Particle Size Distributions from Smokes and Cooking Aerosols Sampled from Room Fire Experiments

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Abstract

The response of smoke alarms/detectors depends on the smoke or aerosol characteristics in addition to concentration. The particle size distribution inside a detector's sensing chamber is an important characteristic in understanding and predicting detector response. Results of particle size distributions from two particle measuring instruments, a fast mobility particle spectrometer and an electrical low pressure impactor, are presented for room-scale smoke alarm experiments. Particle size distributions of flaming and smoldering polyurethane smokes and cooking aerosols are reported.

Keywords: Smoke alarms, size distribution, smoke properties

Introduction

Typical measures to characterize smoke alarms, such as light obscuration and a measuring ionization chamber (MIC) response are integrated values that include the effects of particle size distribution along with concentration and optical properties, in the case of obscuration. However, these measurements don't necessarily correlate with detector response. Detailed measurements of particle size distributions for a wide range of smokes and nuisance aerosols can be used to interpret detector response based on physics, and as inputs for detector response models. Experiments were conducted in a test room constructed at the National Institute of Standards and Technology (NIST) to assess the performance of currently available smoke alarms to the new fire and cooking nuisance tests in ANSI/UL 217-2015 [1]. The smokes and cooking aerosol were sampled and particle size distribution data were collected during those experiments. Additional cooking experiments were conducted to expand the range of nuisance sources examined. Additional measures of some light scattering properties of these smokes and cooking aerosols were made and are presented in a companion paper in this conference [2].

Experimental

For each experiment, aerosol was sampled from a ceiling location near a light obscuration meter. The relative combined standard uncertainty of the obscuration meter was 4 % of the value in units of %/ft. obscuration (U.S. industry standard units) [1]. The sampling flow passed through an aerosol neutralizer to condition the charge distribution of the particles to a known state prior to entering the measuring instruments.

Two instruments were used to gather particle size distribution data: an electrical low-pressure impactor (ELPI) [2] and a fast mobility particle spectrometer (FMPS) based on the electrical aerosol spectrometer design from Tartu University [3]. Each instrument records data continuously at a rate of 1 Hz. The ELPI classifies particles based on their aerodynamic diameter (a spherical particle with a density equal to 1 g/cm^3 has an aerodynamic diameter equal to its physical diameter), while the FMPS classifies particles based on their electrical mobility diameter (a spherical particle of any density has the same mobility diameter as its physical diameter). Each instrument senses net electrical charge on particles to quantify concentrations. The measurement range of the ELPI is from 0.03 µm to 10 µm, while the measurement range of the FMPS is from 0.005 µm to 0.5 µm. The relative combined standard uncertainty for the measured particle sizes is estimated at 10 %. This does not include biases from the finite measurement ranges of the instruments.

Results

Results are presented for flaming and smoldering polyurethane foam, broiling hamburgers, frying hamburger, stir-frying vegetables, toasting bread, and heating cooking oil in a pan. See [1] for details regarding the sources and the room configurations. Figures 1-7 show the number concentration from the FMPS and ELPI (in only Figures 1-6) compared to the beam obscuration at the ceiling sampling location. In all cases the ELPI number concentration is lower than the FMPS since the ELPI does not count particles below about 0.03 µm. This tends to skew the geometric mean size to a larger diameter. The beam obscuration followed the number concentrations in some cases, but lagged in other cases, notably toasting bread and heating cooking oil. These sources tend to produce a large quantity of small particles early on that don't obscure the beam to an observable extent.

The toasting bread experiment was partitioned into two phases depending on the beam obscuration (Figure 5) and considered separately for the size distribution reporting, a light toasting phase from about 200 s to 300 s with an obscuration below 0.2 %/ft., and a dark toasting phase from about 400 s to 500 s with an obscuration range between 3.0 %/ft. and 19 %/ft.

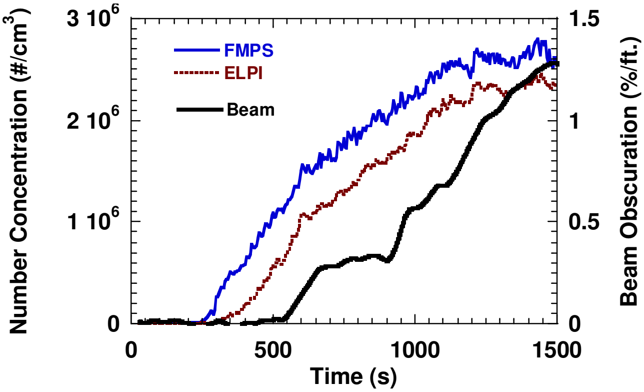

Figure 1. Number concentration results for broiling hamburgers.

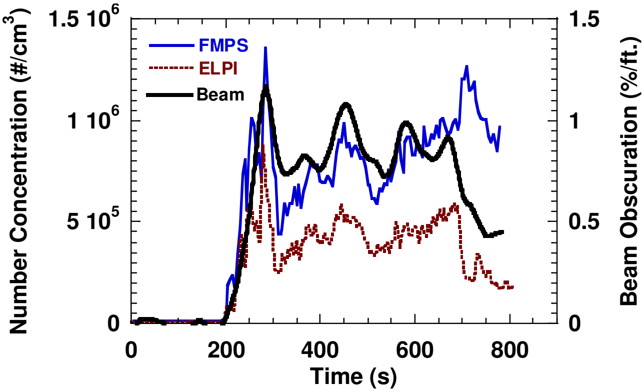

Figure 2. Number concentration results for frying hamburger.

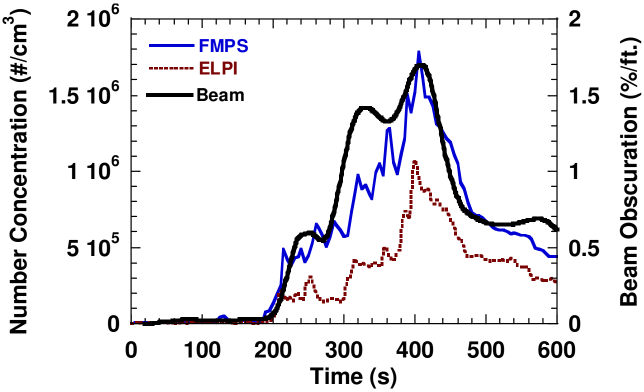

Figure 3. Number concentration results for stir-frying vegetables.

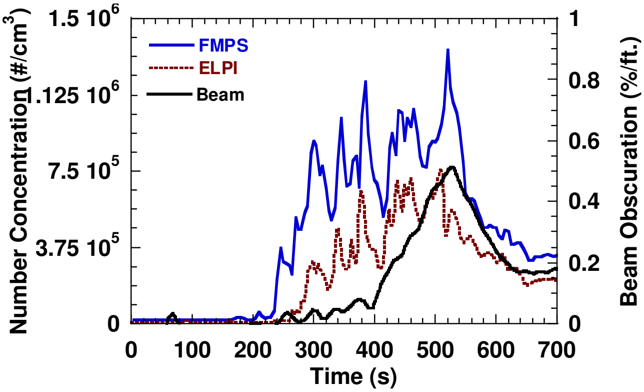

Figure 4. Number concentration results for heating cooking oil.

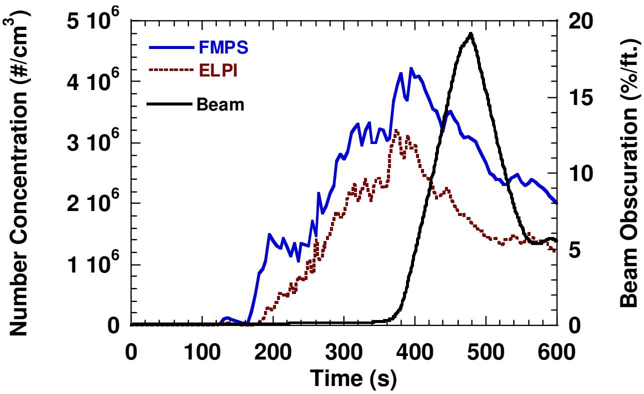

Figure 5. Number concentration results for toasting bread.

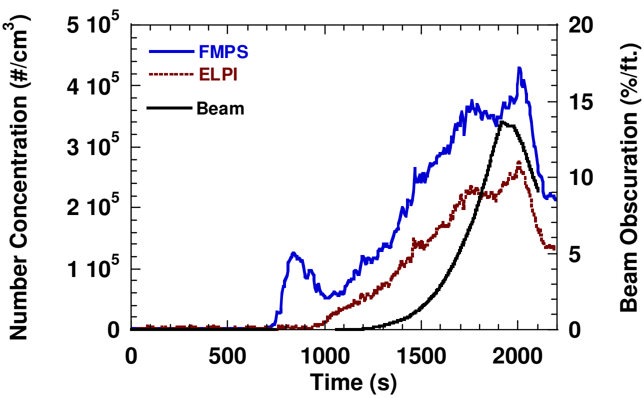

Figure 6. Number concentration results for smoldering foam.

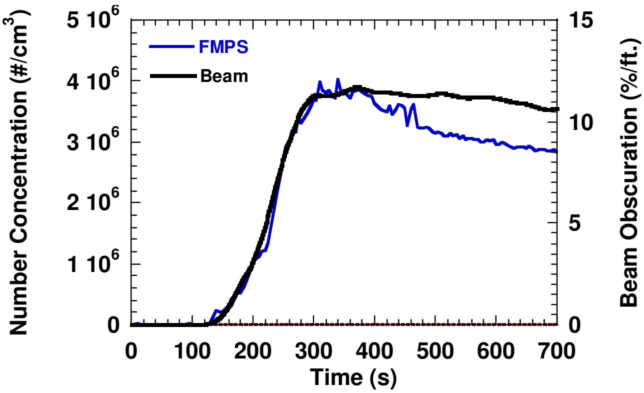

Figure 7. Number concentration results for flaming foam.

Table 1 details the measured and fitted particle sizes from the FMPS and ELPI over a fixed obscuration range.

The geometric mean particle diameter (d_g) was calculated using Eq. 1

$$\ln(d_g) = \frac{\sum(n_i \cdot \ln(d_i))}{N} \qquad \text{Eq. 1}$$

where n_i is the number of particles of size group d_i (channel or impactor stage), and N is the total number of particles. The mass mean diameter (d_{mm}) was calculated using Eq. 2.

$$d_{mm} = \frac{\sum(m_i \cdot d_i)}{M} \qquad \text{Eq. 2}$$

where m_i is the mass of particles of size group d_i, and M is the mass of all particles.

The data were also fitted to a log-normal distribution (d_g or d_{mm} and a geometric standard deviation, σ_g) as is typical of aerosol size distributions. The geometric standard deviation is indicative of the breadth of the distribution, where a value of one indicates a monodisperse single size. In terms of a cumulative fraction of mass or number about 68.2 % is located within sizes d/σ_g and $d \times \sigma_g$ for a lognormal distribution.

No ELPI mass distribution data is presented for the light toast case due to the low mass signal. No ELPI data is presented for the flaming foam case because the device response is complicated by the structure and apparent density of fractal soot agglomerates. A calculated mass mean diameter for the FMPS is not presented.

Table 1. Particle size averaged over a fixed obscuration range

Broiling hamburgers – Obscuration range 0.5 %/ft. to 1.0 %/ft.						
Device	Number Distribution (geometric mean diameter)			Mass Distribution (mass mean diameter)		
	d_g calc (μm)	d_g fit (μm)	σ_g fit	d_{mm} calc (μm)	d_{mm} fit (μm)	σ_g fit
FMPS	0.074	0.084	1.71		0.15	1.56
Std Dev*	0.005	0.006	0.02		0.01	0.02
ELPI	0.092	0.083	2.52	0.41	0.31	1.76
Std Dev	0.004	0.006				
Frying hamburger – Obscuration range 0.75 %/ft. to 1.0 %/ft.						
Device	Number Distribution (geometric mean diameter)			Mass Distribution (mass mean diameter)		
	d_g calc (μm)	d_g fit (μm)	σ_g fit	d_{mm} calc (μm)	d_{mm} fit (μm)	σ_g fit
FMPS	0.057	0.058	1.98		0.21	1.75
Std Dev	0.005	0.005	0.02		0.01	0.02
ELPI	0.099	0.085	2.53	0.60	0.55	1.92
Std Dev					0.03	0.07
Stir-frying vegetables – Obscuration range 1.0 %/ft. to 1.5 %/ft.						
Device	Number Distribution (geometric mean diameter)			Mass Distribution (mass mean diameter)		
	d_g calc (μm)	d_g fit (μm)	σ_g fit	d_{mm} calc (μm)	d_{mm} fit (μm)	σ_g fit
FMPS	0.041	0.039	3.22		0.19	1.68
Std Dev	0.008	0.013	0.30		0.01	0.01
ELPI	0.11	0.11	2.6	0.67	0.52	2.03
Std Dev	0.01	0.01			0.08	0.16
Heating cooking oil – Obscuration range 0.05 %/ft. to 0.5 %/ft.						
Device	Number Distribution (geometric mean diameter)			Mass Distribution (mass mean diameter)		
	d_g calc (μm)	d_g fit (μm)	σ_g fit	d_{mm} calc (μm)	d_{mm} fit (μm)	σ_g fit
FMPS	0.049	0.051	1.93		0.168	1.76
Std Dev	0.005	0.005	0.04		0.08	0.15
ELPI	0.082	0.080	2.16	0.46	0.38	2.01
Std Dev	0.007		0.07	0.07	0.07	0.19

Table 1. Cont. Particle size averaged over a fixed obscuration range

Light toasting bread – Obscuration Range less than 0.2 %/ft.						
Device	Number Distribution (geometric mean diameter)			Mass Distribution (mass mean diameter)		
	d_g calc (μm)	d_g fit (μm)	σ_g fit	d_{mm} calc (μm)	d_{mm} fit (μm)	σ_g fit
FMPS	0.047	0.048	1.49		0.075	1.44
Std Dev	0.007	0.007	0.013		0.008	0.03
ELPI	0.056	0.042	1.63			
Std Dev	0.003	0.001	0.09			
Dark toasting bread – Obscuration range 3.0 %/ft. to 19 %/ft.						
Device	Number Distribution (geometric mean diameter)			Mass Distribution (mass mean diameter)		
	d_g calc (μm)	d_g fit (μm)	σ_g fit	d_{mm} calc (μm)	d_{mm} fit (μm)	σ_g fit
FMPS	0.10	0.11	1.51		0.18	1.48
Std Dev	0.01	0.01	0.02		0.02	0.02
ELPI	0.16	0.20	2.72	0.77	0.68	1.65
Std Dev	0.05	0.06	0.30	0.08	0.10	0.12
Smoldering foam – Obscuration range 1.0 %/ft. to 5.0 %/ft.						
Device	Number Distribution (geometric mean diameter)			Mass Distribution (mass mean diameter)		
	d_g calc (μm)	d_g fit (μm)	σ_g fit	d_{mm} calc (μm)	d_{mm} fit (μm)	σ_g fit
FMPS	0.12	0.13	1.52		0.21	1.55
Std Dev	0.01	0.01	0.03		0.01	0.02
ELPI	0.21	0.30	1.67	1.2	0.92	2.25
Std Dev	0.01	0.01	0.06	0.04	0.06	0.06
Flaming foam – Obscuration range 3.0 %/ft. to 10 %/ft.						
Device	Number Distribution (geometric mean diameter)			Mass Distribution (mass mean diameter)		
	d_g calc (μm)	d_g fit (μm)	σ_g fit	d_{mm} calc (μm)	d_{mm} fit (μm)	σ_g fit
FMPS	0.13	0.14	1.59		0.23	1.36
Std Dev	0.01	0.01	0.05		0.01	0.02

* The standard deviation (Std Dev) is the computed value over the time internal representing the fixed obscuration range.

The d_g measured from the FMPS was always smaller than what the ELPI measured. This is due to the lower size cut off at about 0.03 µm for the ELPI versus about 0.005 µm for the FMPS. The d_{mm} measured from the ELPI was always greater than the size measure by the FMPS, in some cases by a large amount. This is due to the smaller upper size cut off at 0.5 µm for the FMPS and the fact that the mass is proportional to the diameter raised to the third power.

Conclusions

Experiments to assess the performance of smoke alarms were conducted in a test room constructed at NIST and particle size data was collected during those experiments. Two instruments were used to gather particle size distribution data, an electrical low-pressure impactor (ELPI) and a fast mobility particle spectrometer (FMPS), during flaming, smoldering and cooking events,

For the smoke and cooking aerosols measured, the FMPS produces a better estimate of the geometric mean diameter, while the ELPI produces a better estimate of the mass mean diameter. Both instruments complement one another because smoke detectors, depending on the sensor, can respond to particle sizes from the minimum to the maximum sizes measured by both instruments.

Acknowledgements and Disclaimer

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References

[1] Cleary T.G., *A Study on the Performance of Current Smoke Alarms to the New Fire and Nuisance Tests Prescribed in ANSI/UL 217-2015*, Natl. Inst. Stand. Technol., Technical Note 1947, (2016) https://doi.org/10.6028/NIST.TN.1947.

[2] Cleary, T., Mensch, A., *Polarized Light Scattering of Smoke Sources and Cooking Aerosols*, 16th Int. Conf. On Automatic Fire Detection AUBE 17 and Suppression, Detection and Signaling Research and Applications Conference SUPDET 17, College Park, MD, USA, Sept 12-14, 2017.

[3] Keskinen, J., Pietarinen, K., and Lehtimöki, M. (1992). *Electrical Low Pressure Impactor*, J. Aerosol Sci. 23:353.

[4] Tammet H, Mirme A, Tamm E (1998) *Electrical aerosol spectrometer of Tartu University*. J Aerosol Sci 29S(1):S427–S428