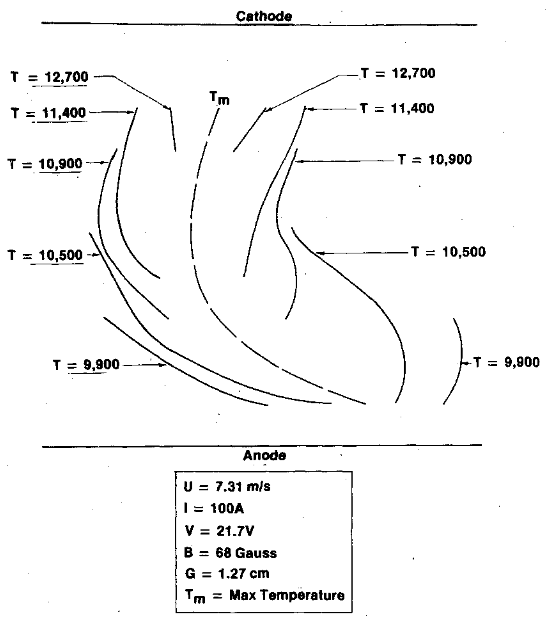

Fig. 6 Arc profile, *S*-shaped arc: $I = 100$ A, $g = 1.27$ cm, $u = 7.31$ m/sec, $B = 68$ G.

tachment. In previously reported experiments on balanced rail arcs, e.g., Refs. 5-7, (1) the slanted arc alone seemed to be found, (2) the cathode root was downstream of the anode attachment, and (3) the arc appeared larger in dimension near the cathode. The differences between the present results and the foregoing with respect to the size of the regions near the roots and thus, most probably, the determination of the downstream attachment, were probably due to electrode and electrode material effects. The present results were consistent with the analysis of Ref. 6 which, assuming the cathode attachment to be fixed (as essentially observed herein), predicted the relative locations of the arc roots and the overall profile of the column. For the flow-determined case therein, the anode root was predicted to be the downstream attachment; the relations describing this case were satisfied in the present experiments. Furthermore, in the limiting case of the flow-determined arc, the column was shown to contain a segment parallel to the flow, as was found in Fig. 2.

Isotherm distributions in the horizontal plane of the column and at midheight between the electrodes (0.64 cm from the cathode) are shown in Fig. 3 for the straight arc (of Fig. 1). The distributions for all column configurations were found to exhibit a mirror plane of symmetry (along the $\theta = 0°\text{-}180°$ axis, i.e., parallel to the direction of flow). The ellipticity of a given isotherm can be characterized by the axis ratio, AR, defined as the ratio of the distance between the intercepts (of the isotherm) along the mirror plane of symmetry ($\theta = 0°\text{-}180°$ axis) to that along the $\theta = 90°$ azimuth. Values of $AR >$ or < 1 suggest an emphasis of magnetic or flow effects, respectively; $AR = 1$ indicates a tendency for a circular distribution. For the case shown in Fig. 3, $AR \sim 1.03$ for the inner and outer isotherms ($T = 11{,}900$ and 10,500 K, respectively). Over the range of velocities with the straight arc (~ 3.7-~ 7.3 m/sec), the axis ratio ranged from 0.93 to 1.04. With pin electrodes, balanced arcs (with attachments at or near the apexes of the electrodes) were found to have axis ratios in the range 1.06 to 1.18,[1,2] with velocities in the range $\sim$ 1.8-5.1 m/sec. (In the absence of applied magnetic fields, observed axis ratios always have been less than unity[3] and were a strong function of velocity, decreasing to $\sim$ 0.1 at speeds near arc blowout.) Electrode effects, as related to the pin and rail configurations, probably accounted for the differences between the present results and those of Refs. 1 and 2. Analysis[8] of a balanced cross-flow plasma, in which the arc was assumed straight and uniform along the column (electrode effects were not considered), predicted, for operating conditions $I = 30$ A, $u = 4.0$ m/sec, an axis ratio $\sim$ 1.5.

Shown in Fig. 4 are isotherm distributions for the *S*-shaped arc (of Fig. 2) obtained in the portion of the column parallel to the direction of flow. The relative elongation of the column in the flow direction is apparent; here, $AR = 0.71$ at the outer ($T = 9900$ K) isotherm. Column profiles (in the mirror plane of symmetry) for the straight and *S*-shaped columns are shown in Figs. 5 and 6, respectively. The profiles reflect the widely different arc configurations obtained.

References

[1] Baker, A.J. and Benenson, D.M., "Effects of Forced Convection Upon the Characteristics of a Steady-State Cross-Flow Arc in the Presence of an Applied Transverse Magnetic Field," *Proceedings of the IEEE*, Vol. 59, 1971, pp. 450-457.

[2] Benenson, D.M. and Baker, A.J., "Transverse Magnetic Field Effects on a Cross-Flow Arc," *AIAA Journal*, Vol. 9, 1971, pp. 1441-1446.

[3] Benenson, D.M. and Cenkner, A.A., Jr., "Effects of Velocity and Current on Temperature Distribution within Cross-Flow (Blown) Electric Arcs." *Transactions of the ASME, Journal of Heat Transfer*, Vol. 92, Ser. C. 1970, pp. 276-284.

[4] Maldonado, C.D. and Olsen, H.N., "New Method for Obtaining Emission Coefficients from Emitted Spectral Intensities. Pt. II—Asymmetrical Sources," *Journal of the Optical Society of America*, Vol. 56, 1966, pp. 1305-1313.

[5] Winograd, Y.Y. and Klein, J.F., "Electric Arc Stabilization in Crossed Convective and Magnetic Fields," *AIAA Journal*, Vol. 7, 1969, pp. 1699-1706.

[6] Bond, C.E., "Slanting of a Magnetically Stabilized Electric Arc in Transverse Supersonic Flow," *Physics of Fluids*, Vol. 9, 1965, pp. 705-710.

[7] Nicolai, L.M. and Kuethe, A.M., "Properties of Magnetically Balanced Arcs," *Physics of Fluids*, Vol. 12, 1969, pp. 2072-2083.

[8] Malghan, V.R. and Benenson, D.M., "Analysis of Cross-Flow Arcs in Transverse Magnetic Fields," *IEEE Transactions on Plasma Sciences*, Vol. PS-1, 1973, pp. 38-46.

Laser Schlieren for Study of Solid-Propellant Deflagration

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Introduction

THE major objective of this study was to develop a laser schlieren (optically active aperture) system designed to eliminate the problem of self-luminous interference during flowfield studies and to apply it to the study of ammonium perchlorate deflagration. Developments in laser light source optical systems, including schlieren, have been reported by Lu[1] and Oppenheim.[2] These systems are potentially valuable tools for propellant combustion studies.

A major problem in observing surface behavior and the gas phase just above the surface during high-pressure combustion of certain propellants is the visible light or self-luminous interference effects from the combustion zone. As the pressure is raised, the combustion zone tends to move closer to the

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solid surface, and the problem is magnified. This interference overpowers schlieren observations, resulting in a yellow overtone in color photography or a washed-out region in black-and-white. With an unlimited light source power supply, it is simply possible conceptually to overpower interference but at the potential risk of affecting the combustion mechanism if the source intensity is high enough to cause heating of the specimen or the flow. A second and preferable potential solution is the use of the monochromatic properties of laser light and a narrow-pass filter with the filter at peak transmission at the laser wavelength. The wavelength of the laser and filter should be displaced significantly from the expected peak of the self-luminous interference.

Interaction of coherent monochromatic laser light with the conventional knife edge produces diffration patterns that render this combination unsuitable for laser schlieren systems.[1,2] In addition, the inherent fringing around the periphery and general inhomogeniety of the laser beam itself may require it to be "cleaned" by spatial filtering or other techniques in order to be suitable for use in a schlieren system. The plane-polarized characteristic of laser light allows the use of optically active crystals to replace the conventional knife edge and thus to minimize or eliminate the associated diffraction patterns. An additional advantage of a laser source is the dual use with a hologram setup or other dual system as reported by Lu.[1]

Experimental Apparatus and Procedures

The optical system employed in this study consisted of a cw argon laser schlieren using high-quality lenses, an optically active aperture in place of the conventional knife edge, and a biconcave lens to diverge the laser beam initially. The schlieren aperture used was an optically active 30° single-crystal quartz prism combined with a polaroid sheet.

Parallel rays passing through a flowfield with density gradients are refracted differentially, resulting in a shift of position of impingment on the perpendicular face of the quartz prism. The displaced light travels through differing thicknesses of quartz, which in turn rotates the plane of polarization by differing amounts. The polaroid acts as filter to pass rays whose rotation is close to the polaroid orientation and absorb the others. In order to avoid the deflection of the entire beam after passsing through the quartz prism, a second complimentary but optically neutral prism of matching index of refraction is necessary.[1,2] The light source used was a Control Laser continuous wave (cw) argon laser, model 902A, operating at the 4800 Å line. The laser was operated at 32 A/220 V ac to deliver a power of 1.3 W.

For motion-picture recording, a Hycam model K2004E-115 high-speed 16-mm motion-picture camera was used. Framing rates of up to 10,000 frames/sec were used, with exposure times of 80 μ-sec or less, depending on the associated shutter used. The lower limiting time capability was 1 μ sec. Movie film types included 7277 4X reversal (ASA 400), 2475 Estar-AH (ASA 1000), and 7224 negative (ASA 500). The 7277 4X was used primarily because it has a color sensitivity peak in the blue-green. The sensitivity of any schlieren system is a function of the focal length of the second schlieren lens/mirror and the type and adjustment of the aperture. The conventional knife-edge system has been described by Liepmann and Roshko.[3]

The optically active aperture (quartz prism-polaroid) controls both sensitivity and contrast, assuming a fixed total refraction and a specified focal length of the second schlieren lens. The polaroid orientation will determine the darkness of the "neutral" background and the light-dark extremes possible in the schlieren record. It is possible to observe identical schlieren records for differing total refractions (density gradients). That is to say, there is a certain cyclic nature or periodicity associated with this schlieren aperture. The nature of the periodicity is dependent on the total system sensitivity and the relationship of reference ray polarization orientation to that of the polaroid sheet transmission axis.

The polaroid sheet has an axis of maximum transmission and, 90° to it, an axis of maximum absorption. In general, the polarization orientation of the reference (or unrefracted) rays, after having passed through the prisms, should bisect the two axes of the polaroid sheet. Ideally, the steepest density gradients in the flowfield, coupled with the total system sensitivity, should cause a maximum differential rotation of $\pm$ 45° for the refracted rays. This would correspond to the extremes of the light-dark and produce the optimum schlieren record. If the deflected portion of the beam is rotated more than $\pm 45°$, an erroneous reversal in the density gradient would be indicated. This cyclic behavior becomes more critical in one direction if the reference axis and polaroid transmission axis are at other than 45°. This is sometimes necessary when a darker schlieren record is required. In the present investigation, approximate calculations of the system sensitivity indicated that less than 10° of rotation could be expected for typical free jet diffusion flames.

During the exposure time for any given frame, the hot gases have a vertical velocity that results in a "smearing" on the film. The smear is simply the distance a "gas particle" may move during the exposure time. Approximate calculations for ammonium perchlorate deflagration at 500 psia indicated that a smear of about 0.0025 cm could be expected using the filming methods just discussed.

Results and Discussion

Initial system checkout was made by taking schlieren photographs of candle flames and turbulent jet diffusion flames. Although the quality was somewhat reduced,[4] the schlieren record was in agreement with conventional schlieren photographs provided by Gaydon and Wolfhard.[5] There are at least three major contributing reasons for the reduced quality: peculiar properties of the laser light itself (i.e., diffractions about solid boundary, etc.), limited schlieren light-dark extremes available due to the transmission and absorption properties of the polaroid (40-70% transmission), and the limited total sensitivity of the reported system.

Figure 1 shows a single-crystal ultrahigh-purity ammonium perchlorate specimen (SC-UHP-AP) 4.7 mm wide burning at 500 psi. The schlieren results were in good agreement with the color schlieren of Murphy and Netzer.[6] Individual surface reaction sites were observed (as evidenced from the gas-phase density gradients) to be distributed quite evenly across the surface. The sites appeared to be on the order of 180-280 μ in width, slightly smaller than reported by Murphy and Netzer.[6] The deflagration appeared to be laminar.

Figure 2 shows a pressed polycrystalline ammonium perchlorate specimen (PP-UHP-AP) 4.83 mm wide and 1.27 mm thick burning at 450 psi. The light-dark schlieren shifts (evidence of individual surface reaction sites) appeared to be spaced 280-300 μ across the surface, with large-scale turbulence beginning about 500-600 μ above the surface. The front surface of the solid phase appears dark because of the

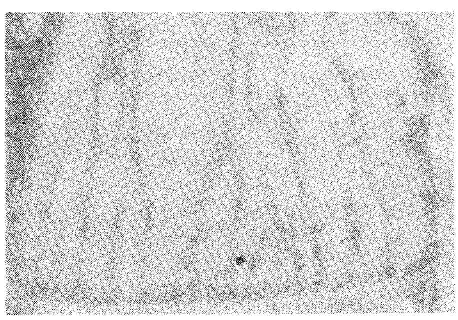

Fig. 1 AP (single crystal), 500 psi.

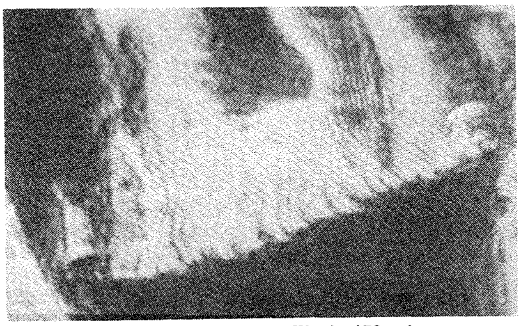

Fig. 2 AP (polycrystalline), 450 psi.

back lighting of the opaque specimen. Surface definition was poor in the interface region between the dark schlieren and the solid-phase surface. Observable from the motion pictures was an apparent motion of the solid-phase surface just below the burning surface. This was attributed to the reflections from the downstream bomb window. In the SC-UHP-AP specimen, this motion was not observed, since the transparent crystal allowed laser light transmission, which overpowered any such reflections.

Smoke absorption appeared to be a major problem, particularly with the limited-power laser light source. Light absorption by the smoke resulted in a darkened area, which was superimposed on any light-dark shift resulting from density gradients and confused the record interpretation. On the right-hand edge of Fig. 2, the smoke was evidenced by the gray region in the gas phase. Smoke accumulation was minimized by controlled purge rate.

Additional schlieren were taken at 1000 and 2000 psi. Details and photographs are presented in Ref. 4. There were two major differences between the 1000- and 500-psi results. The first was a near-constant periodic pulsing of the burning process. At regular intervals, a very thin layer of smoke would move upward from the immediate vicinity of the surface all along the width. This smoke layer was everywhere parallel to the surface locally; that is, it reflected the instantaneous surface contour. This result was similar to those reported by Murphy and Netzer.[6] They reported a "thermal pulsing" when their aperture was positioned to detect vertical density gradients. Boggs and Zurn[7] similarily reported an accumulation and shedding of unreacted products on the surface of potassium-doped AP crystals leading to a "stop-and-go" burning characteristic. The second difference was the lack of light-dark schlieren shifts across and just above the surface. This indicated little or no density gradients (i.e., approximately constant temperature) across the surface with uniform burning. Murphy and Netzer[6] reported similar results with "almost uniform color in the gases just above the surface." These results imply that surface reaction sites are very small or nonexistent at 1000 psi.

At 2200 psi, the surface locally appeared to be nonuniform, with large-scale turbulence very close to the surface. Density gradients were observed which extended to the burning surface. However, the smoke and fringing near the surface prevented a consistent determination of the size of the surface reaction sites. The pulsing behavior observed at 1000 psi was not observed at 2200 psi.

General conclusions concerning the use of laser schlieren for solid-propellant studies are as follows: 1) The basic feasibility of using an optically active aperture laser schlieren system for high-pressure solid-propellant combustion study was demonstrated. 2) The major advantage of this schlieren system over conventional schlieren systems is the elimination of self-luminous interference. 3) For applications where the self-luminous problem is nonexistent (i.e., shock pattern studies, etc.), a cw laser schlieren in general would be inferior to conventional schlieren systems. Conventional color schlieren has the added advantage over this system in that schlieren effects can be distinguished more readily from variable light absorption by smoke. 4) System resolution was limited to approximately 60 μ, primarily by fringing. The fringing could, perhaps, be minimized or eliminated by using a bonded prism set and mirrors in place of the lenses. Another method of improving the schlieren quality would be to increase system sensitivity by using a longer focal length schlieren and/or a greater quartz crystal angle. This would allow the use of a polaroid axis, which would provide a darker background, thereby "darkening out" the fringes so that they would not be seen on the film.

References

[1] Lu, P-L., "Optical Systems for Application of the Laser to Detonation Studies," TM 1938, March 1974, Picatinny Arsenal.

[2] Oppenheim, A.K., Urtiew, P.A., and Weinberg, F.J., "On the Use of Laser Light Sources in Schlieren-Interferometer Systems," *Proceedings of the Royal Society*, Vol. 291, April 1966, pp. 279-290.

[3] Liepmann, H.W. and Roshko, A., *Elements of Gas Dynamics*, 8th edition, Wiley, New York, 1957, pp. 153-162.

[4] Andrews, J.R. and Netzer, D.W., "The Development of an Optically Active Laser Schlieren System with Application to High Pressure Solid Propellant Combustion," NPS-57Nt-75082, Sept. 1975, Naval Postgraduate School, Monterey, Calif.

[5] Gaydon, A.G. and Wolfhard, H.G., *Flames*, 3rd edition, Chapman and Hall, London, 1970, plates 9 and 12.

[6] Murphy, J.L. and Netzer, D.W., "Ammonium Prchlorate and Ammonium Perchlorate—Binder Sandwich Combustion," *AIAA Journal*, Vol. 12, Jan. 1974, pp. 13-14.

[7] Boggs, T.L. and Zurn, D.E., "The Deflagration of Pure and Doped Ammonium Perchlorate," *6th ICRPG Combustion Conference*, CPIA 192, Vol. 1, Dec. 1969. pp. 499-512.

Comparison of Reynolds Stress Diagnostics by Fixed and Rotating Probes

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Introduction

THREE-DIMENSIONAL turbulent-boundary-layer (3DTBL) flows continue to generate strong interest in fluid-mechanics research. The structure and details of such flowfields are of interest, and Reynolds stress measurements can be very useful in verification of empirical mixing length or eddy viscosity models and of computational schemes. Although only two Reynolds stresses, viz., the streamwise and transverse shear stresses, generally are included in a 3DTBL analysis, details on the nature and development of all six of the unknown Reynolds stresses have considerable value. Some more recent computational schemes attempt to include one or more of the Reynolds stress terms usually neglected in a boundary-layer-type analysis, and hence information on all of the

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