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References

[1] Tepper, M., "A Proposed Mechanism of Squall Lines: the Pressure Jump," *Journal of Meteorology*, Vol. 7, Feb. 1950, pp. 21-29.

[2] Tepper, M., "Pressure Jump Lines in Midwestern United States, January-August 1951," Research Paper 37, U.S. Weather Bureau, Washington, D.C., 1954, p. 70.

[3] Matsumoto, S. and Akiyama, T., "Some Characteristic Features of the Heavy Rainfalls Observed over the Western Japan on July 9, 1967, Part I: Mesoscale Structure and Short Period Pulsation," *Journal of Meteorological Society of Japan*, Vol. 47, 1969, pp. 255-266.

[4] Matsumoto, S. and Tsuneoka, Y., "Some Characteristic Features of the Heavy Rainfalls Observed Over the Western Japan on July 9, 1967, Part II: Displacement and Lift Cycles of Mesoscale Rainfall Cells," *Journal of Meteorological Society of Japan*, Vol. 47, 1969, pp. 267-278.

[5] Matsumoto, S., Ninomiya, K., and Akiyama, T., "A Synoptic and Dynamic Study on the Three Dimensional Structure of Mesoscale Disturbances Observed in the Vicinity of a Cold Vortex Center," *Journal of Meteorological Society of Japan*, Vol. 45, 1967, pp. 64-81.

[6] Matsumoto, S., Ninomiya, K., and Akiyama, T., "Cumulus Activities in Relation to the Mesoscale Convergence Field," *Journal of Meteorological Society of Japan*, Vol. 45, 1967, pp. 292-304.

[7] Uccellini, L. W., "A Case Study of Apparent Gravity Waves Initiation of Severe Convective Storms," *Monthly Weather Review*, Vol. 103, June 1975, pp. 497-513.

[8] Baker, D. N. and Davies, K., "F2-Region Acoustic Waves from Severe Weather," *Journal of Atmospheric and Terrestrial Physics*, Vol. 31, Nov. 1969, pp. 1345-1352.

[9] Davies, K. and Jones, J. E., "Ionospheric Disturbances Produced by Severe Thunderstorms," NOAA Professional Paper 6, U.S. Dept. of Commerce, NOAA, Rockville, Md., 1972, p. 47.

[10] Prasad, S. S., Schneck, L. J., and Davies, K., "Ionopsheric Disturbances by Severe Tropospheric Weather Storms," *Journal of Atmospheric and Terrestrial Physics*, Vol. 37, Oct. 1975, pp. 1357-1363.

[11] Smith, R. E. and Hung, R. J., "Observation of Severe Weather Activities by Doppler Sounder Array," *Journal of Applied Meteorology*, Vol. 14, Dec. 1975, pp. 1611-1615.

[12] Georges, T. M. and Greene, G. E., "Infrasound from Convective Storms: Part IV. Is It Useful for Storm Warning?" *Journal of Applied Meteorology*, Vol. 14, Oct. 1975, pp. 1303-1316.

[13] Georges, T. M., "Infrasound from Convective Storms, Part II: A Critique of Some Candidates," NOAA Tech. Rept. ERL 380-WPL49, 1976, p. 59.

[14] Jones, R. M. and Georges, T. M., "Infrasound from Convective Storms, III. Propagation to the Ionosphere," *Journal of Acoustical Society of America*, Vol. 59, April 1976, pp. 765-779.

[15] Hung, R. J. and Smith, R. E., "Study of Stratospheric-Ionospheric Coupling During Time Periods of Thunderstorms and Tornadic Storms," *Space Research*, Vol. 17, 1977, pp. 211-216.

[16] Hung, R. J., Phan, T., and Smith, R. E., "Observation of Gravity Waves During the Extreme Tornado Outbreak of April 3, 1974," *Journal of Atmospheric and Terrestrial Physics*, Vol. 40, 1978 (in press).

[17] Hung, R. J. and Smith, R. E., "Ray Tracing of Gravity Waves as a Possible Warning System for Tornadic Storms and Hurricanes," *Journal of Applied Meteorology*, Vol. 17, Jan. 1978, pp. 3-11.

[18] Hung, R. J. and Smith, R. E., "Dynamics of Severe Storms Through the Study of Thermospheric-Tropospheric Coupling," *Journal of Geomagnetism and Geoelectricity*, Vol. 30, 1978 (in press).

[19] Otnes, R. K., "An Elementary Design Procedure for Digital Filters," *Transaction of IEEE Audio and Electroacoustics*, Vol. AU-16, 1968, pp. 330-335.

[20] Hung, R. J. and Smith, R. E., "Observation of Upper Atmospheric Disturbances Caused by Hurricanes and Tropical Storms," *Space Research*, Vol. 17, 1977, pp. 205-210.

[21] Hung, R. J., Kuo, J. P., and Smith, R. E., "Gravity Waves from Hurricane Eloise," *Hurricanes and Tropical Meteorology,* American Meteorological Society, Boston, Mass., 1978, pp. 630-635.

[22] Georges, T. M., "Infrasound from Convective Storms: Examining the Evidence," *Reviews of Geophysics and Space Physics*, Vol. 11, 1973, pp. 571-594.

[23] Malkus, J. S., "Recent Developments in Studies of Penetrative Convection and the Application to Hurricane Cummuloniumbus Towers," *Cumulus Dynamics*, Pergamon Press, New York, 1960, pp. 65-84.

[24] Saunders, P. M., "Penetrative Convection in Stably Stratified Fluids," *Tellus*, Vol. 14, 1962, pp. 172-194.

[25] Vonnegut, B., Moore, C. V., Espinola, R. P., and Blau, Jr., H. H., "Electric Potential Gradients Above Thunderstorms," *Journal of Atmospheric Science*, Vol. 23, Nov. 1966, pp. 764-770.

[26] Lighthill, M. J., "On Sound Generated Aerodynamically, I. General Theory," *Proceedings of Royal Society*, Series A, Vol. 211, 1952, pp. 564-587.

[27] Lighthill, M. J., "On Sound Generated Aerodynamically, II. Turbulence as a Source of Sound," *Proceedings of Royal Society*, Series A, Vol. 222, 1954, pp. 1-32.

[28] Lighthill, M. J., "Sound Generated Aerodynamically," *Proceedings of Royal Society*, Series A, Vol. 267, 1962, pp. 147-182.

[29] Lighthill, M. J., "Prediction on the Velocity Field Coming from Acoustic Noise and a Generalized Turbulence in a Layer Overlaying a Convectively Unstable Atmospheric Region," *International Astronomical Union Symposium*, Vol. 28, 1967, pp. 429-469.

[30] Shenk, W. E., "Cloud Top Height Variability of Strong Convective Cells," *Journal of Applied Meteorology*, Vol. 13, Dec. 1974, pp. 1611-1615.

Gas Breakdown Thresholds in Flame Induced by Ruby Laser

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Introduction

OPTICAL diagnostic techniques such as spontaneous Raman scattering, fluorescence, and coherent anti-Stokes Raman scattering (CARS) are being developed for applications in combustion media on the strength of their potential for making nondisturbing, real-time point measurements.[1,2] These techniques require the focusing of one or more high-power laser beams into a small sample volume of a medium, in order to generate a desired optical signal in the measurement process. The intensity of the signal generated in the preceding diagnostic processes depends upon the intensity of the incident laser beam(s) in the sample volume. There is, however, a practical limit beyond which an increase in incident intensity will not result in a greater signal. One limiting process is laser-induced gas breakdown. Since gas breakdown severely disturbs the optical and physical properties of the medium through which the beams propagate, its occurrence cannot be tolerated in any optical measurement processes.

This Note reports the results of breakdown threshold measurements in flames. The experiments were performed in

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order to determine the maximum laser intensity which can be safely employed in optical flame diagnostics without causing gas breakdown. Although the laser-induced gas breakdown phenomenon has been studied extensively,[3,4] to the best of the authors' knowledge no experimental data are available on breakdown thresholds in flames.

Experimental

A schematic diagram of the experimental setup is shown in Fig. 1. A single-mode ruby laser beam is generated in an oscillator cavity and then passed through two amplifiers. A portion of the beam is detected by a PIN photodiode and displayed on a Tektronix R7912 transient digitizer. The remainder of the ruby beam continues on through a collection of colored glass and neutral-density filters and enters a glass cross through a 3-in. diam quartz window. Inside the cross, a 55-mm focal length quartz lens focuses the laser energy near the vertical centerline of a flat-flame burner. The laser beam exits the cross through another 3-in. quartz window and is detected through a Schott KG1 filter by means of a thermopile detector head connected to a Scientech No. 362 power/energy meter.

The burner, which was developed by Battelle Columbus Laboratories, produces a disk-shaped flat flame with a visible combustion zone ~2.5 in. in diam and 0.5-2.0 mm thick. The flame thickness depends upon the combustion gases and the total flame pressure. The burner assembly, including flameholder, was constructed of stainless steel. The gas flow rates are controlled by means of pressure regulators which maintain constant gas pressure on the high-pressure side of sonic nozzles (jeweled orifices). For this experiment, a methane flame was produced in the burner using an oxygen-rich gas mixture (CH_4:O_2:N_2 = 0.093:0.220:0.687 in mole-fraction). The peak temperature in the flame, measured by means of a Pt-Pt 10% Rh thermocouple, was ~1830 K.

Fluctuations which occurred in the energy-meter readings were caused by environmental conditions and background radiation. Two steps were taken to minimize these fluctuations:

1) The effects of temperature gradients in the surrounding air upon the thermopile were reduced through the use of an insulated enclosure which allowed a 1-in. diam access to the detector head.

2) A KG1 filter, mounted at this access port, was used to absorb the IR radiation produced in the flame; with this filtering, the background energy affecting the detector was independent of the observed position within the flame.

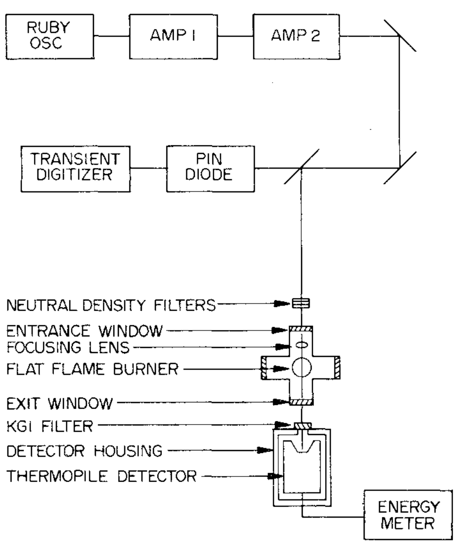

Fig. 1 Schematic diagram of the experimental system for breakdown threshold measurements.

The experimental procedure used to determine the laser energy required for media breakdown consisted of monitoring the laser pulse shape on the transient digitizer, recording the energy-meter reading, and adjusting the laser power to the required levels. The PIN diode/digitizer combination supplied information on the pulse width and the relative amplitude of the laser pulse.

Optical breakdown in the gaseous media manifests itself in three ways. The first two are the generation of a visible discharge and an audible "snap" in the focal volume. The third phenomenon, which was most heavily relied upon, was the pronounced reduction (by a factor of two or more) in the laser energy transmitted through the affected media.

Adjustment of the amount of laser energy focused in the flame was accomplished in two ways. Large-scale power changes were accomplished by insertion of various combinations of neutral-density filters into the beam, and fine adjustments in intensity were made by changing the ruby amplifier flashlamp voltage. Thus, by increasing the laser pulse energy to the breakdown limit and measuring the energy transmitted in a "clean" Gaussian beam, the point of optical breakdown was determined.

To arrive at the power density required to cause breakdown in the media, the following expression was employed:

$$P_d = E_{\text{det}} / [\tau_{pw} T_c (\pi/4) (1.22\lambda f/D)^2]$$

where P_d = power density, E_{det} = detected laser energy, τ_{pw} = laser pulse width (FWHM), T_c = combined transmission of exit window and KG1 filter, λ = ruby-laser wavelength, f = focal length of focusing lens, and D = diameter of laser beam at focusing lens. The values of the parameters used in these measurements were τ_{pw} = 13 ns, T_c = 63%, λ = 6943 Å, f = 55 mm, and D = 3.5 mm. The use of the diffraction limited spot size in the preceding expression is justified, since the ruby laser energy was supplied in a single mode Gaussian beam, as verified by the far-field pattern, and the effects of spherical aberration due to the optics used in this experiment were negligible.

Results and Discussion

Figure 2 shows the variation of breakdown power densities determined through the procedure just mentioned for five sets of conditions existing at the focal volume. Curves 1 and 2 represent the breakdown threshold of room temperature air at 1 atm and at 130 Torr, respectively, which serve as a "gage" for determining the relative threshold levels of flames under various conditions. The threshold value for 1-atm air is approximately one order of magnitude higher than that obtained previously[5] using a multimode ruby laser. This difference in threshold can be attributed, for the most part, to the dif-

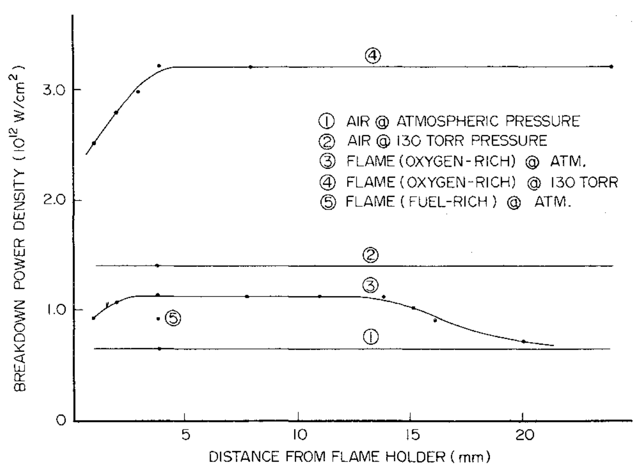

Fig. 2 Laser-induced breakdown threshold profile of the premixed methane flat flame.

ference in the experimental parameters employed; in the previous measurement, the spot size and the pulse duration were ~200 μ and ~30 ns, respectively, as compared to ~14 μ and ~13 ns, respectively, the in the present experiment. It is a well-established fact that a decrease in spot size and pulse duration causes an increase in the threshold.[6-8] Curves 3 and 4 represent the breakdown-threshold profile of the oxygen-rich flame described earlier at 1 atm and 130 Torr, respectively. The threshold measurements were made in the flame region which extended from in or below the visible flame zone well into the postflame zone.

It becomes immediately apparent upon examination of data (by comparing curves 1 and 3 as well as 2 and 4) that the breakdown threshold within a flame is greater than that in air under equal pressure conditions. It is of particular interest that this is true even for the visible flame zone (~1-3 mm), where the most intense part of the combustion processes is in progress. It can also be observed, by comparing curves 3 and 4, that the threshold increases monotonically as the pressure of the flame is decreased. In fact, the shape of curves 3 and 4 show that the threshold profiles of the flames are consistent with the known total number density profiles of these flames.

From these observations, two general conclusions may be drawn concerning the gas breakdown threshold encountered in this experiment: 1) the breakdown threshold increases monotonically as the local molecular number density within the focal volume decreases, and 2) the presence of combustion processes in the flame does not significantly reduce the breakdown threshold of the gas media.

Threshold measurements were also made for fuel-rich (dirty) flames at 1 atm pressure. A typical result is shown by point 5 in Fig. 2. Although there is some reduction in the threshold value relative to that of oxygen-rich (clean) flames, at no time was it lower than that in air.

In conclusion, the optical breakdown threshold power density has been measured for a laboratory premixed methane flame. It has been demonstrated that the presence of combustion processes does not significantly reduce the breakdown threshold power density in flames and that even in dirty (fuel-rich) flames, the threshold is still somewhat higher than that in air at a comparable pressure. This information should be of value in developing laser-based optical combustion diagnostic systems.

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References

[1] Hartley, D., Lapp, M., and Hardesty, D., "Physics in Combustion Research," *Physics Today*, Dec. 1975, pp. 36-47.

[2] Lapp, M. and Penney, C.M., eds., *Laser Raman Gas Diagnostics*, Plenum Press, New York, 1974.

[3] Ready, J. F., *Effects of High-Power Laser Radiation*, Academic Press, New York, 1971, Chap. 5.

[4] Shkarofsky, I. P., "Review of Gas-Breakdown Phenomena Induced by High-power Lasers," *RCA Review*, Vol. 35, March 1974, pp. 48-78.

[5] Nelson, P., Veyrie, P., Berry, M., and Durand, Y., "Experimental and Theoretical Studies of Air Breakdown by Intense Pulse of Light," *Physics Letters*, Vol. 13, 1964, p. 226.

[6] Alcock, A. J., DeMechelis, C., and Richardson, M. C., "Breakdown and Self-focusing Effects in Gases Produced by Means of a Single-Mode Ruby Laser," *IEEE Journal of Quantum Electronics*, Vol. QE-6, Oct. 1970, pp. 622-629.

[7] Belland, P., DeMichelis, C., and Mattiolli, M., "Self-focusing in Laser Induced Gas Breakdown," *Optics Communications*, Vol. 4, 1971, p. 50.

[8] Smith, P. C., "Gas Breakdown Dependence on Beam Size and Pulse Duration with 10.6 μ Wavelength Radiation," *Applied Physics Letters*, Vol. 19, 1971, p. 405.