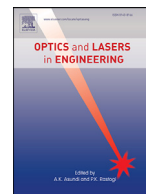




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High speed temperature, pressure, and water vapor concentration measurement in explosive fireballs using tunable diode laser absorption spectroscopy

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ABSTRACT

Results from the design, development, and testing of a probe capable of making quantitative measurements of temperature, pressure, and water vapor concentration in near field explosive detonations are presented. This work extends established tunable diode laser absorption techniques to the field of explosive and energetic materials diagnostics with improved temporal resolution. Simultaneous measurement of temperature, pressure, and water vapor concentration were successfully measured at 30 kHz in a constant volume explosion at a standoff distance of 52 cm from 40 g of PBXN-5. Explosive testing was conducted in the 1.81 m³ blast chamber at the University of Illinois at Urbana-Champaign Energetic Materials Diagnostics Lab. Measured values compared very well to theoretical calculations for shocked air during the blast phase as well as late-time quasi static conditions. Data show a discrepancy between pressure and temperature equilibration times. This observation is attributed to comparatively slow mass diffusion of explosive products and thermal diffusion of heat relative to pressure equilibration through shock reflections.

1. Introduction

Temperature is one of the most critical thermodynamic properties for explosive diagnostics. Its dictation of chemical speciation and equation of state alone have made its measurement the focus of experimentalists for a long time. Unlike pressure, which has a relatively simple method of collection with piezoelectric transducers, unperturbed temperature of an explosion cannot be readily obtained. Thermocouples suffer from time-response limitations that make gas-phase measurements at rates higher than 1 kHz difficult.

Surface temperature of explosive fireballs has been successfully measured through numerous emission techniques [1,2]. In addition to the standard assumptions of excited state equilibrium conditions, these measurements are also limited to characterizing the explosive fireball only up to the attenuation length scale. This dimension can be on the order of centimeters in some cases [3]. Although pyrometry techniques demonstrate impressive temporal resolution, there is uncertainty as to whether these measurements characterize condensed or gas phase species in the event [4]. To characterize the internal gas temperature and speciation of explosive fireballs, a probe was developed to house a tunable diode laser (TDL), infrared detector, and pressure transducer. The probe then survives being engulfed in the explosive shock and detonation products, enabling any number of proven TDL combustion techniques to be fielded

[5–9]. The probe is shown mounted in the explosive blast chamber in Fig. 1.

Temperature measurement in explosive fireballs using the 1300 nm water band has been previously demonstrated at Naval Surface Warfare Center Indian Head (NSWCIH) and Marquette University [10–12]. As was done in the present work, researchers designed and constructed a hardened gauge capable of witnessing high explosive events. In contrast to the current designs swept wavelength source, their process employed pitching a broadband light source across a slab of explosive product gas and collecting it on a catch fiber to be brought out of the chamber and separated in a spectrometer [10,12]. This technique was utilized to evaluate a variety of high explosives including non-ideal formulations that are fuel-rich and are, therefore, expected to produce optically thick product clouds [11].

The new technique presented in this paper strives to build upon the previous work in the field to enhance both temporal scale and resolution while minimizing cost. These new developments extend the ability of the technique to be field deployable. To do this, the use of a spectrometer, pixel array, and broadband light source was eliminated in favor of a single pixel detector and a tunable diode laser. The limited amount of data broadcast by the photodiode allows a longer time scale to be collected, and its small size and low cost also allows it to be placed in the hardened gauge in order to extract an electrical signal as opposed to the

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Fig. 1. The probe (bottom right corner) mounted in the 1.81 m³ explosive blast chamber at the University of Illinois at Urbana-Champaign Explosive Diagnostics Lab.

use of an output fiber, minimizing signal losses. This change also eliminates the need to deploy and calibrate a spectrometer on location in the case of field testing. These variations along with a robust processing algorithm are used to provide a simplified technique and methodology for rapidly deploying a wide variety of lab-proven tunable diode laser absorption techniques to large scale explosive testing.

2. Technique and methodology

A few of the technical challenges overcome in this diagnostic development include blast wave survivability, non-resonant background arising from turbulent flow, broadband thermal emission of explosive products, and substantial pressure broadening of spectral features. In the context of a chambered, or partially vented explosive test, not only the initial blast wave, but constructive reflected shocks will cause multiple atmospheres of accumulated pressure. All these obstacles were overcome by both mechanical design of the probe and novel data analytics.

As previously demonstrated by Mattison et al., this diagnostic employs a 1390 nm tunable diode laser to scan over the water vapor absorption features located at 1389.76 and 1390.05 nm [5,9]. The laser used was an Eblana Photonics® EP1392-5-DM-B01-FA, being driven by an Arroyo Instruments 6301 ComboSource. Injection current to the diode driver was supplied by a BK Precision 4055 arbitrary waveform generator. The detector used to measure the transmitted laser signal was a ThorLabs DET20C. Dynamic pressures were measured with an Endevco® 8530B transducer, amplified with a 4428A signal conditioner. Pressure transducer, and photodiode output voltages were recorded with a PicoTechnology, 4424 digital oscilloscope at a rate of 10 MHz. Other off the shelf supplies included a FC/APC to FC/PC patch cable from ThorLabs (P#: P5-SMF28E-FC-2), a beam collimator from ThorLabs (P#: F220FC-C), a 1" wedged calcium fluoride window also from ThorLabs (P#: WW51050), a low optical depth thin film filter from Roscolux (100 Frost), a bandpass filter, and a short focal length lens. The remaining parts of the apparatus were fabricated in-house, such as aluminum parts for the probe body, a Delrin® mount for the beam collimator and pressure transducer, and a holder to maintain the angle of the bandpass

filter. A depiction of how the internal components of the probe were configured is shown in Fig. 2.

As in all absorption spectroscopy techniques, this measurement is path-averaged and thus cannot resolve gradients between emitter and detector. The probe was designed explicitly to have a field-selectable path length. With all the optoelectronics contained in the vertical tubes, having multiple base plates of different lengths with mounting bolt patterns enables custom selection of a path length that can achieve the optimal balance of species absorption depth to total signal attenuation. This is a critical design feature given the dynamic change of water vapor content between ambient, shocked, and combustion air in a given test.

In climates with very little ambient water vapor, it becomes necessary to use a longer path length to quantify shocked air, as that change does not contribute any absorbing species to the signal. The drawback to this is with the increase path length, the beam steering on density gradients can degrade the signal beyond usability and spatial resolution is reduced. An alternative approach in chambered experiments is to increase chamber vapor content prior to detonation by letting liquid water evaporate, or burning a hydrocarbon in the sealed vessel. In the data presented here, a 28 cm path length was used, and chamber surfaces were slightly wetted prior to testing. Other tests were conducted with 13 cm path lengths without any need for added water vapor due to greater ambient humidity. Shorter path lengths provide better signal quality, with higher spatial resolution.

The charges tested in this work were assembled from 28 g PBXN-5 pellets, both whole and fractured to create appropriate size charges. These charges were initiated with a Teledyne RP-81 detonator. A Teledyne RISI FS-61B fireset was used in conjunction with a Quantum Composers 9520 Series pulse generator for triggering the oscilloscope and charge simultaneously.

The chamber utilized in this work was a 48" cube constructed of $\frac{1}{2}$ " thick steel with one side removable for access held on by 24, $\frac{3}{4}$ " bolts. This chamber is well established by the Energetic Materials Diagnostic Lab at University of Illinois Urbana-Champaign to be able to handle charges of this size. It is equipped with 2 wall mounted piezoresistive static pressure sensors, 2 lollipop mounted, movable piezoresistive static pressure sensors, and 2 piezoelectric pencil-style mounted dynamic pressure sensors. These sensors, while not used directly in the analysis, were utilized for verification of pressure data collected by the probe.

3. Data processing and analytics

Given the overlap of spectral lines in this feature, it is difficult to numerically integrate peaks to obtain absorbance. This problem is only exacerbated with the observed pressure broadening. In line with the work of Carney and Lightstone [10], it was determined that the most accurate way to extract temperature and concentration was to fit the measured spectra to a physically accurate model. Briefly, transition parameters were taken from the HITRAN 2016 database, and all temperature dependent properties were scaled appropriately; the partition function (including nuclear contributions) was reconstructed from polynomials, the Voigt function was taken as the real part of the Fadeeva function, and the temperature scaling exponent for pressure shift coefficients was taken to be 0.96 [7,13,14]. While much of the accuracy of this model exceeds the resolution of the experimental data, it was rigorously validated with comparison to published models spanning the appropriate temperature and pressure domain [15].

Raw voltages recorded on the digital oscilloscope were separated into individual scans and a background was reconstructed using a spline fit between two linear regressions of data outside the water vapor absorption band. One regression is drawn backwards from data points above the spectrum, and one drawn forwards from points below it. The sensitivity to background fit is dominant at lower temperatures, where the lower wavenumber transition is substantially weaker. At higher temperatures when both features are well defined the accuracy of fitted temperature and concentration is obviously enhanced.

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