How Well Are We Measuring Smoke?*

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Estimates of the errors in light extinction measurements of smoke resulting from forward scattered light entering the detector and from the spectral width of the light source are presented. It is shown for specific examples that each of these effects can lead to an error of about 25% in typical applications. A potential method for calibrating extinction instruments is described.

INTRODUCTION

The most common measurement of smoke in the fire research community is the measurement of the light extinction coefficient or, equivalently, the optical density. The physical basis for light extinction measurements is Bouguer's law, which relates the intensity of the incident monochromatic light of wavelength λ, I_λ^0, and the intensity of the light, I_λ, transmitted through a path length L of the smoke

$$I_\lambda/I_\lambda^0 = e^{-KL} \qquad (1)$$

where K is the extinction coefficient. When Eqn (1) is expressed in terms of base 10

$$I_\lambda/I_\lambda^0 = 10^{-D_L L} \qquad (2)$$

the quantity D_L is defined as the optical density per path length L.

The extinction coefficient K is an extensive quantity and can be expressed as the product of an extinction coefficient per unit mass, K_m, which is an intensive quantity depending on the size distribution of the smoke and its optical properties, and the mass concentration of the smoke aerosol, m.

$$K = K_m m \qquad (3)$$

The resulting proportionality between $\ln (I_\lambda/I_\lambda^0)$ and the mass concentration, m,

$$\ln (I_\lambda/I_\lambda^0) = -K_m mL \qquad (4)$$

is the central result for the following discussion of smoke measurements by extinction. This is another form of Bouguer's law, which is also called the Lambert–Beer Law. An ideal extinction instrument is one that satisfies Eqn (4) for all values of m. We shall discuss two deviations from ideality present in most extinction instruments: forward scattered light entering the detector and the spectral width of the light source.

FORWARD SCATTERED LIGHT

In any extinction instrument the measured intensity includes not only the transmitted light but also light scattered in the forward direction. For extinction instruments with apertures before the detector, Hodkinson[1] gives a practical design criterion. This requires that the angle subtended by the diameter of the aperture at its lens, θ (see Fig. 1), be not more than one-tenth of the first angular minimum in the Fraunhofer diffraction pattern of an aperture with area equal to the projected area of the smoke particle. The first minimum in the Fraunhofer diffraction pattern is at $(3.84\ \lambda/\pi D)$ rad, where D is the diameter of the aperture. For a smoke particle of 5 μm diameter and for a 0.55 μm light source, the aperture angle, θ, corresponds to 0.012 rad (0.7°). The smaller the particle diameter the less intense the forward scattering, so the deviation from ideality decreases as the particle size decreases.

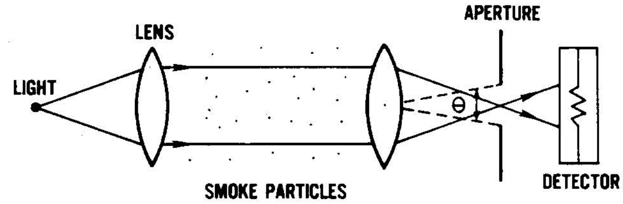

Figure 1. A schematic of the extinction instrument developed by Gross *et al.* is shown here. In the Bukowski design there is no aperture and the detector is located at the focal point of the lens. The angle θ is the angle subtended by the aperture with respect to its lens.

It is seen that particle diameter is an important parameter in determining the appropriate collection optics. Unfortunately, there are only limited size distribution data for smoke. Mulholland and Ohlemiller[2] obtained mass median diameters in the range 2–3 μm for a smoulder source of realistic scale with smoke measured near the source. Measurements of mass median diameters of smoke produced by the combustion of small-size samples for a number of materials including Douglas fir, polypropylene, and urethane foam by Bankston *et al.*[3] yielded mass median diameters in the range 0.34–2.10 μm. Allowing for scale effects and the increase of particle size due to coagulation as the smoke accumulates in an enclosure, it would appear that 5 μm would be a reasonable upper limit to the particle mass median diameter for full-scale fires.

There are many extinction instrument designs currently in use at fire research laboratories. At the

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National Bureau of Standards two designs are used. One was developed by Gross *et al.*[4] for the measurement of the wide range of smoke concentrations generated in the NBS smoke density chamber, which is described and its use specified in ASTM Standard E 662–79.[5] Using the parameters for this extinction beam, 14.3 cm focal length and 0.2 cm aperture, one finds that the angle subtended by the aperture at its lens to be 0.014 rad (0.8°). This is close to the limit given above for a 5 μm particle diameter and a 0.55 μm wavelength light source so that forward scattered light is not a serious problem in this case. However, as discussed below, the broad spectral width of the incandescent light source in this extinction instrument can be a significant source of error.

A second extinction instrument was developed by Bukowski[6] primarily for use in characterizing the performance of smoke detection devices. This application involves precise measurements of very low smoke concentration, $K < 0.1\ \mathrm{m}^{-1}$. In the Bukowski design, the phototube detector is located at the focal point of the lens (10 cm focal length) so the effective pinhole angle, θ, is determined by the size of the detector (1.59 cm × 2.06 cm). Even using the smaller detector dimension, we obtain a large value for θ, 0.079 rad (4.5°). This value is about six times greater than the maximum angle given above based on Hodkinson's criterion. Alternatively, it can be said that, based on the Hodkinson criterion, the Bukowski design is limited to observing smoke particles smaller than 0.8 μm. A quantitative estimate of the error from forward scattering for this case can be obtained from Deepak and Box's[7] theoretical analysis based on Mie scattering. Deepak and Box's plot of the correction factor $\hat{R}$, which is defined as the ratio of the measured to the true extinction coefficient averaged over the optical path, versus the dimensionless parameter y, defined by

$$y = \frac{\pi D}{\lambda}\theta$$

is reproduced in Fig. 2 for the case of lens-pinhole detector. Using the same particle size and wavelength as above and a particle refractive index of 1.5, we obtain $y = 2.27$ and a corresponding $\hat{R}$ of about 0.7. The relationship between the true intensity ratio, I^t/I_0, and the measured ratio, I^m/I_0, is given by

$$I^t/I_0 = (I^m/I_0)^{1/\hat{R}}$$

For a measured ratio of 0.1 and $\hat{R}$ equal 0.7, the true ratio equals 0.037.

The analysis of Deepak and Box assumes no multiple scattering, which refers to the scattering of a single photon two or more times by particles. Multiple scattering increases as the particle concentration increases. Concerning the effect of increased particle concentration, Hodkinson[1] states '. . . the angular distribution of scattered light will become less forwards-directed and so the proportion of scattered light falling on the wrongly placed photocell [referring to detector receiving scattered light] decreases, and the exponential relation between transmittance and particulate concentration [Bouguer's law] no longer applies'. It should be pointed out that for a properly constructed

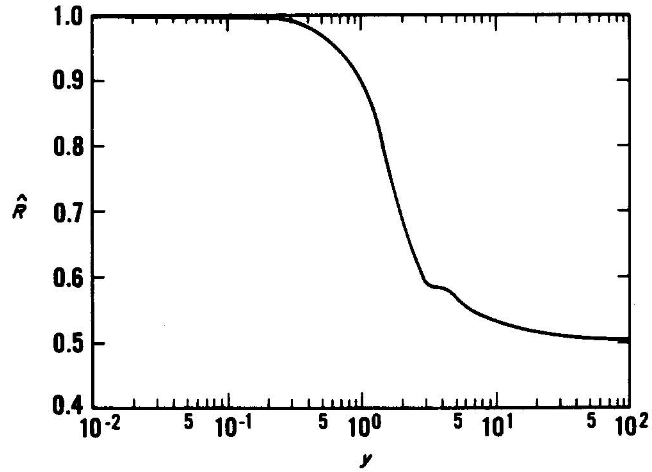

Figure 2. Plot of the path-averaged correction factor $\hat{R}$ as a function of y.

extinction instrument, for which scattered light does not reach the detector, multiple scattering is not a problem. A possible method for experimentally testing Bouguer's law for an extinction instrument is presented in the next section.

EFFECTS OF WHITE LIGHT

The second source of non-ideality is the spectral width of the source. Bouguer's law is only valid for a monochromatic light source. By integrating equation (1) over the spectral width of the source, one obtains

$$\frac{I_t}{I_t^0} = \frac{\int_{\lambda_1}^{\lambda_2} I_\lambda^0\, e^{-KL}\, d\lambda}{\int_{\lambda_1}^{\lambda_2} I_\lambda^0\, d\lambda} \qquad (5)$$

This relationship is for the case of a flat spectral response of the detector over the range λ_1 to λ_2; otherwise, I_λ^0 (Eqn (5)) would be multiplied by the detector response function C_λ. The quantity I_t represents the total intensity of the transmitted light. The extinction coefficient, K, is a function of λ and this is the cause of the breakdown of Bouguer's law.

Foster[8] estimated the deviation from ideal behaviour by performing the integration in equation (5) for a monodisperse aerosol with optical properties appropriate for wood smoke and using an empirically determined spectral response for a tungsten lamp–barrier layer photocell combination. Assuming a 0.2 μm particle diameter, Foster found that $\ln (I_t/I_t^0)/m$, which would be constant for Bouguer's law, monotonically decreased by a total of 22% as the mass concentration increased from 57 mg m^{-3} to 2840 mg m^{-3} (optical density from 0.049 to 1.97). Foster's result must be viewed as approximate because subsequent measurements on smoke from wood fires by Bankston *et al.*[3] indicate a wide range of particle sizes (logarithmic standard deviation, $\sigma_g \simeq 2.0$) rather than a monodisperse aerosol ($\sigma_g = 1.0$).

CALIBRATION

There is great difficulty in quantitatively determining deviations from Bouguer's law experimentally because of the instability of the smoke; particles grow as a result of coagulation on a time scale of seconds, diffuse to the walls of the enclosure, and change size as a result of condensation or evaporation. These dynamic effects are surely a major cause for the large scatter in the data for the studies of Bouguer's law by Foster[8] and by Gross *et al.*[4]

While recently developed aerosol instrumentation would allow measurement of the rapid changes in the concentration and size distribution of smoke, a simpler method for testing the applicability of Bouguer's law for an extinction measurement would be to use stable suspensions of particles of the appropriate size and refractive index in a medium such as water, where dynamic effects such as coagulation and particle loss to the wall are minimized. Cashdollar *et al.*[9] have described an ingenious method for encapsulating particles in a plastic cell. The development of a calibration procedure using particle suspensions for a range in both concentration and path length of the cell would greatly enhance the reliability of light extinction measurements.

Once an extinction instrument with a monochromatic light source is verified to satisfy Bouguer's law, the prediction of the optical transmission as a function of path length and mass concentration is straightforward. For a while light source, on the other hand, Bouguer's law does not apply and 'correction' tables must be developed based on extensive calibration coupled with the calculation of optical transmission from Eqn (5) for realistic optical properties and size distributions. Without this, errors of 25% or greater could result in the prediction of optical transmission for path lengths and mass concentrations different from the calibration conditions. For extinction instrument designs that allow an appreciable amount of scattered light to reach the detector, such as the NBS Bukowski design described above, the errors can be a factor of two greater. As shown above, for 5 μm diameter particles the errors are much greater.

CONCLUSIONS

At low smoke concentration the Bukowski type extinction instrument (no aperture) will require calibration because of the effect of forward scattered light reaching the detector. For the low concentration at which smoke detectors alarm, $K<0.1\ \text{m}^{-1}$, two calibration points will probably suffice. However, over the wide range in smoke concentration characteristic of full-scale tests, $0.05 < K < 10\ \text{m}^{-1}$ or $0.02 < D_L < 4.3\ \text{m}^{-1}$, measurement errors will result from both multiple scattering and the spectral width of the light source. The Gross *et al.* type extinction instrument (aperture, white light) eliminates the problem of scattered light but would still require extensive calibration because of the spectral width of the source. The ideal extinction instrument would utilize an aperture and a monochromatic light source such as a laser or a white light source filtered with a narrow bandwidth filter as in the Cashdollar design.[10]

In the preceding section the difficulties in using white light were pointed out. One advantage of using white light coupled with a detector simulating the photo response of the eye is the relevance to visibility for fire safety applications. Jin[11] has shown that the extinction coefficient of smoke correlates well with the threshold visibility of signs for human subjects. In principle one could combine the simplicity of the monochromatic system with the prediction of the transmitted light intensity for white light by using several monochromatic wavelengths covering the spectral range of the human eye.

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