

Fig. 3 Variation of outer mixing length with Reynolds number.

Figure 3 shows experimental values of $(l/\delta)_{\text{MAX}}$ for two-dimensional turbulent boundary layers^{2,3,5} compared with calculations from Eq. (4) for $k=0.43$ (shown in Ref. 2 to fit the hypersonic helium data) and y_L^+ values of 50, 60, and 70. It can be seen that for $\delta^+ > y_L^+$ Pletcher's model predicts an increase in mixing length as δ^+ decreases, in agreement with the trend of the data. More extensive data may show that y_L^+ is a function of T_w/T_t , as implied by the data; however, the available experimental data are too sparse to say whether or not this is true.

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Detection of Boundary-Layer Transition Using Holography

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THIS Note presents some preliminary findings on the application of holography to the measurement of boundary-layer transition on a sharp tip, axisymmetric cone at zero angle of attack in a hypersonic, high Reynolds number flow. A pulse ruby laser is used in a modified, off axis, single pass schlieren system to record the holograms (Refs. 1-4), and both holographic schlieren and dual plate holographic interferometry are used to observe the transition phenomenon.

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Figure 1 shows typical results obtained for tests conducted in the Air Force Flight Dynamics Laboratory Mach 6, high Reynolds number wind tunnel. The schlieren photograph reveals pronounced changes in the boundary-layer thickness along the upper surface of the cone, and the circled region contains what the author believes is a turbulent burst. The accompanying interferogram is constructed from the same hologram of this flow so that direct correlation can be made between changes in the fringe pattern with changes visible in the schlieren photograph. Point-by-point comparisons show that as the boundary-layer thickness increases, the fringes appear to pull away from the wall and that the angles between the fringes and the surface of the cone increase. Since the density gradient is steeper and the boundary-layer thickness is greater for a turbulent boundary layer than for a laminar boundary layer, light waves traversing a turbulent boundary layer experience more refraction and greater phase shifts, and this means there are characteristic fringe patterns associated with each state of the boundary layer. Hence, it is possible to perform a fringe-by-fringe survey of an interferogram to locate precise points where the boundary layer is changing states. Examples of these characteristic fringe patterns are observable in Fig. 1 particularly in the enlargement of the burst, and from a fringe-by-fringe analysis, another burst can be identified (indicated by the arrow on the interferogram) on the lower surface of the cone. The burst on the lower surface appears to be considerably smaller than the one in the enlargement and, as measured from the interferogram, the smaller burst is approximately 4.25 mm long and 0.64 mm thick. The laminar boundary-layer thickness on both sides of this burst measures 0.24 mm. Thus far, for the general conditions of Fig. 1, bursts have been observed at distances measured from the cone tip which correspond to Reynolds numbers of 4.5-9.0 million, and the formation of the fully turbulent boundary layer occurs consistently at Reynolds numbers of 8-9.5 million. These results agree with those of other researchers investigating boundary-layer transition on similar configurations in similar flow fields.⁵

For this investigation, the ruby laser is adjusted to emit a light pulse that is approximately 35 nanoseconds in duration. This pulse represents the period during which the boundary layer is recorded in a hologram, and by assuming that the frequency of the boundary-layer instabilities has a much greater period, each hologram is an instantaneous measurement of the flow. The validity of this assumption can be determined by comparing representative periods of the boundary-layer instabilities to the period of the laser pulse. As discussed by Reshotko (Ref. 6), the nondimensional frequency, $\beta\nu/U^2$, is the relevant frequency parameter to use when boundary-layer instabilities are considered. In this parameter, U and ν are, respectively, the velocity and kinematic viscosity evaluated at the edge of the boundary layer ($U=3345$ fps, $\nu=1.508 \times 10^{-4}$ ft²/ps), and β represents the characteristic angular frequency of the disturbance spectrum ($\beta=2\pi f=2\pi/\tau$, where τ is the period). Precise values of β are not known for this investigation, but from the Mach 5.8 data of Demetriades,⁷ representative values of the nondimensional frequency can be used in conjunction with U and ν to determine an approximate period for the boundary-layer instabilities. This period is in the range of 1.7-8.5 microseconds, which is approximately three orders of magnitude longer than the period of the laser pulse. Hence the assumption that the holograms contain instantaneous measurements of the boundary layer is reasonable.

The intent of this holographic application is to obtain new and unique boundary-layer measurements of the transition process, but difficulties arise when an attempt is made to define the structure of the burst solely from the optical data. From the results of Fig. 1, one can see that the boundary layer is not axially symmetric near or in a burst, and because multi-viewing is not feasible for the facility currently being used, correct orientation of the bursts is not known. Many different

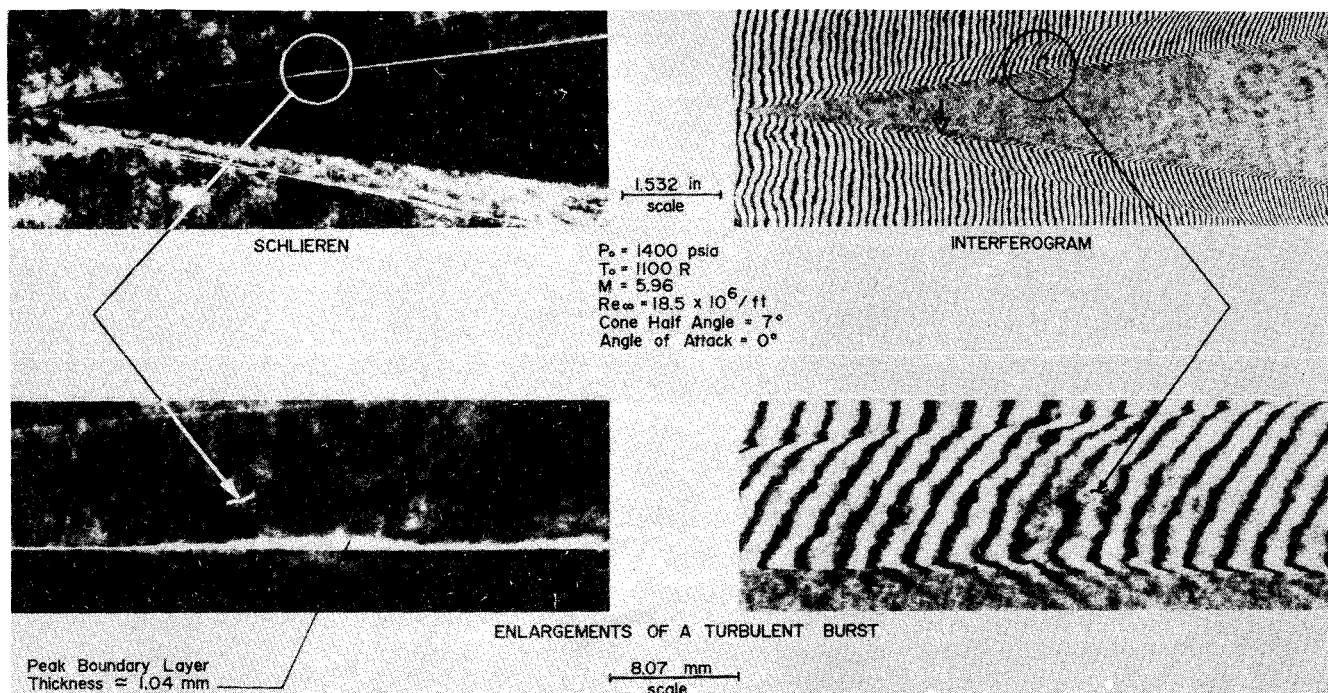


Fig. 1 Holographic Schlieren and interferometric depiction of boundary-layer transition on slender sharp tip cone.

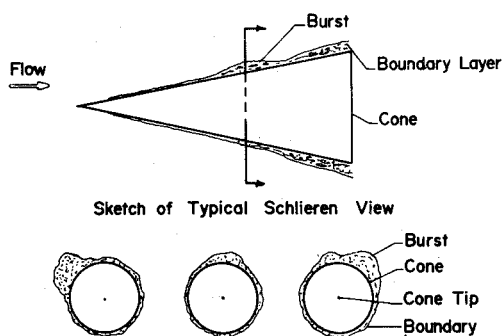


Fig. 2 Illustration of possible orientations of a turbulent burst on a slender sharp tip cone at zero angle of attack. Note the different cross-sectional views of possible burst configurations that could produce the optical effect illustrated above.

shapes could produce the optical results shown in Fig. 1, and some possibilities are illustrated in Fig. 2. Although these cross sections are imaginative, they illustrate that a single view of a burst is inadequate for obtaining a complete description.

A second objective of this holographic application is to obtain density data from the interferometric measurements, but since the geometry and orientation of the bursts are unknown, flow symmetry cannot be assumed, which means the data reduction schemes normally used may be inappropriate. However, the limitations of the data reduction schemes cannot be determined at this time because no quantitative results are available for detailed analysis. Density profile data have not been obtained because precise fringe measurements cannot be made with the existing equipment.

These holographic measurements offer a means to investigate the fundamental structure of boundary-layer turbulence and transition. Acquiring instantaneous measurements of the bursting phenomenon offers the additional possibility to obtain insights on the fluid mechanics resulting in transition. New apparatus are being built to overcome the inadequacies of the existing equipment, and when completed, the new equipment will be used to reinvestigate the cone study shown in Fig. 1, and to boundary layers on other geometries both at zero and small angle of attack.

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Unsteady Aerodynamic Modeling for Arbitrary Motions

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Introduction

UNSTEADY aerodynamic loads due to arbitrary stable motions are of interest in the application of active control techniques to flexible vehicles. These studies are well

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