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LIQUID CRYSTAL COATINGS FOR SURFACE SHEAR STRESS VISUALIZATION IN HYPERSONIC FLOWS

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Abstract

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. Boundary layer transition to turbulence was clearly demarcated by the technique. The dynamic location of the transition 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 hypersonic flows over conical bodies. Normal shock passage over the model during tunnel shutdown was recorded (at 400 frames/second), and the liquid crystal coating was observed to respond to this event in a time interval less than or equal to the time between sequential movie frame exposures (≤ 0.0025 seconds). The liquid crystal technique has thus been demonstrated as a viable diagnostic tool for use in transient/compressible flows.

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Nomenclature

α	angle of attack
M_∞	freestream Mach number
Re_∞	freestream Reynolds number
t	time

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 versus 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/semi-empirical 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.

Liquid Crystals

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 flat-black surface is essential for color contrast). 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 (approximately 10 μm thickness), which 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[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 Reference (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'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."

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.[7] Coatings of such compounds were successfully utilized by Reda[8,9] 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.

One final comment concerning the use of liquid crystal coatings in fluid mechanics research is in order. As noted above, attempts to "calibrate" the shear stress-versus-color 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 the calibration apparatus to the aerodynamic test facility results in significant uncertainties, especially for complex surface contours. While "in-situ" calibration of the liquid crystal coating may be possible, one would then have to measure the distribution of shear stress acting on the test surface with some other technique (e.g., flush-mounted hot-film sensors). Calibration of these devices would then also be required. Given these difficulties, no calibration of the coating's color with the magnitude of the surface shear stress imposed upon it has yet been attempted. It is felt that the liquid crystal technique is perhaps best utilized to "visualize" the presence and to quantify the locations of high surface shear stress zones in time-varying flows (through observations of relative changes in surface color patterns), while measurements of surface shear stress distributions are best accomplished with arrays of calibrated/point sensors.

Experimental Approach

The model employed in the present research was a cone of 6.5° 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 nosetip. The junction between the nosetip 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.

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

Calculations showed the adiabatic wall temperature (for sharp cone edge conditions at α = 0°) 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.

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" ("non-quiet") supersonic and hypersonic wind tunnel environments.[10,11] 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 1 shows a schematic of the experimental setup. Both a video camera (30 frames/second) and a high-speed movie camera (400 frames/second) 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° (upstream and downstream) from the camera line of sight.

Experimental Observations

A summary of all the experimental observations exists in the form of a five-minute 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 2 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 grey-green (see Fig. 2(a); no "mechanical" pre-alignment 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. 2(b)). 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. 2(c)). Narrow high-shear-stress "lines" were seen to sweep across the "side" of the model at the higher angles of attack, consistent with the passage of separation-generated vortical structures. Rusty red color on the cone's upper (leeward) surface indicated the presence of a low shear stress (separated flow) region.

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 nosetip 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 nosetip bluntness. All of these observed trends are consistent with the present understanding of hypersonic boundary layer flows on conical bodies, e.g., References (12) through (18).

Passage of a normal shock wave over the model surface during flow shutdown demonstrated the time response of the liquid crystal coating to sudden changes in the wall shear stress. This event was recorded at 400 frames/second using the high-speed movie camera (see Fig. 3). Frame-by-frame playback of this highly transient event clearly showed the liquid crystal coating responding to shock wave passage with a time constant less than or equal to the time between frames (0.0025 seconds).

Conclusions

Three 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 sec.) 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.

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References

1. Fergason, J. L., "Liquid Crystals," Scientific American, Vol. 211, 1964, pp. 76-85.

2. Klein, E. J., "Liquid Crystals in Aerodynamic Testing," Astronautics and Aeronautics, Vol. 6, 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, 1969.

4. Holmes, B. J. et al., "A New Method for Laminar Boundary Layer Transition Visualization in Flight: Color Changes in Liquid Crystal Coatings," NASA-TM-87666, 1986.

5. Reda, D. C., "Liquid Crystals for Unsteady Surface Shear Stress Visualization," AIAA 88-3841CP, Proceedings, 1st National Fluid Dynamics Congress, Cincinnati, Ohio, Part 2, 1988, pp. 1069-1072.

6. Hall, R. M. et al., "Comparisons of Boundary-Layer Transition Measurement Techniques in the Langley Unitary Plan Tunnel," AIAA89-2205CP, 7th Applied Aerodynamics Conference, Seattle, WA, July 1989.

7. Anonymous, "Liquid Crystals for Windflow Visualization," mixtures TI511 and TI622, BDH Limited, Broom Rd., Poole, BH12 4NN, England, 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 Symposium on Flow Visualization, FED-Vol. 85, ASME Winter Annual Meeting, San Francisco, California, 1989, pp. 63-67.

9. Reda, D. C., "Observations of Dynamic Stall Phenomena on an Oscillating Airfoil with Shear-Stress-Sensitive Liquid Crystal Coatings," ICAS 90-3.4.2, 17th Congress, International Council of the Aeronautical Sciences, Stockholm, Sweden, 1990.

10. 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, 1969, pp. 450-457.

11. Pate, S. R., "Measurements and Correlations of Transition Reynolds Numbers on Sharp Slender Cones at High Speeds," AIAA Journal, Vol. 9, 1971, pp. 1082-1090.

12. 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, 1962, pp. 501-535.

13. 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, 1966, pp. 1-31.

14. van Driest, E. R. and Blumer, C. B., "Boundary-Layer Transition at Supersonic Speeds: Roughness Effects with Heat Transfer," AIAA Journal, Vol. 6, 1968, pp. 603-607.

15. 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, 1969.

16. Potter, J. L., "Boundary-Layer Transition on Supersonic Cones in an Aeroballistic Range," AIAA Journal, Vol. 13, 1975, pp. 270-277.

17. Reda, D. C., "Boundary-Layer Transition Experiments on Sharp, Slender Cones in Supersonic Free Flight," AIAA Journal, Vol. 17, 1979, pp. 803-810.

18. 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," AIAA85-0492 23rd Aerospace Sciences Meeting, Reno, Nevada, 1985.

Figures

Fig. 1. Top View Schematic of Experimental Apparatus.

Fig. 2. Color Photographs of Liquid Crystal Patterns on Sharp Cone. (Flow Is Right to Left.)

(a) Before Flow; $\alpha = 0°$.

(b) $M_\infty = 5$; $\alpha = 0°$.

(c) $M_\infty = 5$; $\alpha = 15°$.

Fig. 3. 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.)

(a) Shock at Model Base; Frame 1, t = 0.000 sec.

(b) Frame 2, t = + 0.0025 sec.

(c) Frame 3, t = + 0.005 sec.

TOP VIEW SCHEMATIC OF EXPERIMENTAL APPARATUS