Prediction of Light Scattering and Ionization Chamber Sensor Response to Smolder Smoke Aerosols[1]

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Abstract

Diagnostic equipment developed for an International Space Station experiment, the Smoke Aerosol Measurement Experiment (SAME), utilized three measurement devices to determine size properties of the smoke aerosols generated. They consisted of a light-scattering photometer, an ionization chamber from a residential smoke alarm, and a condensation particle counter. The ability to predict the ionization chamber and photometer outputs from aerosol size distribution and concentration information was examined. Using dioctyl phthalate aerosols ranging in mean size from about 0.1 μm to 1.0 μm, the relative expanded uncertainty of the ionization chamber prediction using total aerosol length was ± 12 %, while the relative expanded uncertainty of the photometer prediction was ± 33 % using a Mie-scattering model and the aerosol number concentration, size distribution, and refractive index. Smoke was generated from electrically heated silicone, Kapton, Teflon, cotton wick, and dibutyl phthalate samples using the SAME experimental hardware. The smokes were measured with the SAME diagnostic equipment plus additional aerosol instrumentation. Using measured size distributions and particle number concentrations along with estimates of the refractive index, the photometer predictions were within ± 25 % for most smokes except Kapton which appears to have an agglomerate structure as determined by electron microscopy.

Introduction

Models for the prediction of the response of photoelectric and ionization sensors inside alarms have been proposed as part of an overall model for smoke alarms [1]. However, comparative data on the accuracy and uncertainty of these predictive models is sparse. Light scattering intensity and ionization chamber response depends on particle size distribution, concentration, and optical properties in the case of light scattering. Two models examined here are the Hosemann model for ionization chambers [2], and a Mie-scattering model for smoke alarms developed by Gockel [1]. Calibration of diagnostic devices for the International Space Station experiment, the Smoke Aerosol Measurement Experiment (SAME) [3], provided an opportunity to quantify the predictive capability of smoke detector sensor models. The SAME experiment used three primary diagnostic devices, a condensation particle counter (Ptrak[2], TSI model 8525) that provided the aerosol number concentration, a modified residential smoke alarm ionization chamber with forced flow into the chamber, and a light scattering photometer (Dusttrak, TSI model 8520). Suitably calibrated, the ionization chamber and photometer provide estimates of the total aerosol length (sum of the aerosol diameters per unit volume) and the aerosol mass concentration, respectively. Measurements from the three diagnostic devices were used to estimate the aerosol size distribution using the Hatch-Choate relationship assuming a log-normal distribution [4].

Details about the modified ionization chamber and photometer are provided in the paper by Urban *et al*. [5]. The ionization chamber and associated electronics are from a residential smoke alarm with the horn removed. A guard voltage output from the alarm circuitry provides a way to follow changes in the chamber current. The chamber was modified to a flow-through design with a critical orifice on the outlet fixing the flow rate. The photometer used a laser operating at a wavelength of 780 nm, and optical elements collected scattered light centered at 90^{o}. Air was aspirated into the photometer. The output from the photometer was scaled to read the mass concentration of aerosolized ISO test dust in units of mg/m^3. The actual light intensity registered by the detector is proprotional to the scaled output. For simplicity, we assumed all light was scattered at

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[2] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology or the National Aeronautics and Space Administration, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

90°. A photoelectric smoke detector's sensor operates in a similar manner to a photometer. Both have sensing volumes where illuminated particles scatter light to a detector. The typical photoelectric smoke detector has a light source with a wavelength in the near infrared and a detector receiving scattered light over an angle range less than 90°, from particles that are convected into the sensing chamber. Since both the ionization chamber and photometer were aspirated at fixed flow rates, their response times were constant.

Calibration Experiments

An evaporation-condensation aerosol generation setup similar to the one described in Mulholland and Lui [6] was used to generate narrowly-dispersed dioctyl phthalate (DOP) aerosols with mean sizes of about 0.1 μm to 1.0 μm using six different DOP-isopropyl alcohol solutions. DOP aerosol particles are light colored, low vapor pressure liquid droplets similar to smolder smokes. A dilution system provided different aerosol concentrations for each particle size. Aerosols were directed to the ionization chamber, the photometer, an electrical aerosol detector (EAD, TSI model 3070A), a tapered element oscillating microbalance (TEOM, Thermo Scientific model 1105), and an electrical low-pressure impactor (ELPI, Dekati). The EAD measures the first moment of the size distribution, the total aerosol length, with an estimated uncertainty of ± 10%, and the TEOM measures the aerosol mass concentration with an estimated uncertainty of ± 10 %, The ELPI records the size distribution and particle number concentration. Since particles are classified in terms of their aerodynamic diameter, an estimate of the density of the aerosol particles is needed for interpreting ELPI data. Bulk densities of virgin material were used in the analysis. One minute exposures with concentration fluxuations of less than 2% were used for the analysis.

Calibration Results

The voltage signal from the ionization chamber was transformed to the non-dimensional "Y" variable from Hosemann's ionization chamber model [2] as described in NIST TN 1455-1 [7]. Y is proportional to the first moment of the aerosol size distribution, the total aerosol length. Figure 1 is a scatter plot of ionization chamber Y values from about 0.1 to over 1.0 versus the total aerosol length. A best-fit line yields a constant of proportionality of 248 mm/cm^3. This compares with the reference ionization chamber constant of about 300 mm/cm^3 determined by Helsper *et al*. [8]. The difference between the two constants could be related to the method of transforming the ionization chamber output voltage to Y. The relative expanded uncertainty in the mean value is ± 6% over this size range. Combining this uncertainty with the relative expanded uncertainty of the EAD total aerosol length of ± 10 % yields a combined relative

expanded uncertainty of ± 12 % when estimating the ionization chamber signal using the first moment of the size distribution.

Time-averaged log-normal aerosol size distributions were obtained from the ELPI data. Most size distributions were uni-modal and represented reasonably well by a log-normal form. The geometric mean size and geometric stanard deviation was computed from three average ELPI moments (zeroth, first, and third moments) and the Hatch-Choate relationship for each one minute exposure. Geometric mean diameters ranged from 0.017 μm to 1.00 μm and geometric standard deviations ranged from 1.25 to 1.62.

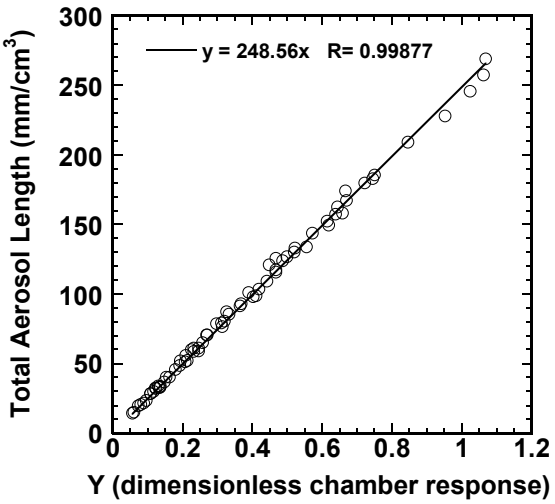

Figure 1. Total aerosol length versus Y for DOP aerosols.

In Figure 2 the photometer concentration was compared to the true DOP aerosol mass concentration obtained from the TEOM for six nominal geometric mean particle sizes. The slopes of the best fit lines for each nominal mean particle size show there was approximately a factor of four difference between the photometer reading and the true mass concentration for DOP aerosols over this size range. Figure 3 shows the predicted photometer reading using the Mie-scattering model and a single scaling constant to convert the predicted light scattering intensity to a scaled photometer reading. The lines bound a ± 33 % spread between the measured and predicted values. Main sources of uncertainty in the predicted values are thought to be deviations from the assumed log-

normal distribution and the simplified optical model (only 90^o scattering) of the photometer. Further study is needed to quantify these errors.

Smoldering smokes were produced from the SAME hardware and sent to the photometer and the ELPI. Table 1 shows the estimated aerosol density and refractive index for each of the SAME materials from reported bulk measurements along with the range of estimated log-normal size parameters for each aerosol produced.

Material	Density (g/cm^3)	Refractive Index (real, imaginary)	Geometric Mean Size Range (μm)	Geometric Standard Deviation
DBP	1.05	1.49, 0	0.49 – 1.35	1.5 – 2.2
Silicone	0.90	1.44, 0	0.34 – 0.43	1.5 – 1.6
Teflon	2.20	1.35, 0	0.04 – 0.16	2.1 – 2.4
Kapton	1.42	1.67, 0.01	0.07 – 0.11	2.3 – 2.4
Wick	1.00	1.55, 0.02	0.13 – 0.14	2.0 – 2.1

Table 1. Estimated material properties and size parameters for smokes.

Figure 4 is a plot of the measured photometer reading versus the predicted photometer reading using Mie-scattering model with the estimated refractive index, and the measured size parameters and aerosol concentration. Except for Kapton, most predicted values fall between the two lines that indicate a $\pm$ 25 % spread. Previous examination of particle morphology by electron microscope suggested that Kapton and Teflon aerosols were agglomerates of small primary particles similar to soot [5]. Both the ELPI data reduction for particle size determination and the Mie-scattering model would need to be modified to account for agglomerated smokes.

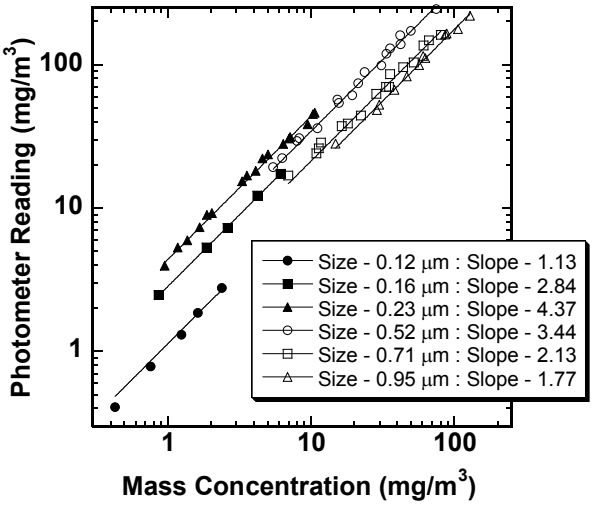

Fig. 2. Mass concentration versus photometer reading for DOP aerosols.

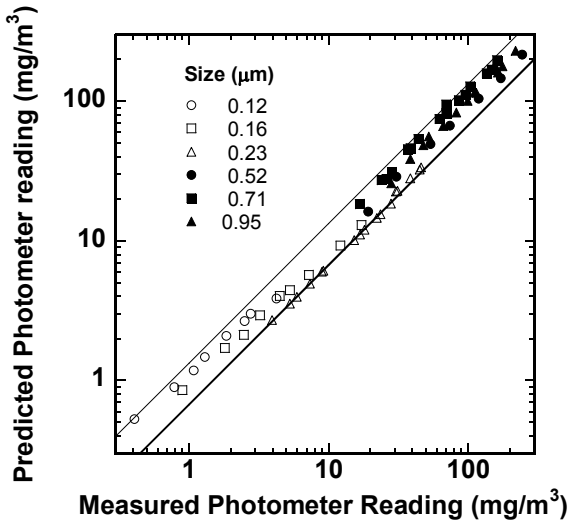

Fig. 3. Comparison of predicted photometer readings to measured readings for DOP aerosols. The lines bound a $\pm$ 33 % spread between the measured and predicted values.

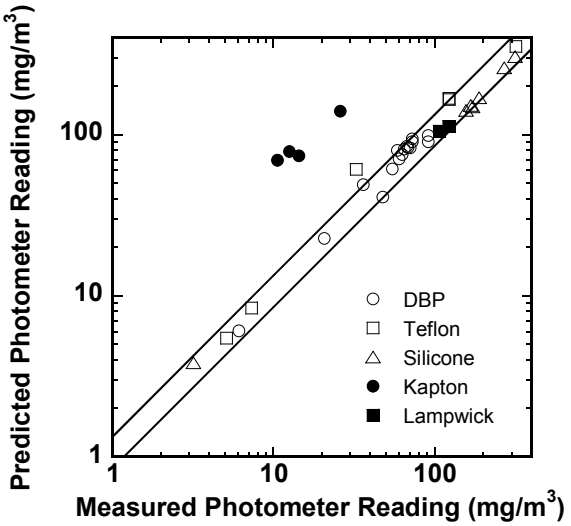

Fig. 4. Comparison of predicted photometer readings to measured readings for SAME experiment smokes. Most predictions fall within a range of ± 25 % deviation from measured with the notable exception of Kapton.

Conclusions

The ability of two models to predict ionization chamber and photometer outputs from aerosol size distribution, concentration and optical properties was examined. The voltage output from a flow-through ionization chamber constructed from a residential smoke alarm was able to predict the total aerosol length with a relative expanded uncertainty of ± 12 % for a wide range of aerosol sizes. A Mie-scattering model was able to predict the response of a photometer with a relative expanded uncertainty of ± 33 % for DOP aerosol mass concentrations ranging from 0.5 mg/m^3 to 125 mg/m^3 and a geometric mean size range of 0.12 μm to 1.0 μm. Main sources of uncertainty in the predicted values are thought to be deviations from the assumed log-normal distribution and the simplified optical model (only 90^o scattering) of the photometer. Further study is needed to quantify these errors. Photometer predictions of smokes generated from electrically heated samples were within ± 25 % for most smoke samples except for Kapton smokes where the predicted values were about a factor of 6 larger. Previous investigation has identified agglomerate particle structures for Kapton and Teflon smokes. Additional analysis is needed to properly account for agglomerates in the Mie-scattering model, and the particle size distribution estimation.

Acknowledgements

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