JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 29, No. 2, March-April 1992

Liquid Crystal Coatings for Surface Shear-Stress Visualization in Hypersonic Flows

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Experiments were conducted to test the surface shear-stress visualization capabilities of shear-stress-sensitive/temperature-insensitive liquid crystal compounds in hypersonic flow. Liquid crystal coatings were applied to the surface of a conical model, which was then exposed to a high unit Reynolds number (2.3×10^7/m) Mach 5 flow. The coating was illuminated by white light, and its response to the various flow situations was monitored and recorded with standard video and high-speed movie cameras. Abrupt changes in surface shear stress (e.g., a transition front) are made visible by an abrupt change in the color of the liquid crystal coating. The dynamic location of such a color change front as a function of model angle of attack (for sharp and blunt cones, with and without boundary-layer trips) was recorded, and observations were found to be consistent with established (published) trends for transition-front movement on conical bodies exposed to hypersonic flows. The highly transient flow over the model during tunnel shutdown was recorded (at 400 frames/s), and the liquid crystal coating was observed to respond to an event reasoned to be normal shock passage in a time interval less than or equal to the time between sequential movie frame exposures (≤ 0.0025 s). The liquid crystal technique has thus been demonstrated as a viable diagnostic tool for use in transient/compressible flows.

Nomenclature

L	= body length along centerline
M_∞	= freestream Mach number
Re_∞	= freestream unit Reynolds number
R_n	= nose-tip radius
t	= time
X	= axial distance from tip along centerline
α	= angle of attack
τ	= surface shear stress

Introduction

THE problem of boundary-layer transition to turbulence in hypersonic flow environments remains of critical concern to designers of high-speed flight vehicles. Thermal protection and aerodynamic stability/control issues for such vehicles require that the state of the boundary layer (laminar vs turbulent) be known with some degree of confidence throughout the system's operational envelope. Theoretical/numerical prediction capabilities for hypersonic boundary-layer stability and breakdown to turbulence are, at present, insufficiently advanced to meet such design goals. As a consequence, significant emphasis is still placed on experimental investigations and associated empirical/semiempirical correlations in order to model this complex phenomenon. A diagnostic technique that provides an areal visualization of the presence and instantaneous location of high-surface shear-stress zones (e.g., transition) in dynamic hypersonic flowfields, with a response that is rapid, continuous, and reversible, would thus prove to be a most valuable research and testing tool. The objective of the present effort was to investigate the feasibility and capabilities of shear-stress-sensitive/temperature-insensitive liquid crystal coatings to meet this need.

Received June 14, 1990; presented as Paper 90-1513 at the AIAA 21st Fluid Dynamics, Plasma Dynamics, and Lasers Conference, Seattle, WA, June 18-20, 1990; revision received Nov. 13, 1991; accepted for publication Jan. 9, 1992.

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Liquid crystals are highly anisotropic "fluids" that exist between the solid and isotropic liquid phases of some organic compounds.[1] As such, they exhibit optical properties characteristic of a crystalline (solid) state, while displaying mechanical properties characteristic of a liquid state. In flow-visualization applications, a mixture of one part liquid crystals to five parts solvent (presently, Freon) is sprayed on the aerodynamic surface under study. A smooth, flat-black surface is essential for color contrast, but no other special surface preparation is required. Recommended applications (after spray losses) are ≈ 10 ml liquid crystals, measured prior to mixing with the solvent, to each square meter of surface area. The solvent evaporates, leaving a uniform thin film of liquid crystals whose thickness, based on mass conservation and estimated spray losses, is approximately 10 μm (0.0004 in.). The liquid crystal coating selectively scatters incident white light as discrete colors. This behavior is traced to the molecular structure of the compounds, a helical structure whose characteristic pitch length falls within the wavelength range of the visible spectrum. For thermochromic liquid crystals, the two primary factors that influence this molecular structure (and, thus, the light-scattering response of the liquid crystal coating) are temperature and surface shear stress.

Klein[2] used the temperature response of thermochromic liquid crystals in high-speed/compressible flows in attempts to measure surface temperature contours from which transition locations could be inferred. Efforts to decouple the influences of temperature and shear stress and to make quantitative measurements of shear stress under isothermal flow conditions were difficult and generally not productive.[3] Further attempts to utilize liquid crystal coatings in fluid mechanics research were thus delayed until the recent investigations by NASA Langley researchers,[4] who successfully applied this technique as a qualitative shear stress (boundary-layer transition) indicator in subsonic flight tests of airplanes, i.e., under incompressible, isothermal, steady-flow conditions. Oscillating airfoil experiments were subsequently conducted by Reda[5] to test the frequency response of thermochromic liquid crystal coatings to unsteady surface shear stresses in incompressible, isothermal flows.

Hall et al.[6] recently applied this technique to flat-plate transition experiments conducted at low supersonic speeds ($1.5 \leq M_\infty \leq 2.5$). Quoting from Ref. 6:

> The crystals were prepared so that the temperature range at which their color changed was above the temperatures seen in the experiment. Consequently, the crystals were only responding to differences in the applied shear stress and had sufficient frequency response to reflect tunnel unsteadiness in turbulent wedges initiated by model defects or sand grit. Also, the crystals illustrated apparent movement in the position of natural transition.

Results obtained in Hall et al.'s[6] experiments showed that "liquid crystal coatings and infrared photography both gave indications of boundary-layer transition before the intermittency factor reached 0.5, as measured by (flush-mounted, heated) thin films." These results showed that transition-front locations measured with the liquid crystal technique were consistent with such measurements made by using other (more established) techniques. Hence, liquid crystal coatings are nonintrusive when properly applied.

Very recent advances in liquid crystal technology have now led to the formulation of compounds that display no temperature response over broad temperature regimes; for these mixtures, color changes result solely in response to applied shear stress, making them potentially more suitable for flow-visualization applications. Details of the mixtures used in the present research are available from the manufacturer (see Ref. 7). Coatings of such compounds were successfully utilized by Reda and Butterfield[8] and Reda[9] in low-speed, unsteady-flow environments. The temperature insensitivity of such coatings (below the crystal melt temperature of 50°C) motivated attempts to apply them to compressible flow environments. It was unknown, however, at the outset whether the liquid crystal compound selected would be compatible with the transition shear-stress levels in the Mach 5 flow (different formulations require different threshold levels of shear stress to induce color change).

A comment concerning the use of liquid crystal coatings to measure surface shear stresses is in order. As noted earlier, attempts to calibrate the color vs shear-stress relationship of a given liquid crystal compound were undertaken by Klein and Margozzi.[3] In this technique, the absolute color (for a given shear stress) seen by the observer (or recording device) is a function of lighting and view angles (with dependence changing from a minor effect at near-perpendicular view angles to a major influence at highly oblique view angles). Therefore, transformation of any such calibration curve from a calibration apparatus to an aerodynamic test facility results in significant uncertainties, especially for complex surface contours. The only viable approach to using liquid crystal coatings for quantitative measurements of surface shear-stress values thus requires an in situ calibration. For fixed lighting and viewing angles, reflected color (wavelength of light) must be related to surface shear-stress values measured by a separate, reliable, independently calibrated instrument, e.g., a Preston probe, a skin-friction balance, or a traversable hot-wire probe (for velocity profile measurements). References 10–12 report on pioneering activities in this area for low-speed through transonic-flow applications. In the present exploratory investigation at Mach 5, no such calibration of the liquid crystal coating was attempted.

Experimental Approach

The model employed in the present research was a cone of 6.5-deg half-angle, 0.356-m frustum (afterbody) length, and base radius 5.08 cm. It was metallic, thick walled (for high thermal capacitance), and could be fitted with either a sharp (8.74-cm-long) or a blunt (5.08-cm-long, 0.508-cm tip radius) solid/metallic nose tip. The junction between the nose tip and frustum was smooth, but disassembly allowed for insertion of a trip collar between the two sections if desired. A thin, axisymmetric protuberance, of height 0.9 mm, was employed during portions of this study.

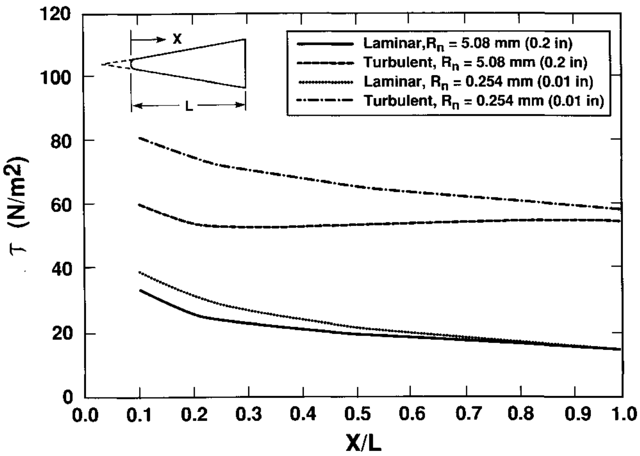


Fig. 1 Predicted laminar and turbulent surface shear-stress distributions along sharp and 10% blunt cones for $M_\infty = 5$, $\alpha = 0$ deg.

Experiments were conducted in the Sandia National Laboratories hypersonic blow-down wind tunnel. Test conditions were the following: freestream Mach number was 5, freestream unit Reynolds number was 2.3×10^7/m, stagnation pressure was 10.7 atm (157 psia), and stagnation temperature was 356 K. The gas was dry air. An angle-of-attack sweep, from 0 to 15 and back to 0 deg, was imposed on the model during each run. Total run time was approximately 30 s.

Calculations showed the adiabatic wall temperature (for sharp cone edge conditions at $\alpha = 0$ deg) to be 327 K (54°C), approximately 4°C above the liquid crystal melt (clear) temperature. A high-thermal-capacitance model, coupled with reasonably short run times, allowed the liquid crystal coating to remain functional during each exposure to the Mach 5 flow. Figure 1 shows predicted laminar and turbulent surface shear-stress distributions along the sharp and blunt cones, respectively, at zero angle of attack.

Freestream turbulence levels, and radiated noise levels (from nozzle wall boundary layers), have yet to be measured for this facility. It is well established that these disturbance factors play a dominant role on smooth-wall transition phenomena occurring on models exposed to conventional (nonquiet) supersonic and hypersonic wind-tunnel environments.[13,14] As a consequence, no quantitative comparisons of liquid-crystal-defined transition locations with existing correlations were attempted. Observed trends concerning movements of transition locations with variations in model angle of attack, model tip bluntness, and/or trip collar utilization are summarized in the next section.

Figure 2 shows a schematic of the experimental setup. Both a video camera (30 frames/s) and a high-speed movie camera (400 frames/s) were utilized to record the liquid crystal coating response. The viewing angle was essentially the same for both cameras, approximately perpendicular to the cone's principal axis and perpendicular to the plane in which the angle-of-attack variations occurred. Illumination of the model was also from the side, but offset ±45 deg (upstream and downstream) from the camera line of sight.

More recent results (obtained since the original feasibility study) have shown that lighting from one side is preferable, with the optimum viewing angle (for a given experimental arrangement and liquid crystal compound) determined in the following manner: 1) fix the lighting angle, 2) spray a test patch of liquid crystal coating onto the test surface, 3) align the crystals in the flow direction (a high-pressure air hose can be used to accomplish this step), 4) sweep through the range of potential view angles and note those angles at which the test patch changes color (thereby defining the angles of the scattered-light spectrum under no-shear conditions), and 5) place the camera just before the first color change angle (here, red to yellow). Experience has shown that, for the case of lighting from upstream, the scattered spectrum comes off the surface

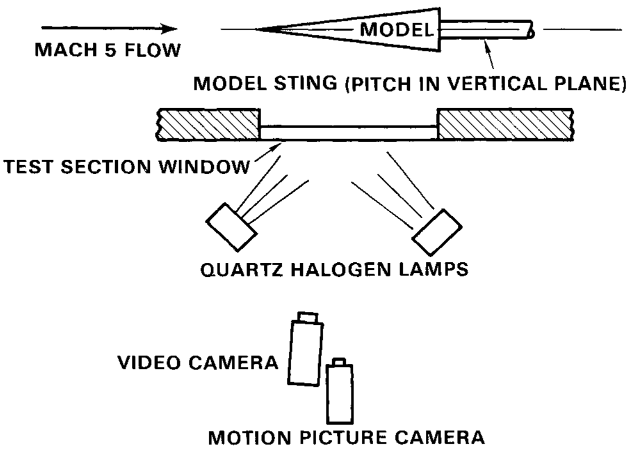
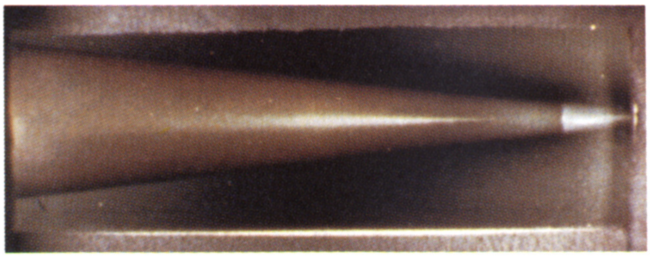
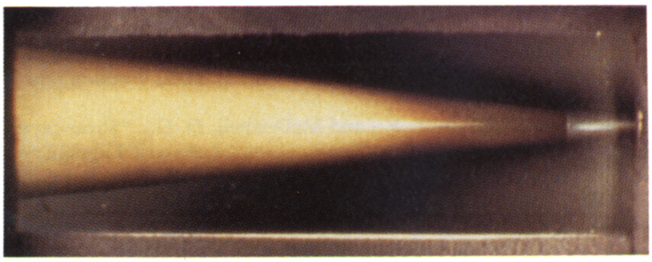


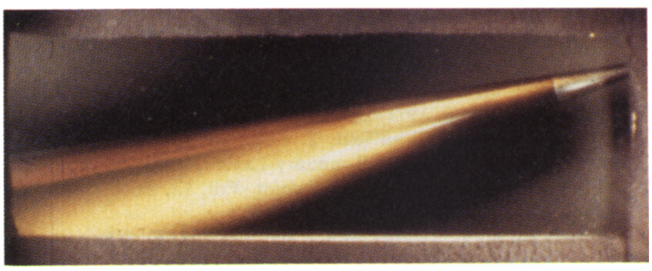
Fig. 2 Top view schematic of experimental apparatus.



a) Before flow; $\alpha = 0$ deg



b) $M_\infty = 5$; $\alpha = 0$ deg



c) $M_\infty = 5$; $\alpha = 15$ deg

Fig. 3 Color photographs of liquid crystal patterns on sharp cone (flow is right to left).

beginning from approximately the normal direction and extends through a range of oblique angles toward the downstream direction. The subsequent application of wall shear stress due to the imposition of flow then causes this scattered spectrum to rotate past the observer toward the upstream direction. Maximum sensitivity thus comes from a recording device positioned at the no-shear/first color change angle.

Experimental Observations

A summary of all of the experimental observations exists in the form of a 5-min color video; interested researchers may request a copy of this video by contacting the second author. Selected color frames are included in the printed paper.

Figure 3 shows three color frames taken for the smooth-wall sharp-cone case. The initial (as-sprayed) no-shear color exhibited by the liquid crystal coating was gray-green (see Fig. 3a; no mechanical prealignment of the liquid crystal structure was imposed here). In all cases, once flow was established over the model (set at its initial, zero angle-of-attack position), a region of rusty red color was seen to form upstream of an abrupt transition to a bright yellow color, indicating the occurrence of a relatively higher shear-stress zone (see Fig. 3b). The bright yellow zone covered the remaining (downstream) portions of the model surface. This color pattern was consistent with earlier observations of transition occurrence on airfoils in incompressible flow environments.[8,9] After flow shutdown, the overall color of the coating remained reddish, illustrating some apparent realignment of the crystal structure (by the flow) from its random/as-sprayed initial condition. Boundary-layer transition was thus indicated by the red-to-bright-yellow color transformation. For a given model geometry, the physical location of this color-change boundary was observed to dynamically respond to changes in the flow environment, e.g., to changes in tunnel stagnation pressure and/or temperature.

Boundary-layer transition, as defined by the liquid crystal technique, was observed to move upstream on the lee surface of the cone for increasing angle of attack (see Fig. 3c). A narrow, high-shear-stress zone was seen to sweep downstream across the side of the model at the higher angles of attack, consistent with the passage of a separation-generated vortical structure. A rusty red color on the cone's upper (leeward) surface indicated the presence of a low-shear-stress (separated flow) region. Figures 4 and 5 show schematic interpretations of the liquid crystal patterns of Figs. 3b and 3c, respectively.

The transition location at zero angle of attack occurred farther aft on the frustum in the presence of nose bluntness. For both the sharp and blunt nose-tip cases, the addition of the trip collar caused transition to move forward on the frustum (apparently via a separation of the laminar boundary layer upstream of the collar, followed by a turbulent reattachment downstream of the device), the most dramatic shift occurring in the presence of nose-tip bluntness. All of these observed trends are consistent with the present understanding of hypersonic boundary-layer flows on conical bodies, e.g., Refs. 15–21.

The highly transient flow over the model surface during tunnel shutdown demonstrated the time response of the liquid crystal coating to sudden changes in the wall shear stress. An

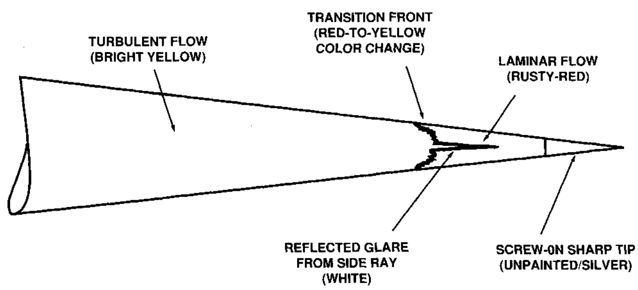


Fig. 4 Schematic of surface shear-stress pattern, $M_\infty = 5$, $\alpha = 0$ deg.

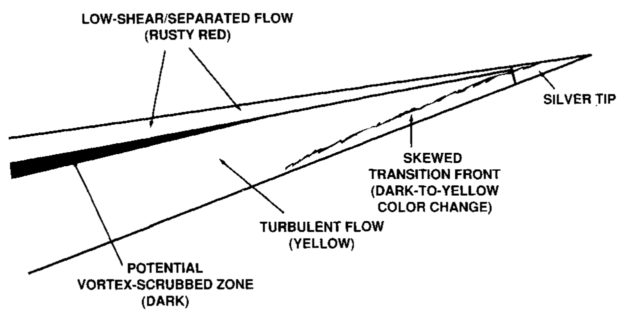
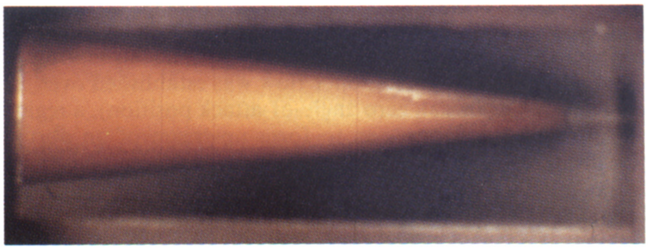
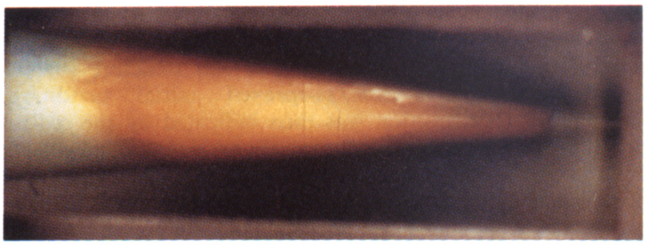


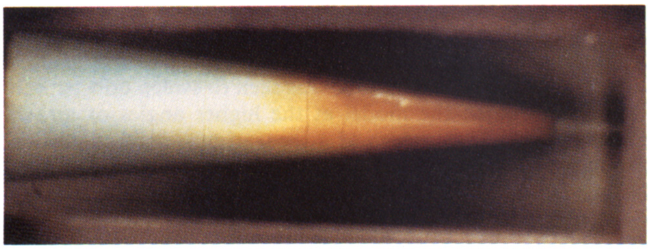
Fig. 5 Schematic of surface shear-stress pattern, $M_\infty = 5$, $\alpha = 15$ deg.



a) Shock at model base; frame 1, $t = 0.000$ s



b) Frame 2, $t = +0.0025$ s



c) Frame 3, $t = +0.005$ s

Fig. 6 Three sequential color photographs of liquid crystal patterns on blunt cone during tunnel shutdown (flow is right to left; normal shock motion is left to right).

event reasoned to be normal shock passage was recorded at 400 frames/s using the high-speed movie camera (see Fig. 6). Frame-by-frame playback of this transient event clearly showed the liquid crystal coating responding to apparent shock wave passage with a response time less than or equal to the time between frames (0.0025 s).

Conclusions

Four conclusions can be drawn from these feasibility studies concerning the use of liquid crystal coatings in hypersonic flows.

1) Given the formulation of the new shear-stress-sensitive/temperature-insensitive liquid crystal compounds, the liquid crystal coating technique has now been extended as a viable diagnostic tool for surface shear-stress visualization in compressible flow environments.

2) The time response of such liquid crystal coatings is sufficiently rapid (≤ 0.0025 s) to allow their use in highly transient flows.

3) The technique's rapid, continuous, and reversible color-change response to changing shear-stress distributions now allows surface shear-stress visualization experiments to be conducted on models undergoing maneuvers [e.g., $\alpha(t)$ variations] and/or trajectory simulations [e.g., $Re_\infty(t)$ variations] in hypersonic flows.

4) The limitation concerning the relationship between absolute color and lighting/viewing angles (particularly at highly oblique angles) remains a difficulty for both the calibration of the technique (to measure surface shear stress) and for the interpretation of surface shear-stress patterns for flows over complex, three-dimensional configurations. Attainment of simultaneous/multiple views of such models could potentially aid in the solution of such problems.

Acknowledgments

This research was sponsored by the U.S. Department of Energy under Contract DE-AC04-76DP00789. The authors gratefully acknowledge the assistance of R. E. Tate, K. N. Harmon, R. H. Croll, and C. B. Lafferty in operating the Sandia Hypersonic Wind Tunnel; D. W. Kuntz for performing the shear-stress calculations and for helpful discussions; and A. A. Sehmer for the high-speed photography.

References

[1]Fergason, J. L., "Liquid Crystals," *Scientific American,* Vol. 211, Aug. 1964, pp. 76–85

[2]Klein, E. J., "Liquid Crystals in Aerodynamic Testing," *Astronautics and Aeronautics,* Vol. 6, July 1968, pp. 70–73.

[3]Klein, E. J., and Margozzi, A. P., "Exploratory Investigation on the Measurement of Skin Friction by Means of Liquid Crystals," NASA-TM-X-1774, May 1969.

[4]Holmes, B. J., Gall, P. D., Croom, C. C., Manuel, G. S., and Kelliher, W. C., "A New Method for Laminar Boundary Layer Transition Visualization in Flight: Color Changes in Liquid Crystal Coatings," NASA-TM-87666, Jan. 1986.

[5]Reda, D. C., "Liquid Crystals for Unsteady Surface Shear Stress Visualization," AIAA Paper 88-3841, July 1988.

[6]Hall, R. M., Obara, C. J., Carraway, D. L., Johnson, C. B., Wright, R. E., Cowell, P. F., and Azzazy, M., "Comparisons of Boundary-Layer Transition Measurement Techniques in the Langley Unitary Plan Tunnel," AIAA Paper 89-2205, July 1989.

[7]Anon., "Liquid Crystals for Windflow Visualization," mixtures TI511 and TI622, BDH Ltd., Poole, England, UK, 1988; American distribution by EM Industries, Inc., Hawthorne, NY.

[8]Reda, D. C., and Butterfield, C. P., "Visualization of Boundary Layer Transition Zone Movement on Oscillating Airfoils with Shear-Sensitive Liquid Crystal Coatings," *Proceedings of the ASME Symposium on Flow Visualization,* FED-Vol. 85, Dec. 1989, pp. 63–67.

[9]Reda, D. C., "Observations of Dynamic Stall Phenomena Using Liquid Crystal Coatings," *AIAA Journal,* Vol. 29, No. 2, 1991, pp. 308–310.

[10]Gaudet, L., and Gell, T. G., "Use of Liquid Crystals for Qualitative and Quantitative 2-D Studies of Transition and Skin Friction," Royal Aerospace Establishment, TM AERO-2159, London, June 1989.

[11]Bonnett, P., Jones, T. V., and McDonnell, D. G., "Shear-Stress Measurement in Aerodynamic Testing Using Cholesteric Liquid Crystals," *Liquid Crystals,* Vol. 6, No. 3, 1989, pp. 271–280.

[12]Toy, N., Savory, E., and Paskin, S., "The Development of a System for Real-Time, Full-Field Surface Shear Stress Measurements Using Liquid Crystals," *Proceedings of the 12th Symposium on Turbulence,* University of Missouri-Rolla, Rolla, MO, 1990.

[13]Pate, S. R., and Schueler, C. J., "Radiated Aerodynamic Noise Effects on Boundary-Layer Transition in Supersonic and Hypersonic Wind Tunnels," *AIAA Journal,* Vol. 7, No. 3, 1969, pp. 450–457.

[14]Pate, S. R., "Measurements and Correlations of Transition Reynolds Numbers on Sharp Slender Cones at High Speeds," *AIAA Journal,* Vol. 9, No. 6, 1971, pp. 1082–1090.

[15]Potter, J. L., and Whitfield, J. D., "Effects of Slight Nose Bluntness and Roughness on Boundary-Layer Transition in Supersonic Flows," *Journal of Fluid Mechanics,* Vol. 12, Pt. 4, 1962, pp. 501–535.

[16]Nagamatsu, H. T., Graber, B. C., and Sheer, R. E., "Roughness, Bluntness and Angle-of-Attack Effects on Hypersonic Boundary Layer Transition," *Journal of Fluid Mechanics,* Vol. 24, Pt. 1, 1966, pp. 1–31.

[17]Van Driest, E. R., and Blumer, C. B., "Boundary-Layer Transition at Supersonic Speeds: Roughness Effects with Heat Transfer," *AIAA Journal,* Vol. 6, No. 4, 1968, pp. 603–607.

[18]Stainback, P. C., "Effect of Unit Reynolds Number, Nose Bluntness, Angle of Attack and Roughness on Transition on a 5° Half-Angle Cone at Mach 8," NASA TN D-4961, Jan. 1969.

[19]Potter, J. L., "Boundary-Layer Transition on Supersonic Cones in an Aeroballistic Range," *AIAA Journal,* Vol. 13, No. 3, 1975, pp. 270–277.

[20]Reda, D. C., "Boundary-Layer Transition Experiments on Sharp, Slender Cones in Supersonic Free Flight," *AIAA Journal,* Vol. 17, No. 8, 1979, pp. 803–810.

[21]Stetson, K. F., Thompson, E. R., Donaldson, J. C., and Siler, L. G., "Laminar Boundary Layer Stability Experiments on a Cone at Mach 8, Part 3: Sharp Cone at Angle of Attack," AIAA Paper 85-0492, Jan. 1985.

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