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Fire Detection Modeling – The Research-Application Gap

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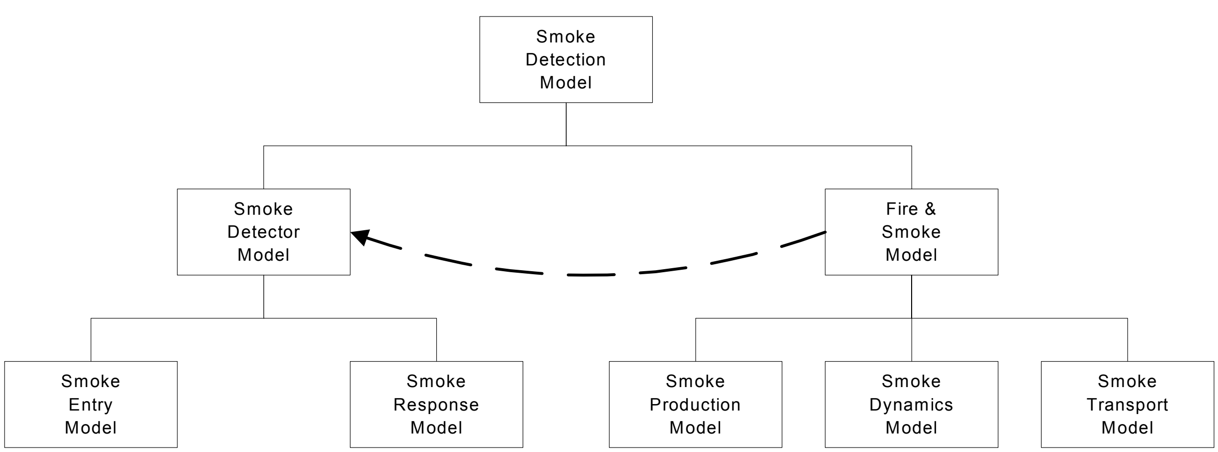
1. ABSTRACT

Fire detection is a rapidly evolving discipline. New sensor technologies and sampling algorithms are being developed to monitor traditional parameters of smoke and heat as well as new parameters involving gas and radiation. However, the engineering application of fire detection has lagged behind and has remained essentially unchanged for the past 20 years. In fact, there are very few engineering tools for fire detection applications. Also, the few tools that do exist do not have a known degree of accuracy. This paper uses smoke detection as a catalyst to discuss the widening gap between the fire researcher, the sensor designer, and the application engineer.

2. INTRODUCTION

In order to model *smoke detection*, the application engineers need a *fire model* or *fire data* and a *detector/sensor model*. The relationships between these models are shown in Figure 1. The fire model or fire data must be in a form suitable for use by the sensor model.

Figure 1 Smoke Detection Model



For example, fire researchers most often measure and report data on heat release rate, temperature and velocity of fire gases, and the optical density or obscuration per unit distance of the smoke at various locations. Of these, only optical density or obscuration relates directly to smoke. Although called obscuration, it is more accurately called attenuation since the light beam may be absorbed, reflected or refracted by the smoke.

Optical density and obscuration are useful data for evaluating visibility. However, the only commercially available smoke detector that operates by sensing the attenuation of a light beam is the projected beam type smoke detector. Further, these measurements are sensitive to the wavelength of light used. Thus, to be valuable for estimating the response of a projected beam smoke detector, the data must be measured and reported using the same wavelength as the light source used by the detector. Alternatively, the error introduced by modeling or using data generated at a different wavelength needs to be incorporated into the results. The two most common types of smoke detectors are ionization type and photoelectric type. Neither type operates using light attenuation. Without a correlation between the optical density data and the response characteristics of a particular detector, accurate modeling is not possible.

Examining Figure 1 it seen that when data is presented for smoke measurements at a detector location, it is only valid for use in modeling situations where the *Production*, *Dynamics* and *Transport* are substantially the same as in the test that generated the data.

In addition, detectors often use complex response algorithms rather than simple threshold or rate-of-change response levels. These algorithms vary from detector to detector and are generally not published by the manufacturers. Thus, even if correlations between optical density and the response of scattering and ionization type smoke detectors were available, the signal-sampling algorithm affects the actual response of each model.

In order to determine whether or not a smoke detector will respond at a given time after ignition or at some threshold heat release rate, a large number of factors must be evaluated. These include: smoke aerosol production and characteristics, aerosol transport, including dynamic changes during transport, detector aerodynamics, and sensor response.

Smoke aerosol characteristics at the point of production or generation are a function of the fuel composition, the combustion state (smoldering or flaming), and the degree of vitiation of the combustion air. The characteristics considered include particle size and distribution, particle number or concentration at various sizes, composition, color, and refractive index. Given the dynamic nature of fire growth, fire spread and fuels involved, ventilation conditions will change over time, thus affecting the characteristics of the smoke produced.

Smoke dynamics during transport changes to the aerosol characteristics that occur with time and distance from the source. For instance, do particles agglomerate or coagulate? How does the size and number concentration vary? How do the optical properties change?

Smoke transport considerations include transport time and velocity as well as soot deposition causing changes in airborne concentrations. Transport time is a function of the characteristics of the travel path from the source to the detector, and includes ceiling height and configuration (sloped, beamed, etc.), intervening barriers such as doors, and buoyancy effects such as layering and thermal inversions.

Once smoke reaches the detector, other factors become important, namely the aerodynamic characteristics of the detector and the type of sensor. The aerodynamics of the detector relate to the ease with which smoke can pass through the detector housing and enter the sensor. In addition, the location of the entry portion of the housing relative to the velocity profile of the detector normal to the plane of the ceiling is also a factor. Finally, different sensing modes (e.g., ionization or photoelectric) will respond differently, depending on the characteristics of the transported aerosol. Within the family of photoelectric devices, there will be variations depending upon the wavelengths of light and the scattering angles employed. Also, algorithms used to sample and weight the sensor's response are introduced by the manufacturer and affect the detector's response.

Standard practice for the design of smoke detection systems is much the same as that for heat detection systems. Recommended spacing criteria are established based on detector response to a specific parameter, such as the optical density within an enclosure. A variety of smoke tests are used to verify that the detector responds between defined upper and lower activation thresholds and within required response times to a range of different types of smoke. This information translates into recommended spacing criteria that are intended to ensure that the detector responds within defined parameters. In some cases, the recommended spacing can be increased, or must be decreased, depending on factors such as compartment configuration and airflow velocity.[1]

In applications where estimating the response of a detector is not critical, the recommended spacing criteria provides sufficient information for design of a basic smoke detection system. If the design requires detector response within a certain time frame, optical density, specified heat release rate, or temperature rise, additional analysis may be required. In this case, information concerning the expected fuel, fire growth, sensor, and compartment characteristics is required.

3. MODELING SMOKE DETECTOR RESPONSE – GENERAL

The response of smoke detectors to fire conditions is not easily modeled. The response characteristics of smoke detectors vary widely compared with thermal detectors. In addition, less is known about the production and transport of smoke in the early stages of a fire. Natural and forced air currents have a larger effect on the movement of smoke at the time of interest (very early in the fire) than they do on the stronger thermal currents required to alarm heat detectors.

A comparison of how smoke detectors operate with the smoke measurement methods most often employed and reported by researchers shows that smoke measurements do not generally include the factors that we need to model smoke detector response[2]. Thus, there is a gap between the data generated by fire researchers and the data needed to model smoke detector response.

Researchers most often use optical density or obscuration as a measurement of smoke. These are calculated as follows:

Percent obscuration, %Ob.:

$$\%Ob. = 100\left(1 - \frac{I}{I_0}\right) \tag{1}$$

Percent obscuration per unit distance, $\%O_u$:

$$\%O_u = 100\left[1 - \left(\frac{I}{I_0}\right)^{1/l}\right] \tag{2}$$

Optical density, D:

$$D = \log_{10}\left(\frac{I_0}{I}\right) = -\log_{10}\left(\frac{I}{I_0}\right) \tag{3}$$

Optical density per unit distance, D_u (m^{-1}):

$$D_u = \frac{D}{l} = \frac{1}{l}\log_{10}\left(\frac{I_0}{I}\right) = -\frac{1}{l}\log_{10}\left(\frac{I}{I_0}\right) \quad \text{m}^{-1} \tag{4}$$

Where I_0 is the initial intensity of a light beam reaching a photocell and I is the intensity of the light beam in the presence of smoke.

Optical density and obscuration are useful data for evaluating visibility. However, the only commercially available smoke detector that operates by sensing the attenuation of a light beam is the projected beam type smoke detector. Further, these measurements are sensitive to the wavelength of light used. Thus, to be valuable for estimating the response of a projected beam smoke detector, the data must be measured and reported using the same wavelength as the light source used by the detector.

The two most common types of smoke detectors are ionization type and photoelectric type. Neither type operates using light attenuation. Without a correlation between the optical density data and the response characteristics of a particular detector, accurate modeling is not possible.

In addition, detectors often use complex response algorithms rather than simple threshold or rate-of-change response levels. The algorithms are used to reduce false and nuisance alarms and to enhance fire signature matching. These algorithms vary from detector to detector and are generally not published by the manufacturers. Thus, even if correlations between optical density and the response of scattering and ionization type smoke detectors were available, the signal-sampling algorithm affects the actual response of each model.

Nevertheless, there are methods that can be used to grossly estimate smoke detector response. These estimation methods may not provide accurate prediction of time to detector response because the potential errors in the estimation methods are not generally known and because the response algorithms for a particular detector are not known. Without knowledge of the accuracy of the models and the potential errors, these estimation methods should not be used to compare detector response to other model calculations such as egress time calculations or time to untenability. Estimation methods are best used to compare changes in the response of a particular detector as a result of changes in spacing or location, while holding all other variables constant.

In addition to these estimation methods, actual fire tests with detectors present may provide information to compare smoke detector response to other factors such as egress time, structural response, heat release rate, etc. Product performance tests may be sources of data. Although, the actual response may not be reported in manufacturer's literature, the minimum and maximum permissible performance imposed by the test standard provides ranges of possible response.

4. MODELING SMOKE DETECTOR RESPONSE - LIGHT OBSCURATION SMOKE DETECTORS

For projected beam type detectors, fire or smoke models that calculate the optical density per unit length, D_u, in a space or the total optical density in the path of the detector, D, may be used to determine when the detector would respond. Manufacturer specifications will typically indicate at what levels of total obscuration or total optical density the detectors respond. Projected beam smoke detectors generally have adjustable response thresholds.

Many fire models estimate the unit optical density, D_u, in a uniform upper layer or volume. This is referred to as zone modeling. The optical density over the entire length of the beam is then determined by multiplying D_u by the path length, l. The path length is the distance between the source and receiver or the projected beam smoke detector. This method assumes homogenous distribution of smoke throughout the path, an assumption that may not be valid.

Another method to model the response of projected beam obscuration type detectors is to calculate the unit optical density, D_u, at several discrete points or in several discrete segments between the source and the receiver of the projected beam smoke detector. This is a form of field modeling. The optical density per unit length is then multiplied by the length of that particular segment. The total optical density of the path is then the sum of all of the densities for the individual segments.

5. MODELING SMOKE DETECTOR RESPONSE - LIGHT SCATTERING (PHOTOELECTRIC) SMOKE DETECTORS

The amount of light scattered by smoke is very complex and is related to factors such as the particle number density and size distribution, refractive index, the wavelength of the light source, and the angle between the source and the receiver. The manufacturer for a particular detector can describe some of these variables. Some require information about the smoke produced by the fuel and its transport to the detector location.

Information about smoke properties related to light scattering is presently limited to a few types of fuels and is not readily available to practicing fire protection engineers. In addition, the data may not be in a useable format. For instance, the data must match the wavelength of the light source used in the detector being modeled. Scattering data at other wavelengths introduces errors and uncertainties.

Meacham has shown that it is possible to model the response of light scattering detectors using information about smoke properties obtained by small scale testing of various fuels.[3, 4] However, the recommended test methods have not been further developed, tested and incorporated into fire test programs.

At the present time, there are no practical methods available to directly model the response of light scattering type detectors. However, obscuration or optical density modeling, as was discussed above for obscuration type detectors, can be used in a limited way to estimate scattering type smoke detector response.

A scattering type detector will respond at different optical densities for different types of smoke. For example, a scattering type smoke detector that responds at an optical density of .029 m^{-1} (2.0%/ft obscuration) to smoke produced by a smoldering gray cotton lamp wick may not respond until an optical density of 0.15 m^{-1} (10%/ft) is reached for smoke from a kerosene fire. At the response threshold, both types of smoke are scattering the same amount of light to the receiver of the scattering photoelectric smoke detector. There are many factors involved in this effect. One is that the darker smoke from the kerosene fire does not reflect as much light as the lighter colored smoke from the lamp wick.

Another way to understand the differing response of a scattering type detector to two types of smoke is to consider the amount of light being scattered when both smoke samples have the same optical density. Both samples of smoke equally block our vision of the light reflected by an object. One type of smoke may be composed of large, highly reflective smoke particles that cause the incident light to scatter in many directions. Thus, it reduces the amount of light in the forward direction. The other type of smoke may consist of a smaller number of larger particles that absorb light more readily than they reflect it. Though they have equal optical densities, one is more likely to scatter light and set off a scattering type detector.

In order to model the response of a scattering type detector using obscuration or optical density, it is necessary to know the optical density required for a particular type of smoke to alarm a particular model detector. For example, many manufacturers label their smoke detectors with a unit optical density, D_u, or unit obscuration, $\%O_u$ based on a calibration test that is part of UL standard number 268.[5] That number indicates the unit optical density required for that detector to respond to smoke having very specific characteristics. The optical density required to alarm a particular detector as quoted by the manufacturer is just one value for a given particle size distribution, concentration, color, etc. used in the laboratory calibration test of that model detector. If the smoke and conditions are similar to that used in the test of the detector, the specified alarm threshold can be used in calculations.

It is not sufficient to have data for a particular fuel and detector combination. It is known that smoke changes as it moves away from a fire.[6] There may be changes in the number of particles, their size, shape and velocity. The optical density at response to any smoke signature other than the laboratory calibration test will be different and will vary with different fuels and burning modes.

Threshold response data to various fuels for a particular detector are not readily available. Some manufacturers may provide data if available and when requested. Product performance and safety tests as well as fire tests with detectors present are useful sources of limiting performance data. Product standards typically test detectors in rooms with specified fuels and smoke build-up rates and velocities. The detectors must respond at certain levels or within certain time limits. While the exact performance data may not be made available, the test limits are useful for estimating the range of possible detector response.

6. MODELING SMOKE DETECTOR RESPONSE - IONIZATION SMOKE DETECTORS

The signal produced by the chamber of an ionization detector has been shown to be proportional to the product of the number of particles and their diameter.[7, 8, 9, 10] The exact signal produced by an ionization smoke detector is given by a more complex equation in the literature and requires an additional number called the chamber constant. The chamber constant varies with each different model of detector.

Given the quantity and size distribution of smoke particles and the chamber constant (from the manufacturer), it is possible to model the ionization smoke detector. Unfortunately, there are no fire models that provide the required detector model input. In addition, manufacturer specifications do not presently include chamber constants.

Newman modified the chamber theory to account for ionization detector sensitivity to the small electrical charge carried by some fire aerosols.[11] Newman also developed a method to model ionization smoke detector sensitivity as a function of the soot yielded by a particular fuel. Using his method, the change in a detector's signal, ΔI, can be related to the optical density of smoke measured at a particular wavelength, $D_{u\lambda}$.

To use the method proposed by Newman it is necessary to know what change in detector chamber signal, ΔI, will cause a detector or system to alarm. Although manufacturers do not presently provide this data they may be persuaded to do so in the future.

Newman's work was done using a small-scale apparatus and three ionization smoke detectors. A wider range of tests, including some full scale testing is needed to verify this method.

Presently, the only way to model ionization detector response is to use the optical density estimations as discussed for obscuration type detectors.

7. MODELING SMOKE DETECTOR RESPONSE - ENTRY RESISTANCE

In addition to smoke characteristics and the detector's operating mechanism, the ability to get the smoke into the chamber effects the response of the unit. For spot type photoelectric and ionization type smoke detectors, bug screens, chamber design and the detector's aerodynamic characteristics cause entry resistance.

In a scenario where the optical density at the detector location is increasing with time, the optical density inside the detector chamber will always be less than that outside the detector chamber. Similarly, if a detector is placed in a smoke stream having a constant optical density, there will be a time delay before the optical density inside the chamber approaches that outside the detector. As with heat transfer to heat detectors, smoke entry resistance can be characterized by a detector time constant, τ:

$$\frac{dD_{ui}}{dt} = \frac{1}{\tau}\left(D_u - D_{ui}\right) \quad s^{-1}m^{-1} \tag{5}$$

Where D_{ui} (m^{-1}) is the optical density per unit length inside the detector chamber, D_u (m^{-1}) is the optical density per unit length outside the detector and τ (s) is the detector time constant.

If the time constant and the rate of change of optical density outside the detector are constant, then this equation can be solved. Further, substituting D_{ur} for the optical density outside the detector at response and D_{uo} for the optical density required inside the detector to produce response yields the following [12, 13]:

$$D_{ur} = D_{uo} + \tau\left(\frac{dD_u}{dt}\right)\left\{1 - \exp\left[-D_{ur}\frac{1}{\tau}\left(\frac{dD_u}{dt}\right)\right]\right\} \quad \text{m}^{-1} \tag{6}$$

Heskestad proposed that the time constant could be represented by the following:

$$\tau = \frac{L}{u} \quad \text{seconds} \tag{7}$$

Where L is the detector's characteristic length and u is the velocity of the ceiling jet flowing past the detector.

The characteristic length is thought to be a property of the detector that is independent of the smoke and ceiling jet properties. It is interpreted as the distance the smoke would travel at the velocity u before the optical density inside the detector reaches the value outside of the detector. Combining the equations:

$$D_{ur} = D_{uo} + \frac{L}{u}\left(\frac{dD_u}{dt}\right)\left\{1 - \exp\left[-D_{ur}\frac{u}{L}\left(\frac{dD_u}{dt}\right)\right]\right\} \quad \text{m}^{-1} \tag{8}$$

The exponential term is small compared to the rest of the equation, allowing the equation to be simplified.[12] Simplification of the equation is not necessary when calculations are made using a computer. However, the simplified form clearly shows the effect of entry resistance.

$$D_{ur} = D_{uo} + \tau\left(\frac{dD_u}{dt}\right) \quad \text{or} \quad D_{ur} = D_{uo} + \frac{L}{u}\left(\frac{dD_u}{dt}\right) \quad \text{m}^{-1} \tag{9}$$

This form of the entry resistance equation clearly shows that when the optical density outside a detector is increasing with time, the optical density inside the detector will lag behind if there is any entry resistance.

Heskestad and later Bjorkman et al. have plotted test data to determine the L number for a variety of smoke detectors. Additional work has been done by Marrion and by Oldweiler to study the effects of detector position and gas velocity on the L number.[14, 15]

Bjorkman et al., Marrion and Oldweiler all observed variations in L that may be attributed to a dependence on velocity. Marrion and Oldweiler's data also imply that there may also be a dependence on the characteristics of the smoke. Table 1 below summarizes the results from the works cited above.

Table 1– Range of Characteristic Length (L) Numbers

Researcher	Ionization Detector L (m)	Scattering Detector L (m)
Heskestad	1.8	15 (a)
Bjorkman et al.	3.2 +/- 0.2 (b)	5.3 +/- 2.7 (c)
Marrion	Not tested	7.2 (d), 11.0 - 13.0 (e), 18.4 (f)
Oldweiler	4.0 - 9.5 (g), 4.3 - 14.2 (h)	Not tested

Notes:

a) Older style detector with more elaborate labyrinth.

b) L determined by best fit for three test velocities.

c) L based on a single test velocity & a limited number of tests (complete equation used).

d) Low L number at low test velocity.

e) Range of L for several fuels and detector positions.

f) L increased by adding "fence" to further restrict smoke entry.

g) Range of L for a variety of velocities using simplified equation for entry resistance

h) Range of L for a variety of velocities using complete equation for entry resistance

Examination of the data and analysis work cited above shows that more work needs to be done to study the effects of low velocities and the effects of smoke characteristics on detector entry characteristics. The sharp increase in L at lower velocities appears to indicate that entry resistance may be related to smoke particle size. It is also possible that L is a function of the smoke momentum at low velocities. Thus, the time lag would be inversely proportional to the velocity squared.

Engineers can use L as a measure of entry resistance and the resulting time lag. However, in scenarios where the ceiling jet velocity is low, there will be greater uncertainty in the results.

Without validation of L as a measure of lag time, manufacturers and test laboratories are not measuring or reporting L in their literature. Nevertheless, the range of L numbers reported in Table 1 can be used to estimate possible errors in detector response time.

8. MODELING SMOKE DETECTOR RESPONSE – SMOKE DILUTION AND THE EFFECTS OF FORCED AIRFLOW

Smoke dilution refers to a reduction in the quantity of solid and liquid aerosols (smoke) available for detection. Dilution can occur through natural convection (entrainment in the plume or the ceiling jet) or through the effects of by forced ventilation systems.

Air flow effects become less as fire size increases. Conversely, when detection is desired at smaller fire sizes, air flow effects may become a dominant factor in the response of the smoke detector. Velocity profiles of the air movement within a room or smoke tests under various conditions may assist in determining optimum smoke detector placement.

Computational fluid dynamics (CFD) modeling has been used to show the effects of ducted air supply and air return on smoke spread.[16, 17, 18] That work used three dimensional color graphics plots to show areas of non-activation for given scenarios and assumptions. That research effort verified a long standing rule that smoke detectors should not be located within approximately one meter of conventional air supply diffusers and air return grills due to the high level of dilution. However, because air dilution and smoke movement in a compartment is such a complex problem with a large number of variables, the research program was not able to create simplified engineering relations or tools for use in design of smoke detection systems.

CFD modeling can be a useful tool for complex scenarios involving airflow. However, potential sources of error exist. For example, CFD models generally do not model fires. Instead, they model the transport of the mass and energy "injected" or "produced" at the fire location. Thus, many of the same discussions above concerning mass optical density, soot deposition, smoke particle characteristics, optical density vs. temperature correlations are also applicable to this type of modeling.

9. TEMPERATURE APPROXIMATION METHOD FOR MODELING SMOKE DETECTION

The temperature approximation theory is a method used to estimate the optical density produced by flaming fires. The theory hypothesizes that the mass concentration of smoke particles at a point is proportional to the change in temperature due to the fire (at that point).[19] The following assumptions are necessary:

- Particle size distribution is constant in space and time
- Mass generation rate is proportional to mass burning rate
- There is no heat transfer between particles or between the particles and the confining surfaces
- The smoke does not continue to react as it travels

Heskestad then hypothesized that the ratio of optical density to temperature rise would be a constant for a particular fuel and burning mode (flaming, smoldering, vertical combustion, horizontal combustion, etc.). There are actually three parts to this hypothesis.

The first is that each fuel and burning mode results in a unique optical density required to alarm a particular model and type of detector. This was discussed previously regarding photoelectric, ionization and projected beam smoke detectors. This phenomenon is regularly observed, explained by theory, and accepted by the scientific and engineering community.

The second part of the hypothesis is that for each fuel and burning mode the optical density at a point is proportional to the mass concentration of particles.

$$D_u \propto C \qquad (10)$$

The final part of the hypothesis is that for each fuel and burning mode the mass concentration of particles is proportional to the change in temperature at a point.

$$C \propto \Delta T \qquad (11)$$

Combining these proportionalities, optical density is proportional to the change in gas temperature for a given fuel and combustion mode:

$$D_u \propto \Delta T \tag{12}$$

Therefore, the ratio of optical density to temperature rise is constant for a given fuel.

$$\frac{D_u}{\Delta T_g} = CONSTANT \tag{13}$$

This hypothesis assumes that the only way to move the smoke particles from the source to the detector at the ceiling is by buoyant forces.

Heskestad and Delichatsios examined experimental data for obscuration and temperature rise at various locations on a ceiling for different fuels. They concluded that while the data showed some variation in time at different radial positions relative to the fire source, the ratio could be approximated as a constant. Table 2 lists the ratios recommended by Heskestad and Delichatsios for various fuels.[19]

Table 2

Material	$\frac{10^2 D_u}{\Delta T} \left(\frac{1}{ft\,^0F}\right)$	**Range of Values**
Wood	0.02	0.015 - 0.055
Cotton	0.01/0.02	0.005 - 0.03
Paper	0.03	Data not available
Polyurethane	0.4	0.2 - 0.55
Polyester	0.3	Data not available
PVC	0.5/1.0	0.1 - 1.0

Foam rubber PU	1.3	Data not available
Average	0.4	0.005 - 1.3

Examining the original data, the last column has been added to show the range of values for each fuel. Averages have also been calculated and listed in the last row of the table for reference.

Others experiments have resulted in data that differ from that of Heskestad and Delichatsios. Bjorkman et.al. reported values for polyurethane that are approximately one half that reported by Heskestad and Delichatsios.[20]

The data produced by Heskestad and Delichatsios show the ratio of optical density to temperature rise was not constant. The authors concluded that the variation was the result of slowly changing characteristics of the smoke particles as they left the flaming source and traveled in the plume and ceiling jet. Nevertheless, they concluded that a constant value could be used as a rough approximation to allow engineers to model optical density produced by a fire. Although it has not yet been done, it is possible to examine their original data and place error bars on the values recommended in the above table. With today's availability of desktop computers to perform modeling calculations, it may be possible to develop and use a functional relationship for the ratio of optical density to temperature rise in lieu of a constant.

A fire model can be used to calculate the temperature rise at a smoke detector location or in a layer. Then, using the ratios reported by researchers, the optical density at that location as a function of time can be approximated.

10. MASS OPTICAL DENSITY METHOD FOR MODELING SMOKE DETECTION

The fuel characteristics of primary concern for smoke detection are: (1) material and (2) mode of combustion. These two parameters are important for determining pertinent features of expected products of combustion, such as particle size, distribution, concentration, and refractive index. Assuming a well-mixed smoke-filled volume, data on smoke characteristics for given fuels can provide an estimation of detector response. Some fire models calculate the optical density of smoke in a space using the following relationship for the optical density per unit length, D_u:

$$D_u = \frac{D}{l} = D_m \frac{\Delta m}{V_c} \qquad (m^{-1}) \tag{14}$$

l is the path length (m)

D_m is the mass optical density (m^2/g)

Δm is the mass of the fuel burned (g)

V_c is the volume that the smoke is dissipated in (m^3)

This method will be referred to as the mass optical density method. D_m varies depending on the fuel, and is determined experimentally. Tables of D_m can be found in the SFPE Handbook of Fire Protection Engineering.[6, 21]

The mass optical density method for estimating the optical density of smoke produced by a fire requires that the variable D_m be selected for the particular fuel and burning mode. The most complete set of data available are in the SFPE Handbook of Fire Protection Engineering. However, not all fuels and burning modes have been tested and reported. Also, more complex fuel packages, such as upholstered chairs, require that D_m be chosen for one fuel even though more than one may be burning at the same time. When a model using this method is employed, users should check to see if the model selects an appropriate value of D_m for the fuel being studied. Some models may use a single value of D_m regardless of the fuel. In that case, answers can be modified by dividing the calculated D_u by the D_m used in the program, then multiplying by the appropriate value of D_m selected from the available data.

$$D_{u(new)} = D_{u(calc)} \frac{D_{m(new)}}{D_{m(calc)}} \quad m^{-1} \tag{15}$$

Mass optical density can be derived by burning a sample in a closed chamber and measuring the optical density in the chamber. The following equation is used to calculate D_m:

$$D_m = \frac{DV_c}{l\Delta m} \qquad \frac{m^2}{g} \tag{16}$$

Where

D is the optical density measured in the test

l is the path length over which D was measured (m)

V_c is the volume of the test chamber (m^3)

Δm is the mass of the fuel sample consumed in the test (g)

A different equation is used for open test arrangements that involve a flow of air and combustion products through a test chamber.

D_m data are often measured in small scale tests due to the need for accurate measurements of mass loss and optical density. The use of D_m from small scale tests to calculate the resulting D_u in a large scale scenario introduces error. Some comparisons show qualitative correlation. However, it has been reported that the correlation breaks down with complex fires.[6]

The value of optical density, D, measured in the test depends on the wavelength of the light used. For a given set of test conditions, if the wavelength of the measuring light beam is reduced, the measured optical density will increase. This occurs because particles must have a diameter on the same order of magnitude or larger than the light wavelength in order to obscure the light. Shorter wavelength lights will be obscured by the smaller particles not seen by the longer wavelength light. Also, most light sources produce a range of different wavelengths, usually having some specific distribution and some nominal peak. The exception is when a precise laser light source is used. Finally, the receiver that senses the light and produces a corresponding output also has a response distribution curve for various wavelengths.

Examination of test data reported by Tewarson show that D_m found using a nominal wavelength of 1.06 μ (microns) might be as much as 5 times less than D_m found with a 0.458 μ light source.[21] Unfortunately, the tables of data for various fuels in the SFPE Handbook do not all list the wavelength used to determine D_m. If the wavelength (and distribution) of the light used to determine D_m is the same as the wavelength of light used to test a smoke detector and report it's sensitivity, then no error is introduced. For these data to be useful in modeling smoke detector response, they should be determined using a light source and receiver having characteristics similar to most commercially available smoke detectors. Commercially available detectors use light sources having peak wavelengths in the infrared band. Meacham has reported that two manufacturers use LED sources having peak wavelengths on the order of 880 to 950 nm (0.880 to 0.950 μm).[3]

Another method for determining D_m involves a calculation using the yield of smoke for a particular fuel. Tewarson examined data from several sources and arrived at the following equations[21]:

$$D_m = 0.10 \ln Y_s + 0.52 \quad \left(\frac{m^2}{g}\right) \quad \text{for flaming fires} \tag{17}$$

$$D_m = 0.17 \ln Y_s + 0.65 \quad \left(\frac{m^2}{g}\right) \quad \text{for smoldering fires} \tag{18}$$

In these equations Y_s is the yield of smoke in grams per gram of fuel consumed. These equations provide an additional method for determining D_m when test reports include Y_s. However, the determination of Y_s may also introduce errors in the calculation of D_m

and hence D_u. The nature and extent of these possible errors is beyond the scope of this paper.

Models that calculate the optical density in a space using D_m assume that the smoke produced is distributed evenly throughout a specific volume. This is called a zone model. In short, one zone is the hot upper layer which has a uniform temperature and smoke optical density throughout. The second zone is the cooler, near ambient lower layer. Some models treat the lower layer as being at the initial, ambient conditions, while others consider the amount of smoke and heat added to the layer. Since real fires tend to produce varying optical density throughout the space, the uniform zone assumption introduces error in any detector response modeling. Larger volumes and larger horizontal distances from the fire plume increase the errors caused by the use of simplified zone modeling.

When the mass optical density method is used, all smoke produced by the fire is assumed to contribute to the optical density of the smoke in the assumed volume. However, the actual mass loss and smoke production occurs over time. Depending on the actual conditions in the space and the nature of the fuel, some amount of the smoke will have been deposited on the walls, ceilings, furnishings and other surfaces as soot. In addition, the potential for transport out of the space exists whenever vents are present. Most computer fire models do not contain a routine to account for soot deposition when calculating the resulting optical density.[2]

Most fire models determine the volume of the upper smoke layer by calculating the distance below the ceiling at which the temperature drops off significantly. In an actual fire, the demarcation between the two layers is not necessarily distinct, as some amount of the smoke cools and diffuses into the lower layer.

It has also been shown that smoke ages, changing its characteristics with time. Smoke aging effects include agglomeration of small particles into larger particles, possible continued oxidation of unburned fuel mass in the smoke layer and other chemical and physical changes that affect the optical density of the smoke. The effects of smoke deposition and smoke aging on smoke detector response modeling may be negligible in the early stages of a fire and when a detector is close to and in the same room as the fire. In cases where the detector is far from the fire, in another room, or where the smoke must travel an indirect path to the detector, results will be less accurate. These phenomenons have been investigated by Yamauchi[22] but have not yet been incorporated into available detector models.

11. SMOKE DETECTION CALCULATION EXAMPLES THE FOLLOWING EXAMPLES SHOW VARIOUS PERFORMANCE-BASED APPROACHES TO EVALUATING SMOKE DETECTOR RESPONSE.

Example 1

The smoke level measured outside of a detector at the time of response in a laboratory calibration test is listed on manufacturer's specifications as the optical density or obscuration required to alarm the unit. Because of entry resistance, the smoke level inside the detector will be less. The specified response is for a particular type of smoke and is measured in a laboratory test apparatus. An example of one calibration test is the gray smoke test listed in the U.L. 268 smoke detector test standard.[5]

In the test, the smoke detector response threshold must not exceed 0.0581 m^{-1} (4.0%/ft). Velocity in the test chamber is 9.8 m/min. The test starts with clear air. A smoldering cotton lamp wick is used to increase the optical density in the test chamber. The rate of increase of optical density in the chamber must fall within the following limits:

$$3.7 \text{ x } 10^{-3} \leq \frac{dD_u}{dt} \leq 5.3 \text{ x } 10^{-3} \quad m^{-1}\,min^{-1} \tag{19}$$

What is the range of optical density inside of the detector at the time of response (D_{uo}) if the detector has an L of 3 m? What would it be if the detector had an L of 14 m?

For L = 3 m and $dD_u/dt = 3.7 \times 10^{-3}\ m^{-1}\ min^{-1}$

$$D_{ur} = D_{uo} + \frac{L}{u}\left(\frac{dD_u}{dt}\right) \quad m^{-1} \tag{20}$$

$$D_{uo} = D_{ur} - \frac{L}{u}\left(\frac{dD_u}{dt}\right) \quad m^{-1} \tag{21}$$

$$D_{uo} = 0.0581 - \frac{3}{9.8}\left(3.7x10^{-3}\right) = 0.057 \quad m^{-1} \tag{22}$$

For L = 3 m and $dD_u/dt = 5.3 \times 10^{-3}\ m^{-1}\ min^{-1}$

$$D_{uo} = 0.0581 - \frac{3}{9.8}\left(5.3x10^{-3}\right) = 0.056 \quad m^{-1} \tag{23}$$

For L = 14 m and dD_u/dt = 3.7 x 10-3 m-1 min-1

$$D_{uo} = 0.0581 - \frac{14}{9.8}\left(3.7x10^{-3}\right) = 0.053 \quad m^{-1} \tag{24}$$

For L = 14 m and dD_u/dt = 5.3 x 10-3 $m^{-1}\ min^{-1}$

$$D_{uo} = 0.0581 - \frac{14}{9.8}\left(5.3x10^{-3}\right) = 0.051 \quad m^{-1} \tag{25}$$

These calculations indicate that the actual quantity of this particular type of smoke required to alarm the detector varies from 0.051 to 0.057 m^{-1} or from 3.5 to 3.9 %/ft.

Example 2

The design objective is to detect the smoke from a flaming 200-g (0.5-lb) polyurethane pillow in less than two minutes. The pillow is located in a 36 m^2 room with a ceiling height of 2.5 m (8 ft). Assume that the pillow is burning at a steady rate of 50 g/min. Can the design objective be met? What assumptions are required?

At a rate of 50 g/min., the mass consumed after two minutes is 100 g. The SFPE Handbook Table 2-15.5 in Section 2, Chapter 15 lists two possible values for D_m , 0.22 m^2/g and 0.33 m^2/g. [6]

The optical density in the room can now be calculated:

$$D_u = \frac{D}{l} = D_m \frac{\Delta m}{V_c} \quad (m^{-1})$$
$$D_u = 0.22 \frac{100}{2.5(36)} = 0.24 \quad (m^{-1}) \tag{26}$$

or

$$D_u = 0.33 \frac{100}{2.5(36)} = 0.37 \quad (m^{-1}) \tag{27}$$

Example 3

Polyurethane mattresses are stored in a room that is 50 m x 75 m x 10 m high. A goal has been set to detect a flaming fire before approximately 350 g of fuel has been consumed. Using a projected beam smoke detector with sensitivity settings that can vary from 20% to 70% total obscuration in 10% increments, what is the minimum sensitivity setting for response to this fire? Assume the smoke is mixed evenly throughout the space.

The mass optical density, D_m, for a flaming polyurethane mattress is given in the SFPE Handbook, p. 2-223 as 0.22 m^2/g. [6] The volume of the room is 37,500 m^3.

From the equation for mass optical density calculate the resulting unit optical density in the room when 350 g of fuel is consumed:

$$D_m = \frac{D_u V}{\Delta m} \qquad \frac{\text{m}^2}{\text{g}} \tag{28}$$

$$D_u = \frac{\Delta m D_m}{V} \qquad \text{m}^{-1} \tag{29}$$

$$D_u = \frac{350(0.22)}{37{,}500} = 0.002 \qquad \text{m}^{-1} \tag{30}$$

Knowing D_u and assuming the path length of the beam to be 75 m, the ratio of light reaching the receiver of the unit can be calculated:

$$\frac{I}{I_0} = 10^{-D_u l} \tag{31}$$

$$\frac{I}{I_0} = 10^{-0.002(75)} = 0.708 \tag{32}$$

Next, the percent obscuration caused by the smoke is calculated:

$$\%Ob. = 100\left(1 - \frac{I}{I_0}\right) \tag{33}$$

$$\%Ob. = 100(1 - 0.708) = 29.2 \tag{34}$$

Thus, a projected beam smoke detector would have to be set to respond at about 30% total obscuration or less to meet the design objective.

Example 4

In the previous example a projected beam smoke detector was used to detect a flaming polyurethane mattress fire. As a design alternative, consider using spot type photoelectric smoke detectors. Assume the detectors will respond at an optical density, D_u, of approximately $0.05m^{-1}$. Using the temperature approximation method, what temperature rise is required at the detector for the detector to respond. Ignore entry effects.

Table 2 lists a range of 0.2 to 0.55 for $\frac{10^2 D_u}{\Delta T} \left(\frac{1}{ft^0F}\right)$ or 0.002 to 0.0055 $\frac{D_u}{\Delta T} \left(\frac{1}{ft^0F}\right)$. Multiply by 3.28 ft/m to get 0.0066 to 0.018 ($m^{-1}\ {}^0C^{-1}$).

The ratio of optical density to temperature rise for a given material and burning mode has been called the Detector Material Response Number (DMR). Solving for the temperature rise:

$$
\begin{aligned}
&\frac{D_u}{\Delta T_g} = CONSTANT = DMR \\
&\Delta T_g = \frac{D_u}{DMR} \\
&\Delta T_g = \frac{0.05}{0.0066} = 7.6 = 8\ {}^0\mathrm{F} = 4\ {}^0\mathrm{C} \\
&\text{and} \\
&\Delta T_g = \frac{0.05}{0.018} = 2.8 = 3\ {}^0\mathrm{F} = 2\ {}^0\mathrm{C}
\end{aligned}
\tag{35}
$$

Thus, for the limited data available, it is expected that a temperature range of approximately 2 to 4 ^{0}C will be needed for the detector to respond. Naming the ratio of optical density to temperature rise for a given material and burning mode the DMR is useful. It serves as a constant reminder that a particular number is valid only for a specific detector (manufacturer and model) combined with a very specific fuel and burning mode. We do not know how accurate our calculations are because the detector in our scenario is almost certainly not the same detector used by Heskestad and Delichatsios in the mid 1970s.

12. DISCUSSION RELATED TO THE USE OF FIRE MODELS FOR HEAT AND SMOKE DETECTOR MODELING

Some computer fire models or sets of computational tools include routines for calculating heat or smoke detector response. It is important for users to understand the underlying detector models being used so that limitations and potential errors can be understood. For heat detection, most use a lumped mass model. However, for smoke detection some use a temperature rise model and some use a mass optical density or specific extinction area model. The specific extinction area, σ_f is similar to the mass optical density except that it is based on calculations using the natural log, e, rather than $\log_{10}$. Most do not include entry resistance modeling. Some permit the use of fuel specific parameters for smoke yield and mass optical density. Others use preset values.

13. CONCLUSIONS

It is not possible to accurately compare smoke detector response to other fire related models such as egress time or structural response to heat. If smoke detection is to be a part of tomorrow's performance based solutions fire models and detector models must evolve and work together. The evolution of the *fire* and *detector* models must include a feedback loop to ensure that they can be integrated to form a *detection* model.

Additional research is needed to test and verify certain aspects of detector models. Most important is additional work on the entry resistance model and the scattering detector model. Additional work should also be done to further test and refine Newman's model for ionization detector response.

Detector manufacturers, product certification laboratories and application engineers need to agree on a method for cataloging specific detector response algorithms. This needs to be done in a way that protects manufacturer's patents and confidentiality rights while still providing useful engineering information. Further, it must be done in a way that is easy to measure and verify.

Fire researchers need to examine detector models and develop instrumentation and data gathering methods that match the detector models. Raw data should be made available for input to detector models. Where possible, functional models produced from data should be developed in a format suitable for incorporation into detector models.

Detector and fire models, whether modular or integrated to form a detection model, need to better report and present limitations and potential errors. Finally, application engineers must be more conscious of the limits on a model's accuracy and precision and must provide useful feedback to researchers involved in product development and fire research.

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