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Diagnostics of flame temperature distribution of solid propellants by spectrographic analysis

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Abstract

A diagnostic technique based on spectrographic analysis for nitrogen ion emission spectra was developed to measure the flame temperature distributions of solid propellants. The experimental equipment consists of a combustion chamber with a window, an optical scanning unit, a grating spectrograph, and data collection and treatment units. It has been applied to double base (DB), hydroxyl-terminated polybutadiene (HTPB), nitrate ester plasticized polyether (NEPE), and hexanitrohexaazaisowurtzitane (HNIW) propellants. The existence of the dark zone for a DB propellant could be revealed by this method. The highest measured flame temperature is comparable with the theoretical one and those obtained by thermocouple methods. The assumptions of the method and fluctuations in the temperature profiles are discussed.

Keywords: Spectrographic analysis; Flame temperature; Solid propellant

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1. Introduction

A wealth of attention has been paid to estimation of the burning rates and flame structures of solid propellants, based on theoretical models [1–3], to arrive at an in-depth understanding of their combustion mechanisms. Validation of the theoretical results requires measurement of temperature and species profiles in propellant flames. An accurate diagnosis of the flame temperature distribution is thus extremely important for solid propellant combustion research.

The diagnostics of flame temperature distribution involves intrusive and nonintrusive techniques. Intrusive diagnostics can be achieved by embedding thermocouples within propellant strands. It can provide the entire temperature profile from the preheat zone, subsurface, surface, and primary flame to the final flame [4,5]. Several nonintrusive techniques have been developed to determine temperature and species concentration profiles, including coherent anti-Stokes Raman spectroscopy (CARS) [6,7], planar laser-induced fluorescence (PLIF) [8], and ul-

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traviolet (UV)–visible [9] and Fourier transform infrared (FTIR) [10,11] absorbance spectroscopy.

In this paper, a new diagnostic technique for the flame temperature distribution of solid propellants is reported, based on spectrographic analysis of the nitrogen ion emission spectrum in the visible region.

1.1. Principles of the diagnostic system

For a characteristic spectral line emitted by an atom or ion, assuming an optically thin flame in a local thermodynamic equilibrium (LTE) state, its emission coefficient ε_ν can be written as

$$\varepsilon_\nu = \frac{h\nu}{4\pi} A_{\mathrm{ul}} g_{\mathrm{u}} \frac{N(T)}{U(T)} \exp\left(-\frac{E_{\mathrm{u}}}{kT}\right). \tag{1}$$

Here, ε_ν is defined as the power emitted per unit solid angle and unit volume at frequency ν of a spectral line, with E_{u} energy of the upper level; $N(T)$ number density of particles; $U(T)$ partition function; and A_{ul} transition probability for the emission. $A_{\mathrm{ul}} = 7.407 \times 10^{-22} \nu^2 f_{\mathrm{lu}} g_{\mathrm{l}}/g_{\mathrm{u}}$, where $g_{\mathrm{u}}, g_{\mathrm{l}}$ are the statistical weights for the upper and lower energy level, respectively; f_{lu} is oscillator strength; h is the Planck constant; and k is the Boltzmann constant.

Equation (1) defines a relationship between ε_ν and T. For there are two spectral lines with frequencies ν' and ν for the same species in the flame, where ε'_ν and ε_ν can be obtained simultaneously in the emission spectra, and a relative intensity method based on the equation

$$\frac{\varepsilon_\nu}{\varepsilon'_\nu} = \frac{g_{\mathrm{l}} f_{\mathrm{lu}} \nu^3}{g'_{\mathrm{l}} f'_{\mathrm{lu}} \nu'^3} \exp\left(\frac{E'_{\mathrm{u}} - E_{\mathrm{u}}}{kT}\right) \tag{2}$$

can be used to calculate flame temperature with the known E_{u}, g_{l}, and f_{lu}.

In practical spectrographic analysis, the emission intensity I, instead of ε_ν, of the spectral line is measured, but for an axially symmetrical flame, ε_ν can be computed through Abel's transformation for I.

For an axially symmetrical flame, the Abel transformation at radial section R can be expressed following Eqs. (3)–(5), which concerned the emission intensity $I(y)$, as shown in Fig. 1, with the emission coefficient $\varepsilon(r)$ of the spectral lines:

$$I(y) = \int_0^x \varepsilon(r)\,\mathrm{d}x, \tag{3}$$

$$I(y) = 2\int_y^R \frac{\varepsilon(r) r\,\mathrm{d}r}{\sqrt{r^2 - y^2}}, \tag{4}$$

$$\varepsilon(r) = -\frac{1}{\pi}\int_r^R \frac{\mathrm{d}I(y)/\mathrm{d}y}{\sqrt{y^2 - r^2}}\,\mathrm{d}y. \tag{5}$$

Here, $r = (x^2 + y^2)^{1/2}$ and $I(R) = 0$.

1.2. Characteristic spectral lines of propellants

For the common DB and HTPB propellants, their emission spectra recorded at atmospheric conditions with a grating spectrograph are shown in Fig. 2. The emission spectra from 500 to 800 nm contain a weak continuous spectrum, as well as many characteristic spectral lines and bands.

Three spectral lines of nitrogen (II) ions at $\lambda = 624.241$, 701.398, and 701.473 nm for both DB and HTPB propellant flames were observed in the emission spectra in Fig. 2.

It should be noted that the two spectral lines at 701.398 and 701.473 nm are so extremely close as to be inseparable. For $\lambda = 624.241$ nm, ε_ν is obtainable; but for $\lambda' = 701.398$ nm and $\lambda'' = 701.473$ nm, ε'_ν or ε''_ν cannot be determined individually. Instead, a total emission coefficient $\varepsilon'_\nu + \varepsilon''_\nu$ is obtained for this wavelength region. Therefore, supposing that the inseparable spectral lines have the same upper-level energy, $E'_{\mathrm{u}} \approx E''_{\mathrm{u}}$, and frequency, $\nu' \approx \nu''$, Eq. (2)

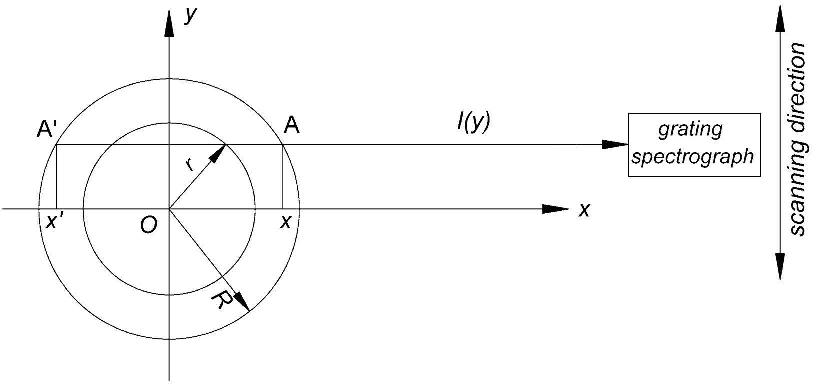

Fig. 1. Sketch map on Abel transformation from $I(y)$ to $\varepsilon(r)$.