RADIATIVE CHARACTERISTICS OF FLAMES

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A method is proposed for determining the flame temperature from the location of the maximum of the spectral density of the radiation as determined from a finite number of frequency moments.

Determining the radiation temperature of a flame is of importance both for increasing the operational reliability of fire detectors and for monitoring the progress of engineering processes. The methods currently in use do not lack shortcomings [1]. Thus, in methods based on a generalized inversion of spectrum lines, absorption and emission, and pyrometry, experimenters use the Wien radiation law. This, in turn, places a limit of $T > 3000$ K on the temperature measurement. When the temperature is measured from the Doppler broadening of spectrum lines it is not entirely clear how to isolate effects owing to collisions among gas molecules (Lorentz broadening). For a discussion of the shortcomings of the other methods see [1]. In addition, these methods do not yield the desired measurement accuracy.

In this paper we propose a method for determining the actual radiation temperature of a flame from the location of the maximum of the spectral density of the radiation (an analog of the Wien displacement law). This can be used to determine the radiation temperature both in the well-studied Wien region and for $T < 3000$ K. This method has been tested on the emission spectra of the carbides of zirconium and titanium [2] as well as tungsten [3]. It is shown that if the experimental profile of the radiation is smooth, then it is well approximated by an Edgeworth series. The error in the approximation is less than 5%. The fit parameters are obtained from the moments of the spectral density of the radiation which, in turn, are determined from the measured values of the emissivity of real bodies. We note that the method proposed in [2] and [3] has fairly good accuracy. The latter is limited essentially only by the accuracy with which the frequency moments of the spectral radiation density can be found. The procedure for finding the temperature can be completely automated.

The location of the maximum of the fundamental mode of the spectral density is given by [2, 3]

$$\nu_{\max} = \frac{m_1}{m_0}\left(1 - \frac{m_0\overline{m}_3}{2m_1\overline{m}_2}\right). \tag{1}$$

Here $m_n = \int \nu^n I(\nu,\ T)\,d\nu$, $\overline{m}_n = \int (\nu - \overline{\nu})^n I(\nu,\ T)\,d\nu$ are the zeroth order and central moments of the distribution function $I(\nu, T)$; $n = 0, 1, 2, 3, \ldots$ are the orders of the moments. The zeroth moment m_0 is equal to the area of the distribution and the ratio m_1/m_0 is its center of gravity. The second central moment is related to the width of the distribution and the third, to its asymmetry. It has been shown that in the case of an absolute black body, Eq. (1) transforms to the standard Wien displacement law [4] and the error in the temperature determination is then less than 1%.

We shall be concerned with a study of the temperature dependence of $\nu_{\max}$ for a variety of flames. A flame whose fuel contains hydrocarbons contains suspended carbon particles (soot) when hydrocombustion is incomplete. In this case the soot particles radiate as black bodies and have a continuous emission spectrum with a high black body coefficient. Thus, the radiation from the entire flare of a luminous flame is composed of the intrinsic radiation from atoms and molecules in discrete regions of the spectrum plus the radiation from soot particles suspended in the flare. If the flames are not stationary, then the thermal inertia of the soot particles causes their temperature to lag behind the temperature of the flare. Thus, if a procedure for separating the components owing to the intrinsic radiation from the flame and the soot particles is known, then the actual temperatures of the separate components can be obtained from the measured maxima of the spectral radiation density according to Eq. (1).

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In the following we use a variety of flames (acetone, amylacetane, etc.) to illustrate this method for determining the actual radiation temperature in the case of steady-state combustion, when the temperature of the soot particles and the surrounding gas are close so that there is no need to isolate the two contributions mentioned above.

Given the Planck formula [5] for the volume density of radiant energy from an absolute black body,

$$u_\nu^0 = \frac{8\pi h}{c^3} \frac{\nu^3}{l^{\frac{h\nu}{kT}} - 1}, \tag{2}$$

where h is Planck's constant, c is the speed of light, k is Boltzmann's constant, and ν is the frequency, it is possible to write the volume density of radiant energy from real bodies in the form

$$I(\nu, T) = \varepsilon(\nu, T) u_\nu^0, \tag{3}$$

where $\varepsilon(\nu, T)$ is the emissivity of a heated body. It has been shown [1] that for a variety of flames

$$\varepsilon(\nu, T) = \varepsilon_0 \nu^n \tag{4}$$

where n is different for different kinds of flames. (See the Table.)

Calculated ratios of the moments and location of the maximum of the volume density of radiant energy for different flames.

Let us construct the spectral density of the radiation for an acetone flame (n = 1.43). Using Eqs. (2)-(4), we find the zeroth moment of $I(\nu, T)$ using the formula

$$m_0 = \int_0^\infty I(\nu, T)\, d\nu = \varepsilon_0\, 5.98 \cdot 10^{-0.3} T^{5.43} \left(\frac{\mathrm{J}}{\mathrm{K}^{5.43} \cdot \mathrm{m}^3 \cdot \mathrm{sec}^{1.43}} \right). \tag{5}$$

Here and in the following we use the following integral for calculating the higher order moments [6]:

$$\int_0^\infty \frac{z^{x-1}}{l^z - 1}\, dz = \Gamma(x)\, \zeta(x), \tag{6}$$

where $\Gamma(x)$ is the gamma function and $\zeta(x)$ is the Riemann function (both these functions have been tabulated). According to Eqs. (2)-(4) and the frequency moments of the spectral density of the radiation for acetone are given by

$$\begin{aligned} m_1 &= \int_0^\infty \nu I(\nu, T)\, d\nu = \varepsilon_0\, 6.55 \cdot 10^{10.7} T^{6.43} \left(\frac{\mathrm{J}}{\mathrm{K}^{6.43} \cdot \mathrm{m} \cdot \mathrm{sec}^{2.43}} \right), \\ m_2 &= \int_0^\infty \nu^2 I(\nu, T)\, d\nu = \varepsilon_0\, 8.74 \cdot 10^{21.7} T^{7.43} \left(\frac{\mathrm{J}}{\mathrm{K}^{7.43} \cdot \mathrm{m}^3 \cdot \mathrm{sec}^{3.43}} \right), \\ m_3 &= \int_0^\infty \nu^3 I(\nu, T)\, d\nu = \varepsilon_0\, 1.35 \cdot 10^{33.7} T^{8.43} \left(\frac{\mathrm{J}}{\mathrm{K}^{8.43} \cdot \mathrm{m}^3 \cdot \mathrm{sec}^{4.43}} \right). \end{aligned} \tag{7}$$

Using the relationship between the zeroth order and central moments $\bar{m}_2 = m_2 - m_1^2/m_0$, and $\bar{m}_3 = m_3 - 3(m_2 m_1/m_0) + 2(m_1^3/m_0^3)$, we obtain

$$\begin{aligned} \bar{m}_2 &= m_2 - \frac{m_1^2}{m_0}, \quad \bar{m}_3 = m_3 - 3\frac{m_2 m_1}{m_0} + 2\frac{m_1^3}{m_0^2}, \\ \bar{m}_2 &= \int_0^\infty (\nu - \bar{\nu})^2 I(\nu, T)\, d\nu = \varepsilon_0\, 1.34 \cdot 10^{21.7} T^{7.43} \left(\frac{\mathrm{J}}{\mathrm{K}^{7.43} \cdot \mathrm{m}^3 \cdot \mathrm{sec}^{3.43}} \right), \\ \bar{m}_3 &= \int_0^\infty (\nu - \bar{\nu})^3 I(\nu, T)\, d\nu = \varepsilon_0\, 0.51 \cdot 10^{32.7} T^{8.43} \left(\frac{\mathrm{J}}{\mathrm{K}^{8.43} \cdot \mathrm{m}^3 \cdot \mathrm{sec}^{4.43}} \right), \end{aligned} \tag{8}$$

where $\bar{\nu} = 1.09 \cdot 10^{11} T$ (1/K ·sec).

TABLE 1

N	n	$\frac{m_1}{m_0}10^{11}\cdot T$, 1/K·s	$\frac{m_0\overline{m_3}}{2m_1\overline{m_2}}$	$\frac{h\nu_{\max}}{kT}$
Acetone	1,43	1,09	0,17	4.35
Amylacetane	1,39	1,01	0,19	4,27
Benzene	1.23	1,07	0,20	4,12
Benzene	1,05	1,03	0,22	3,91
Nitrocellulose	1,14	1,05	0,21	3,99

Substituting Eqs. (5), (7), and (8) in Eq. (1), we obtain the temperature dependence of the location of the radiation maximum for acetone:

$$\nu_{\max} = 0.91\cdot 10^{11}T\left(\frac{1}{\mathrm{K\cdot s}}\right). \tag{9}$$

Finally, according to Eq. (9) the Wien displacement law takes the form

$$h\nu_{\max}/kT = 4.35.$$

The Wien displacement law is derived for the other kinds of flames in the same way.

The Table lists the calculated ratios of the moments of the distribution function used in Eq. (1) and the Wien displacement law $h\nu_{\max}/kT$ for five types of flame. It is clear that a unique determination of the radiation temperature of a flame will require precision measurements of only the location of the maximum of the volume energy density of the radiation.

We note here that if the location of the maximum of the volume energy density of the radiation is determined in the standard way ($\partial I(\nu, T)/\partial\nu = 0$, $\partial^2 I(\nu, T)/\partial\nu^2 < 0$) then a computer is needed to solve the transcendental equation. On the other hand, Eq. (1), which gives the location of the radiation peak in terms of a finite number of moments, yields the same results from a simple calculation. Furthermore, if the emissivity $\varepsilon(\nu, T)$ of real bodies is given in the form of tables, then it is impossible to determine $\nu_{\max}$ in the standard way. When Eq. (1) is used, however, it is quite possible to obtain the displacement law for the maximum [2, 3].

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