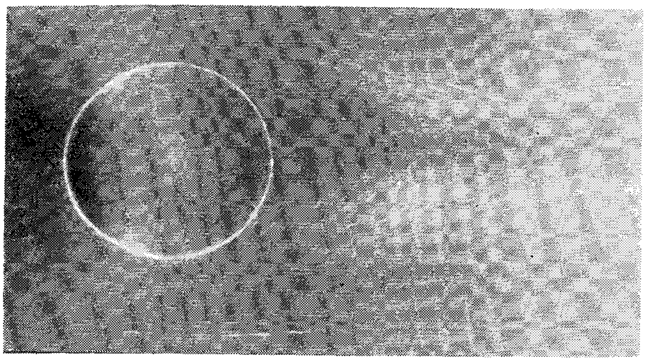

Fig. 3 Flow pattern around the sphere at the same speed when current density is increased to 0.111 amp/cm².

graphs taken under these conditions were not satisfactory. The maximum amount of current which could be passed through the fluid was limited by the kind of electrolytic liquid chosen for the experiment.

Working with a rubber sphere, however, we found that there was no appreciable change in the flow pattern after currents of various amount were passed through the liquid. Because of the limitation of equipment on hand, direct measurement of total drag was not attempted.

It was found analytically that an aligned electric current decreases the drag of a sphere moving in a fluid which is less conducting than the sphere, and increases the drag if the fluid is more conducting, based on a purely hydromagnetic formulation.[3]

The effect of electromagnetic force on flowfield is characterized by the magnetic pressure number R_h. It is the ratio of the magnetic pressure $\mu_e J_o^2 a^2/2$ over the dynamic pressure $\rho U_o^2/2$, where ρ and μ_e are the density and the magnetic permeability of the fluid, a and U_o are the radius and the velocity of the sphere, and J_o is the uniform current density far from the body. Corresponding to the experimental conditions in Fig. 3 the calculated magnetic pressure number is 0.002, which gives only a negligibly small effect on the flow according to that theory, although the result in the laboratory for a copper sphere agrees qualitatively with what was predicted. It was shown in that theoretical work that appreciable effect appears in the flow if R_h is of the order of 10^{-1}, which is two orders higher than our experimental value.

From these findings it appears that the large change in the wake is not caused by the electromagnetic force $\mathbf{J} \times \mathbf{B}$, and that some other important factors must be included in the analysis when an electrolyte is used as the conducting fluid. One of them could be the electrochemical reactions discussed by Levich,[4] which takes place in a thin diffusion boundary layer along the surface of a conducting body when it moves in a current-carrying electrolytic fluid. This view is supported by the fact that the current which can change the flow around a copper sphere apparently does not affect that around a rubber sphere, at whose surface electrochemical reactions do not occur. The reactions may change the current distribution or may effectively alter the viscosity coefficient of the electrolyte. Exactly how these electrochemical reactions influence the flowfield is not yet clear, and the observed phenomenon still requires an appropriate explanation.

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Measurements of Local Skin Friction Downstream of Grit-Type Boundary-Layer-Transition Trips at $M = 2.17$ and Zero Heat Transfer

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Introduction

WIDE use has been made of grit-type boundary-layer transition trips during small-scale-model wind-tunnel drag-evaluation tests to artificially promote boundary-layer transition from laminar to turbulent flow near the leading edges of various model components. Reference 1 shows that for supersonic Mach numbers the minimum grit size required to artificially fix transition near the trip is large relative to the boundary-layer thickness; a grit with diameter approaching the boundary-layer thickness is the minimum requirement at a Mach number of 3, while a grit diameter twice the boundary-layer thickness is indicated for a Mach number of 4. It is pointed out in Ref. 2 that the use of relatively large-sized ("over three times as high as the boundary-layer thickness") grit-type transition trips can either decrease or increase the local skin friction downstream of the trip. The present authors are unaware of any studies of local skin friction behind relatively large-sized grit-type-transition trips which would explicitly justify their use to promote boundary-layer transition. The data presented herein are an initial effort by the authors to validate the use of grit-type boundary-layer transition trips and to determine limitations and interpretive procedures applicable to the technique. Although these data are very preliminary, it is felt that the results will be of interest to researchers conducting wind-tunnel drag evaluations on small-scale aircraft configurations.

Skin-Friction Measurements

Presented herein for various unit Reynolds numbers (R/x, per in.) are local skin-friction coefficients, c_f, measured downstream of several sizes of grit-type boundary-layer-transition trips on a flat plate with zero heat transfer. The measurements were made in the Ames 1- by 3-ft. Supersonic Wind Tunnel at a freestream Mach number of 2.17. The plate had a sharp leading edge and was mounted in the wind tunnel with nominal values of zero sweep and zero incidence. The friction coefficients were determined from direct measurements of local shear forces on a floating element balance manufactured by the Kistler Instrument Corporation. The 0.500-in.-diam floating element of the balance was located 5.875 in. behind the leading edge of the plate and was centered by means of a self-nulling circuit for each measurement. In conformance with manufacturer's specifications, no cooling of the balance jacket was required since tunnel total temperature did not exceed 100°F. Grit-type transition trips were formed by $\frac{1}{8}$-in. wide bands of randomly distributed grit of a specified size located $\frac{1}{4}$ in. behind the leading edge of the plate. Grits were sieved for uniformity and accuracy in sizing. In addition to the grit trips, a trip consisting of 0.0146-in.-high triangular-shaped roughness particles cut from adhesive tape (discussed in Ref. 2) was also tested.

Results and Discussion

The results of these tests, including measurements made with natural transition, are presented in Fig. 1. To aid in interpreting the data, the figure also includes values of skin

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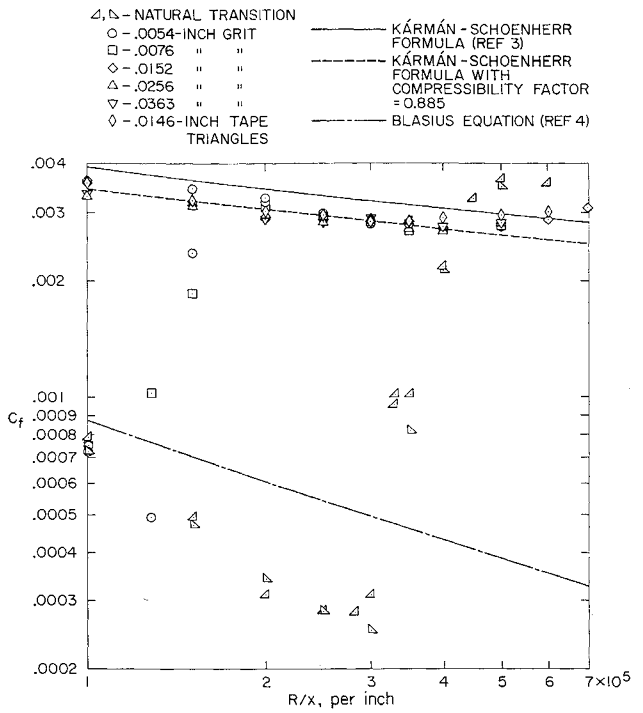

Fig. 1 Local skin friction (measured 5.875 in. behind the leading edge of plate) for various unit Reynolds numbers.

friction obtained from the incompressible Kármán-Schoenherr formula,[3] and from the formula modified by a compressibility factor of 0.885, together with laminar flow values obtained from the Blasius equation.[4]

It is interesting to note the consistency and character of these data. The data indicate that natural boundary-layer transition from laminar to turbulent flow occurred behind the floating element for $R/x \leq 3 \times 10^5$. The discrepancies between these laminar data and the Blasius curve are probably associated with the fact that, for the laminar data, the output signal from the friction balance was less than 8% of the manufacturer's full-scale rating; balance selection for these tests was based on the necessity of measuring the higher skin-friction values associated with all-turbulent flow. The "overshoot" of c_f at $R/x \geq 5 \times 10^5$ shows that natural transition occurred a short distance forward of the floating element. Similarly, the data indicate that the smaller sized (0.0054 and 0.0076 in.) grit-type trips were effective in producing all-turbulent flow only if $R/x > 2 \times 10^5$. However, the tape triangles and the larger sized (0.0152 in. and larger) grit transition trips produced essentially the same c_f for any particular test Reynolds number. For $R/x \leq 4 \times 10^5$ the results from these larger sized trips agree well with the Kármán-Schoenherr formula modified by the 0.885 compressibility factor. For $R/x > 4 \times 10^5$ the measurements downstream of the trips indicate friction coefficients that are not only greater than the compressible Kármán-Schoenherr values but even larger than the incompressible values. Recalibration of the balance at the conclusion of the tests failed to reveal any nonlinearities which would explain these results at the higher Reynolds numbers.

Several conclusions as to trip effectiveness and influence on local skin-friction coefficient can be drawn regarding the ratio of the grit size, k, to the boundary-layer thickness, δ (evaluated at the trip position by the method of Ref. 5). First, it can be concluded that the grit size has to be approximately the thickness of the boundary layer in order to be effective as a trip in producing all-turbulent skin friction. At $R/x = 2 \times 10^5$, k/δ is 0.8 and 1.1 for $k = 0.0054$ and 0.0076, respectively. Second, there is no apparent indication of a limitation on the k/δ ratio once all-turbulent skin-friction levels are developed at the floating element. In this study at $R/x = 4 \times 10^5$ the measured skin-friction coefficients are essentially the same although k/δ varied from 1.1 to 7.5. Third, the relationship between the distortion of the boundary layer due to the use of large-size grit-type transition trips and the skin friction downstream of the trips is not clearly evident from these results since the transition-fixed values differed from the desired all-turbulent skin-friction values only at the higher Reynolds numbers. However, the lack of dependence of the measured skin friction upon the grit size used to induce transition lends encouragement to eventual verification of the test technique applied to drag evaluation studies—provided a clear-cut means can be determined to account for the pressure drag of the trip elements.

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High Mach Number Viscous Flow past a Cylinder

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LIGHTHILL[1] demonstrated the existence of a similar solution, in the inviscid approximation, of the flow in the region between a spherical shock wave and the (corresponding) body when the upstream Mach number is infinite and (consequently) the variations of density in this region are negligible; the stream function in this case is the sum of powers of the radial distance. Later, Whitham[2] extended this study to the case of a cylindrical shock-wave and obtained the solution in terms of (modified) Bessel functions. For the case of the spherical shock wave, Oberai[3] incorporated the effects of the (viscous) boundary layer near the body surface by expanding various flow variables in powers of $\mathrm{Re}^{-1/2}$ $(= \epsilon)$ and obtained terms up to the order ϵ^2 (as explained in the section entitled "fully viscous flow" of this Note, calculation of these terms necessitates correcting the Rankine-Hugoniot relations). In this Note are reported the corresponding results for the case of a cylindrical shock-wave.

Procedure and Results

Velocity (components) and density are nondimensionalized with respect to the upstream values and distances with respect to a, the nose radius of the corresponding body. The upstream Mach number is assumed to be very large ($M_\infty^{-2} \ll 1$), the density in the shock layer (the region between the shock

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