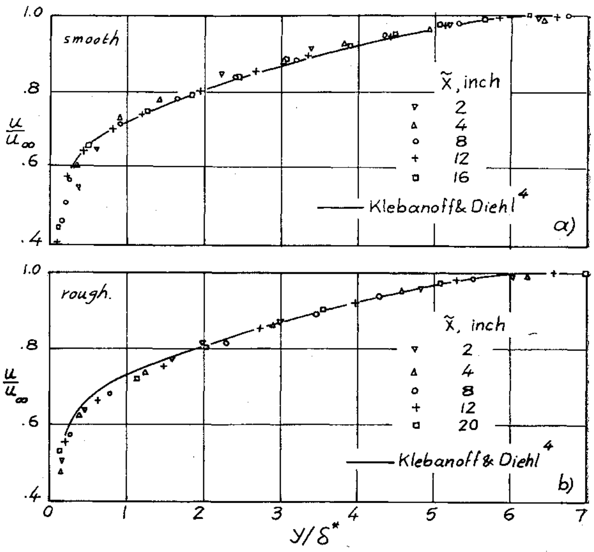

Fig. 2 Velocity profiles.

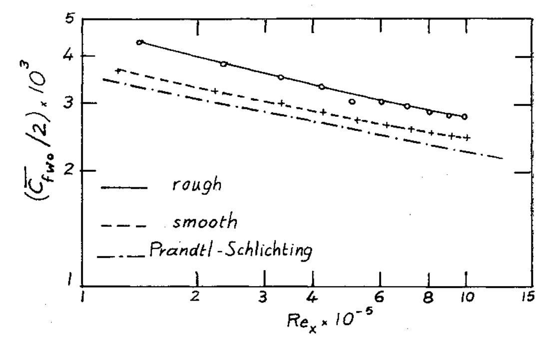

Fig. 3 Average skin friction.

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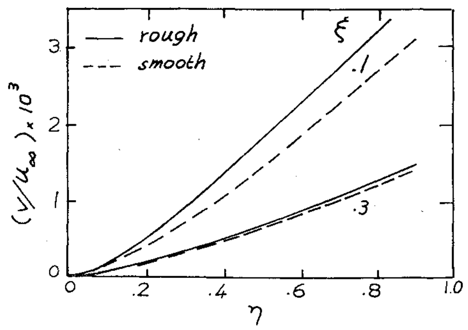

Fig. 4 Distribution of radial velocity component.

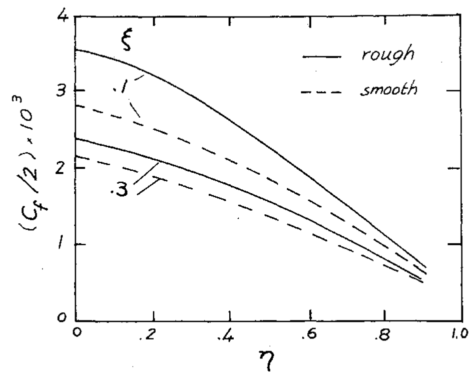

Fig. 5 Distribution of shear.

located. By means of appropriate mass and momentum balances, the skin friction and the distributions of the radial velocity component and the shear stress throughout the boundary layer were calculated.[3] The foregoing procedure was repeated on an identical cylinder but having a smooth surface. Freestream conditons were about the same in both cases, including a velocity of 104 fps and a Reynolds number per inch of 4.7×10^4. By comparing the results of measurements on the rough and smooth cylinders, the effects of surface roughness could be distinguished.

From Fig. 1, surface roughness increases all boundary-layer thicknesses by up to 15%. The percentage increase is more pronounced near the forward part of the model than toward the end. This agrees with the fact that roughness effects should decrease along the model, since the magnitude of the surface depressions relative to the boundary-layer thickness decreases due to boundary-layer growth along the model.

Figures 2a and 2b show the axial velocity profiles for the smooth and rough cylinders, respectively. Both agree closely with the Klebanoff and Diehl profile[4] for a smooth flat plate, except that near the rough wall the velocity is somewhat smaller than the smooth wall for a given value of (y/δ^*).

The average skin friction for the rough and smooth cylinders is compared in Fig. 3. It is seen that surface roughness increases the skin friction by up to about 15% and that its effect tends to diminish along the cylinder. Also, the skin friction for the smooth cylinder appears to be in satisfactory agreement with the Prandtl-Schlichting relation for a smooth flat plate, indicating that transverse curvature effects are neglible. This conclusion agrees with the predictions of transverse curvature effects in Ref. 5. The foregoing remarks also apply to the local skin friction.

Because of the cylindrical geometry, the distributions of the radial velocity and shear throughout the boundary layer depend on the boundary-layer thickness relative to the cylinder radius. Both distributions are shown in Figs. 4 and 5, respectively. Surface roughness increases the radial velocity component for a given boundary-layer thickness and distance from the wall. The percentage increase becomes smaller as the boundary layer grows, i.e., as the ratio of the depressions relative to boundary-layer thickness diminishes. Similar observations apply to the shear.

It may be concluded that relatively small values of surface roughness of the order reported here cause substantial increases in the thickness of the turbulent boundary layer and skin friction. Furthermore, surface roughness effects extend throughout the entire boundary layer and, in particular, modify the distributions of the radial velocity component and the shear.

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Blowing Effects on Pressure Interaction Associated with Cones

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The injection of mass (blowing) into a boundary layer through means of ablation or forced injection can significantly alter the character of the boundary layer. The general effects are well known: alteration of boundary-layer profiles, increase in boundary-layer thickness, and reduction in skin friction and heat transfer. This analysis will be concerned with only one aspect of the blowing phenomena, namely, the pressure interaction on a cone possessing a boundary layer with ablation-type blowing. Presently, there are no closed-form analytical methods for predicting the pressure interaction with blowing similar to that given by Probstein[1] for the no-blowing case. An extension of the technique used by Probstein to define the pressure interaction with blowing satisfactorily in terms of an analogous interaction parameter seems unlikely. An available and rigorous approach is to solve the conventional boundary-layer equations and additional species equation, all equations being coupled through the thermodynamic and transport properties of the gaseous mixture.

Thus, an accurate description of the boundary layer is obtained, and, from this boundary-layer solution, the pressure interaction can then be calculated. This will be the general procedure to be followed in this analysis.

Figure 1 illustrates the flow-field model. Applying the continuity equation to the axisymmetric boundary layer gives

$$\frac{V_e}{U_e} = \frac{\rho_w V_w}{\rho_e U_e}\left(\frac{1}{1+(\delta/r)}\right) + \frac{d\delta}{dx}\left[1 - \left(\frac{1}{1+(\delta/r)}\right)\right] + \frac{d\delta^*}{dx} - \frac{\delta - \delta^*}{\rho_e U_e r}\,\frac{d}{dx}(\rho_e U_e r)$$

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