Physics Based Assessment of Light Scattering in Multi-Color Smoke Detection

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Abstract:

Optical smoke detectors depend on light scattering properties and complex algorithms to determine the presence of smoke. A large body of knowledge and many products in the market today include wavelength dependent scattering, which utilize the optical properties of particulates to discriminate smoke. Yet, smoke detector design and evaluation lacks a model-based approach to extend scattering properties to detector surfaces, which can play a large role in overall performance. The development of detector design tools that utilize optical models are needed to evaluate concepts that have potential to meet UL 217/268 fire tests. Additionally, such a model can be used to help quantify the relative roles various false alarm, nuisance sources and optical scattering properties of materials play in detector performance.

Using ray tracing to model light scattering, a Monte Carlo method was implemented to determine the performance of key elements from light source to detector. The investigation utilized properties of smoke with respect to source and fire type[i]. The intensity of light scattering from smoke is described by Mie Theory [ii]. Scattering is dependent on wavelength, particulate radius, shape, polarizability, and angle. A first evaluation, without the influences of chamber surfaces, enables the understanding of performance variables for an array of particulates. Multiple wavelength and angular combinations were evaluated to determine the impact on algorithm performance for smoke detection and discrimination against nuisance alarm sources. With a model based understanding of particulates scattering established, subsequent studies analyzed the impact of light scattering on chamber surfaces and the potential role of dust accumulation. The resulting work forms the kernel of a physics based design tool for multi-color point smoke detectors. This highlights some of the challenges associated with optical scattering measurements of particulates in the presence of real-world surfaces.

Key Words:

Commercial, smoke detection, NFPA 72, UL 217/268, detector, design tools

Applicable Codes:

NFPA 72- NATIONAL FIRE ALARM AND SIGNALING CODE
UL STANDARD 217 - Standard for Smoke Alarms
UL STANDARD 268 - Smoke Detectors for Fire Alarm Systems

Introduction:

Optical scattering smoke alarms, also referred to as photoelectric smoke detectors presently dominate the commercial fire detector market. Despite their significant presence, these devices constitute complex alarm systems backed by significant research and development efforts expanded over the past decades. Their optical chambers are carefully designed for optimum sensitivity to smoke aerosols and rejection of nuisance alarm sources such as dust, water mist droplets and other airborne matter. To this end, chamber geometry, light source parameters, material selection and surface properties play a significant role in performance. In order to determine the limits of achievable performance a significant amount of testing and development time is spent. The figure below shows the interdependence of factors and smoke detector performance metrics. However, the potential exists for a change in effectiveness due to changes in requirements, algorithms, environment and manufacturing processes. To date, a trial and error approach combined with well-developed empirical correlations have been applied to this selection process.

The trial and error approach encourages incremental, Edisonian technology advancement. Consequently, the ability to perform virtual prototyping through physics-based modeling approaches becomes an attractive alternative. In order to enable adoption of physics based models for prototyping, the relevant performance parameters need to be captured. This requires simplifications of the model from electro-magnetic wave theory to ray tracing where practical. The figure below outlines the model architecture with inputs of smoke and detector parameters on one side and performance metrics as the output. Utilizing Mie Theory to approximate the interaction of light requires electro-magnetic wave theory calculations. Simplifying the particle scattering to a distribution function enables integration with ray tracing calculations. The ray tracing is useful for modeling geometries that are much larger than the wavelength of light. The resulting model architecture enables simulations of smoke detection systems at relevant size and complexities. Thus a methodology can be developed for virtual prototyping and validation.

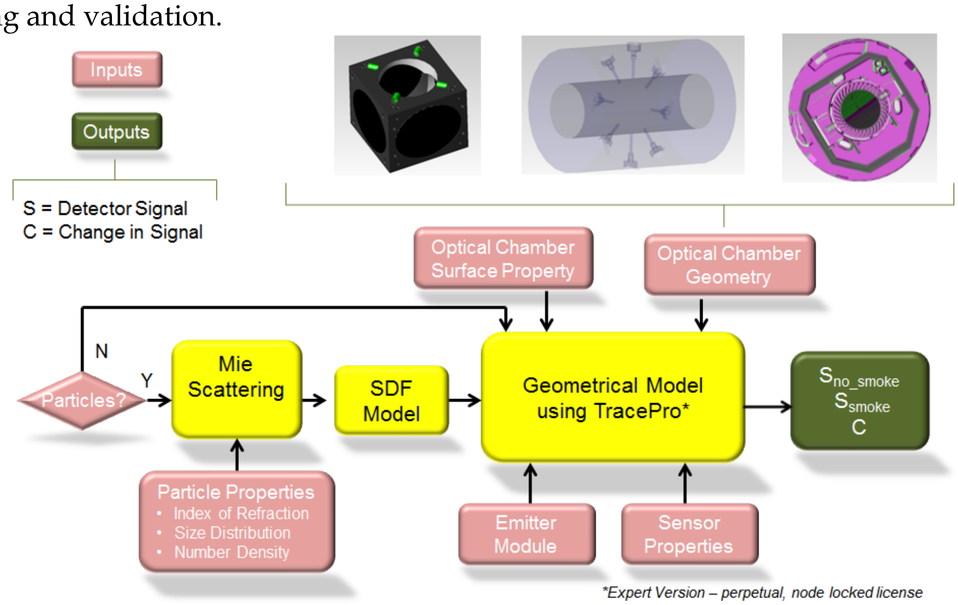

Figure 1. Model Architecture that incorporates Mie scattering, the scattering distribution function (SDF) and ray tracing approaches for a physics based assessment of multi-wavelength smoke detection systems.

Optical Simulation Methodology:

The optical scattering properties of smoke are highly dependent on the physical parameters; however, it is only one factor in the modeling of the total scattering of smoke detectors. The scattering from surfaces constitutes the second and more significant part of the scattering. Using commercially available and custom ray tracing software, a series of kernels were developed to evaluate the individual parts of the smoke detection model. Surface, emitter, and sensor properties are generated from experimental data and are assigned to the solid model. If particle scattering is to be included in the model, an additional bulk scattering volume must be created and assigned properties to describe the scattering behavior of the smoke. For the particle sizes and wavelengths of interest, the scattering can be well-described using Mie scattering. A Mie calculator was used to determine scattering behavior based on particle size, index of refraction and wavelength, while assuming a spherical particle shape. The scattering behavior was fit to a scattering distribution function (SDF) and the scattering coefficient was used to indicate particle number density. Both the SDF and scattering coefficient serve as inputs to the geometrical model.

The propagation of light through a smoke chamber has been modeled utilizing a "non-sequential ray-tracing" method. This approach launches light rays into a model without making any previous assumptions as to the order in which objects and surfaces will be intersected.[iii] The TracePro software package from Lambda Research Inc. was adopted for this purpose. This tool can handle complex CAD-generated solid geometries as well as model the optical properties of surfaces. The software can handle: specular reflection and refraction, diffraction, and the scattering of light. It utilizes the Monte Carlo method to simulate the scattering and diffraction of light, which are treated as random processes. Instead of propagating a distribution of light, discrete samples of the distribution, or rays, are propagated. These rays are randomly chosen, using the scattering distribution as a probability density. Along with variance reduction techniques inherent to TracePro, this allows reduction in the number of rays required for a reliable result.

A typical simulation run consists of tracing 10^6 -10^8 light rays emerging from the LED source and diffusing through the smoke chamber. As the rays propagate along different paths, TracePro keeps track of the optical flux associated with each ray. When a ray intersects a solid surface, it is either, absorbed, transmitted, or scattered and the ray's optical flux, transmission and scatter directions are calculated probabilistically. Analogous laws govern absorption, transmission and scattering throughout bulk volume based on assigned aerosol properties. In the end, the optical flux incident upon photodiode detector surface is computed by adding the fluxes due to all impinging light rays.

A model chamber geometry was developed that could easily translate between simulation and experiment. The chamber model geometry shown in the figure below has an LED mounted on one corner of an open cube with sensors on the other three corners. Black anodized aluminum sleeves are places over the LEDs and photodiodes to help reduce the amount of light and avoid saturation. Smoke particles flow through the open cube and the signal is compared to the no smoke/particle signal.

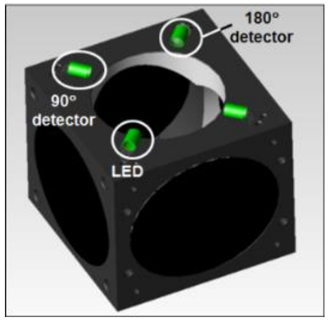

Figure 2. Model of the smoke detector chamber geometry.

The simulation investigated 3 colors; each simulation ran for 30 hours on a Xeon 2.10 Gigahertz processor with 64 megabytes of RAM. The simulations were run with experimental data that provided the smoke particle number density and particle size for a cotton wick smoke. In order to estimate stability of the results, the simulations were repeated nine times. The results in the table below indicate that average power of light received by the detector was on the order 1E-7 W/cm² at 2% smoke obscuration.

In comparison, a smoke box was utilized to create an environment with a controlled burn of a cotton wick. The velocity of the air was 32 ft/min and a beam detector was employed to measure the obscuration levels. The experimental results agree well with the physics based model on both the order of magnitude and trend.

Table 1. Multi-wavelength simulation results of a transmissive chamber geometry with smoke.

	Experiment			Simulation	
	Average (W)	**Min (W)**	**Max (W)**	**Min (W)**	**Max (W)**
IR-90	1.24e-7	0.43e-7	2e-7	1.66E-07	1.85E-07
Red-90	3.6e-7	0.59e-7	4.7e-7	4.48E-07	3.38E-07
Blue-90	3.0e-7	1.2e-7	3.9e-7	2.1E-07	5.5E-06

Although the simulations took over a month to compute, a significant potential exists by comparing to the trial and error approach that can take years and results in an empirical understanding of smoke detection.

Aerosol Scattering Effects:

As light propagates through a heterogeneous medium such as smoke aerosol in air, it is both absorbed and scattered. Rays that enter a material with non-zero absorption coefficient are attenuated according to Beers'-Lambert's Law of transmission:

$$(1)\ P_t = P_i e^{-\alpha l}\ or\ P_a = P_i\left(1 - e^{-\alpha l}\right)$$

Where, P_a, P_t and P_i are absorbed, transmitted and initial optical flux, respectively, l represents an optical path length through the material, and α is the absorption coefficient related to the imaginary part of the material's refractive index, k:

(2) $\alpha = \frac{4\pi k}{\lambda}$ $\quad and \quad$ $m = n + ik$

Here, m is the material's complex refractive index, while λ represents wavelength. However, this requires that scattering is negligible compared to absorption. When both, absorption and scattering contribute to total extinction of propagating light beam, a Bougher's modified law should be used instead.[iv]

Within TracePro, bulk absorption is specified through the α' coefficient with the units of 1/mm. If the refractive index and volume fraction, ϕ, of aerosol particulates are known, the absorption coefficient of the aerosol dispersion, α' may be estimated from:

(3) $\alpha' = \alpha * \phi$

The transmitted light intensity is then attenuated.

Scattering of light occurs whenever light interacts with matter dispersed within another medium. Two types of scattering are present: (1) Rayleigh due to molecules and small aerosols, and (2) Mie scattering for larger aerosols. The limit of Rayleigh scattering occurs where size factor, x', is less than 0.3:

(4) $x' = \frac{2\pi a}{\lambda}$

Where, a represents the aerosol particle radius. For x > 0.5, scattering becomes asymmetrical with increasing angular modes. For visible light particles smaller than 200 nm show very little angular variation in the scattering intensity. Meanwhile, particles larger than 200nm produce distinct scattering in the forward direction. Further description of Mie and Rayleigh scattering can be found in the reports and articles listed below and their references.[v,vi]

Within TracePro package as with many other commercial packages (FRED, Z-max, etc.), aerosol scattering is not treated explicitly. Instead, a few selected bulk scattering models may be invoked directly (Henyey-Greenstein[vii,viii] and Gegenbauer[ix] functions), while any other cases such as Mie function require software customization using the embedded macro-language.

When a light ray enters an object with assigned bulk scattering property, it propagates according to a probability distribution according to the scattering coefficient and its direction is deviated according to a pre-defined scattering distribution function (SDF) defined as the scattered intensity at location **r** per unit incident flux:

(5) $SDF \equiv p(\theta_s) = \frac{\delta P_s(\vec{r})}{\delta P_i}$

SDF defines the probability of scattering a ray through scatter angle θ_s and takes on values between 0 and 1. How far a ray travels between successive scattering events is dictated by a scattering coefficient, P_s, expressed in units of 1/mm, according to the probability distribution:

(6) $P(x)dx = e^{-\mu_s x}dx$

Where, x represents distance in the direction of the propagating ray. The inverse of the scattering coefficient is the mean free path of the ray in the bulk material. When a ray enters a piece of material that is thin compared to the mean free path, it is likely to pass through it without being scattered. Conversely, if the material is thick compared to the mean free path, the ray is almost certain to scatter. When a strong scattering coefficient is combined with a strong absorption coefficient, rays will be only weakly transmitted through the material.

For typical aerosol dispersion, both, bulk absorption and scattering contribute to the extinction of transmitted light. The Beers'-Lambert's law may be generalized:

$$(7)\ P_t = P_i e^{-\tau_{ext} l} \quad and \quad \tau_{ext} = N(\sigma_{abs} + \sigma_s)$$

Here, τ_{ext} is the extinction coefficient combining absorption and scattering through the corresponding cross-sections, σ_{abs} and σ_s expressed in $1/\text{cm}$, while N represents the number of aerosol particles per unit volume A measurement of beam attenuation within a smoke test box or smoke room can provide the experimental τ_{ext} value. However, in order to quantify light attenuation due to absorption and scattering, the appropriate cross-sections, σ_{abs} and σ_s need to be supplied as well. Typically, these two parameters are lumped together and reported as mass scattering cross-section. They can be found in the literature for several common test fires and nuisance aerosols.[x,xi,xii,xiii,xiv,xv,xvi] Note, that the measurement of aerosol concentration is still required before experimental τ_{ext} value may be used within the ray-tracing software to estimate P_t. The correlation of results from the model and experiments requires accurate determination of particle number density, size distribution and fire type during typical test fires, such as cotton wick smoke box test (similar to UL 217).

Concluding Remarks:

In the presentation, the recent development work on the kernel for multi-color point smoke detectors will be reviewed. Some challenges will be highlighted that are associated with optical scattering measurements of particulates in the presence of real-world surfaces. The presented results lead to insights on improving performance and reducing nuisance alarms.

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