Polarized Light Scattering of Smoke Sources and Cooking Aerosols

Thomas Cleary, Amy Mensch
National Institute of Standards and Technology, Gaithersburg, MD, USA

Abstract

Light scattering data was gathered during experiments conducted in an ANSI/UL 217 test room constructed at the National Institute of Standards and Technology (NIST) to assess the performance of currently available smoke alarms. Smoldering and flaming fires along with cooking experiments were conducted. The light scattering device was configured to measure polarized light scattering characteristics of the fire smokes and cooking aerosols. Results are presented for forward scattering, polarization and asymmetry ratios. The results show a high degree of discrimination by a 90° polarization ratio between flaming soot and other smoldering smokes and cooking aerosols, and to a lesser degree discrimination by forward scattering and asymmetry ratios at the chosen angles.

Keywords: Smokes, cooking aerosols, light scattering

Introduction

The purpose of multiple measurement angles and/or light sources in smoke detection is to provide some discrimination of aerosols to distinguish smokes from non-fire sources. Weinert examined polarized light scattering from a number of fire and nuisance sources and showed a level of source discrimination using various measures [1]. Detectors and alarms that use multiple light scattering measures including different wavelengths, scattering angles and polarization states, perhaps combined with other sensor signals, may have the ability to distinguish between fire and non-fire conditions to a high degree. Given that new requirements in ANSI/UL 217-2015 [2] specifically require a cooking nuisance source test and apparently no current smoke alarms would pass the new requirements [3], there is an industry focus on detector modifications to meet the new standard. Data on the light scattering characteristics of the new fire and nuisance source tests and additional fire and nuisance aerosol sources may provide a foundation for developing new discriminating detection schemes. Thus, NIST has begun to collect and analyze such data.

Experimental

Measurements were made with the NIST nephelometer/polarimeter [4] to gather polarized light scattering characteristics of fire smokes and nuisance source aerosols. The nephelometer section was configured to record vertically polarized light scattering intensities at two diode laser wavelengths, 638 nm and 980 nm, and five angles (15°, 22.5°, 45°, 90° and 135°) for each wavelength. In addition, horizontally polarized light scattering intensity at 90° for each wavelength was recorded. The acceptance angle for the scattered light reaching the detectors was about ± 3°. The data was acquired at 1 Hz to provide temporal resolution for the changing environment during each experiment. Neutral density filters were used to attenuate scattering signals to the measurement range of the photodetectors when needed. Additionally, laser light intensity (0°) was recorded and used to normalize the scattering intensities by the incident laser intensity. Figure 1 is a schematic of a cross-section for one beam. The aerosol flows through the central opening while the laser beam bisects the opening. What is not shown are polarization elements including a Glan-Thompson polarizer in front of the source beam to provide the incident polarization state, and ½ waveplates before the photodetectors to pass only scattered light with the desired polarization state.

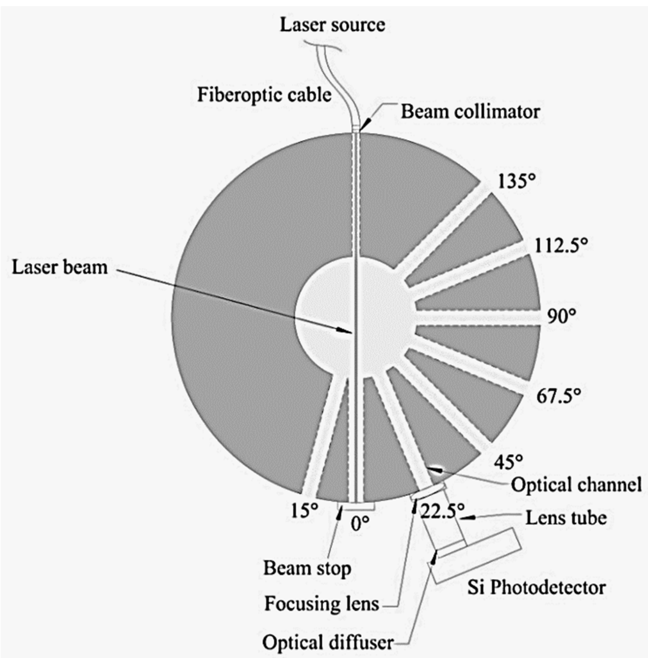

Figure 1. Schematic of a section of the nephelometer.

Following Weinert [1], forward scattering ratios (FR, $I_{vv15^o}/I_{vv22.5^o}$), asymmetry ratios (AR, I_{vv45^o}/I_{vv135^o}) and polarization ratios (PR, I_{hh90^o}/I_{vv90^o}) were computed. Here, I is the scattering signal intensity, and the subscripts denote the horizontal (h) and vertical (v) polarization states of incident and scattered light, and the scattering angle. Initial calibrations were performed with nearly monodisperse di-ethyl-hexyl-sebacate (DEHS) particles of several aerodynamic diameters, from 0.18 µm to 1.0 µm, produced by a condensation/evaporation aerosol generator. The particle size distribution was measured with an electrical low pressure impactor and fitted to a log-normal distribution (d_g - geometric mean diameter, and σ_g - geometric standard deviation). The relative combined standard uncertainty in the mean diameter is estimated to be less than 10 %. Mie scattering calculations were performed with the results integrated over the size distribution and the acceptance angle of the nephelometer.

Results

The results are compared to Mie scattering calculations in Table 1. Some values were not tabulated which indicates either a low signal or a saturated signal of one of the photodetectors. The relative combined standard uncertainty for the computed ratios is estimated to be less than 10 % for the tabulated values.

Table 1. Measured size distributions and corresponding measured and computed scattering ratios for DEHS particles.

d_g (µm)	σ_g	$FR_{638\ nm}$ Measured/ Computed	$PR_{638\ nm}$ Measured/Computed	$AR_{638\ nm}$ Measured/Computed
0.18	1.49	- /1.15	0.013/0.19	3.64/8.60
0.26	1.39	1.03/1.17	0.065/0.34	6.98/14.5
0.30	1.26	1.06/1.11	0.110/0.29	11.2/16.2
0.39	1.28	1.09/1.22	0.660/0.78	29.2/26.3
0.52	1.27	1.16/1.39	- /1.01	14.4/18.6
0.66	1.25	1.30/1.61	- /1.10	24.0/8.54
0.83	1.25	1.68/1.98	- /1.33	5.19/5.29
1.02	1.30	2.35/2.40	- /1.40	9.84/6.31
d_g (µm)	σ_g	$FR_{980\ nm}$ Measured/ Computed	$PR_{980\ nm}$ Measured/Computed	$AR_{980\ nm}$ Measured/Computed
0.18	1.49	- /1.07	0.025/0.051	1.16/3.70
0.26	1.39	- /1.08	0.016/0.073	1.97/4.92
0.30	1.26	- /1.05	0.011/0.025	2.21/3.60
0.39	1.28	- /1.09	0.011/0.15	3.92/9.39
0.52	1.27	- /1.15	0.030/0.50	14.1/22.9
0.66	1.25	1.26/1.24	0.125/0.94	- /27.5
0.83	1.25	1.54/1.39	0.182/1.00	12.9/18.5
1.02	1.30	1.64/1.69	- /1.16	8.60/7.83

Figures 2-4 are plots comparing the various measured and computed ratios for the 638 nm wavelength beam. The measured and computed values follow the same trends with the exception of polarization ratios for the 980 nm wavelength beam. The trend is the same, but with a difference of a factor of about 10 to 20. This could indicate alignment issues.

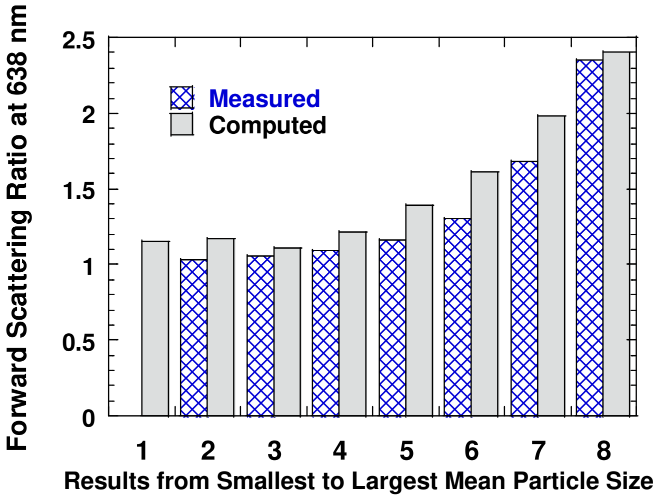

Figure 2. Results of the forward scattering ratios of DEHS particles.

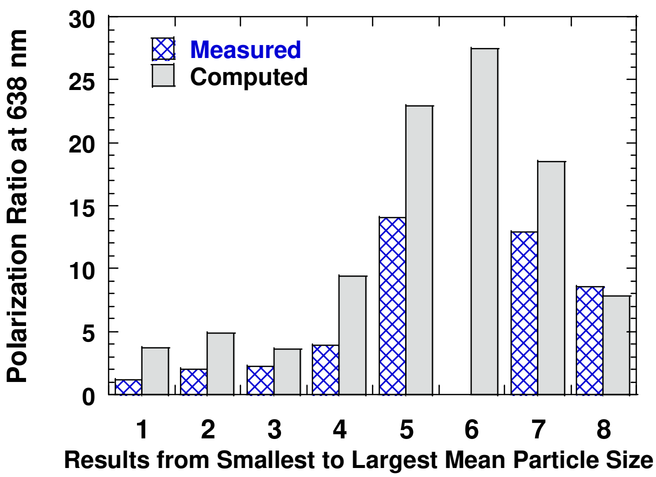

Figure 3. Results of the polarization ratios of DEHS particles.

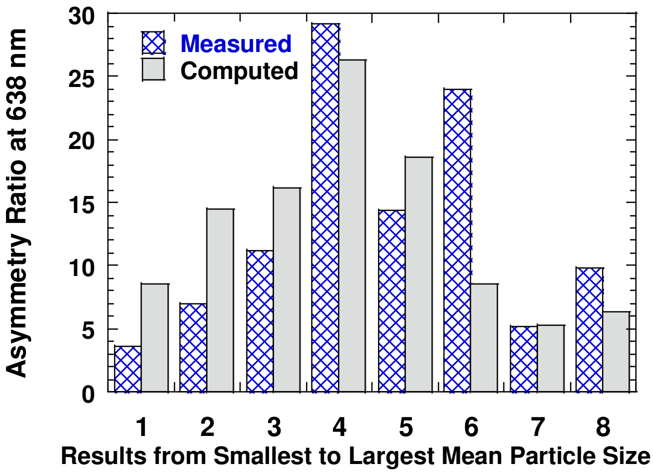

Figure 4. Results of the asymmetry ratios of DEHS particles.

Given the uncertainty in alignment and particle size, measured and computed values compare favorably, thus the instrument configuration provides realistic estimates of light scattering ratios except $PR_{980\ nm}$.

Aerosol samples from full-scale ANSI/UL 217-2015 room experiments were directed to the nephelometer/polarimeter. The flaming sources included polyurethane foam, a heptane/toluene pool and shredded copy paper. The smoldering sources included polyurethane foam and wood blocks on a hot plate. The cooking nuisance sources included broiling hamburgers, frying hamburger, stir-frying vegetables and heating cooking oil. The flaming and smoldering polyurethane foam and broiling hamburger experiments were conducted in the manner following ANSI/UL 217-2015 as described in reference [3].

Figures 5 and 6 show comparisons of smokes and cooking aerosols between ceiling beam obscuration and 45° forward light scattering at a wavelength of 638 nm normalized by the incident beam intensity. The difference between scattering and obscuration for the flaming foam smoke and the smoldering and cooking smokes is indicative of the relatively large absorption coefficient of black soot compared to the other sources. Table 2 shows the calculated ratios for the two wavelengths of the various sources. Values were averaged over an obscuration range indicative of smoke alarm activation concentration. Figures 7 and 8 are plots of the values for polarization ratio and asymmetry ratio at 638 nm wavelength. The flaming foam and heptane/toluene pool fire sooty smokes are easily discriminated from the other sources. However, the smoldering smokes and flaming paper smoke are not clearly distinguished from the cooking aerosols.

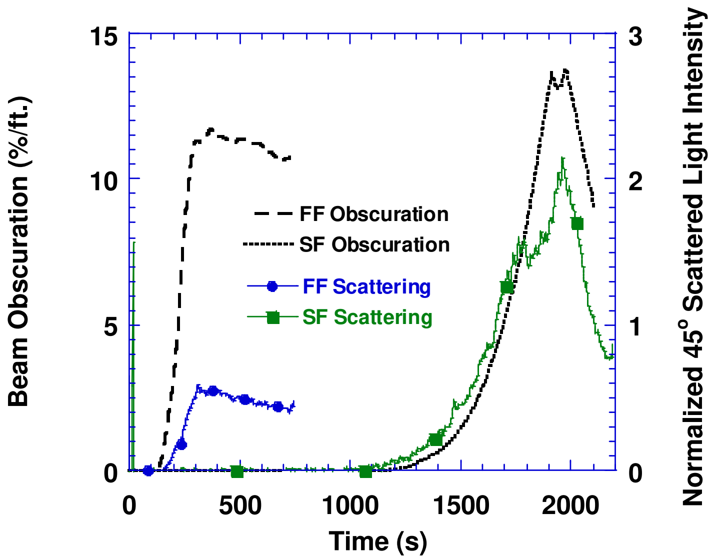

Figure 5. Ceiling beam obscuration and forward scattering signal for flaming polyurethane foam (FF) and smoldering foam (SF).

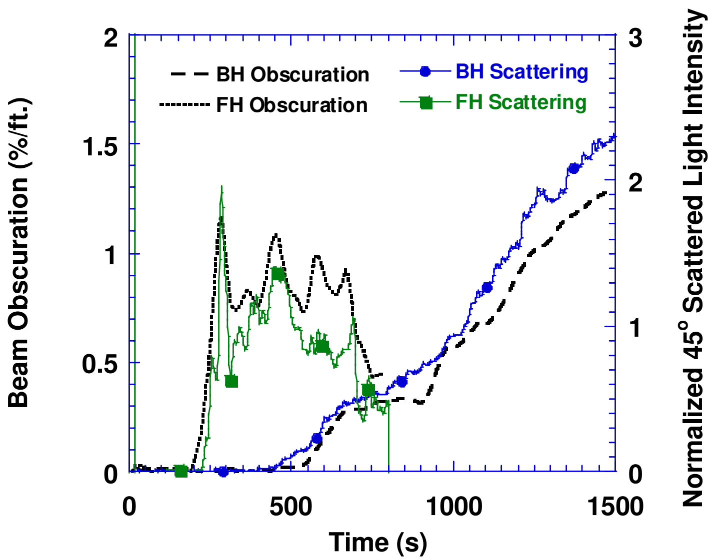

Figure 5. Ceiling beam obscuration and forward scattering signal for frying hamburger (FH) and broiling hamburgers (BH).

Table 2. Tabulated values of scattering ratios averaged over the indicated beam obscuration range for the various sources.

Source	Obsc. Range (%/ft.)	PR_{638} Ratio, SD*	AR_{638} Ratio, SD	PR_{980} Ratio, SD	AR_{980} Ratio, SD
Flaming Foam (FF)	2-6	0.014, 0.005	4.59, 0.19		3.80, 0.27
Heptane/ Toluene (H/T)	4-8	0.012, 0.001	4.65, 0.03		3.89, 0.01
Flaming Paper (FP)	1.5 - 2	0.23, 0.03	9.26, 1.13	0.44, 0.24	7.39, 0.29
Smoldering Foam (SF)	2-4	0.25, 0.01	15.0, 0.4	0.44, 0.04	4.35, 0.50
Smoldering Wood (SW)	0.5 – 0.75	0.27, 0.06	13.9, 2.5		
Broiling Hamburger (BH)	0.5 - 1.5	0.17, 0.01	9.98, 0.19	0.19, 0.01	5.45, 0.22
Frying Hamburger (FH)	1	0.37, 0.02	17.9, 0.4	0.28, 0.02	7.18, 0.63
Stir-frying Vegetables (SV)	1-1.5	0.39, 0.04	15.8, 0.7	0.36, 0.03	7.85, 0.72
Cooking Oil (Oil)	0.3 -0.7	0.27, 0.04	20.4, 1.0	0.23, 0.06	7.22, 0.50

* SD – standard deviation of the ratio over the obscuration range

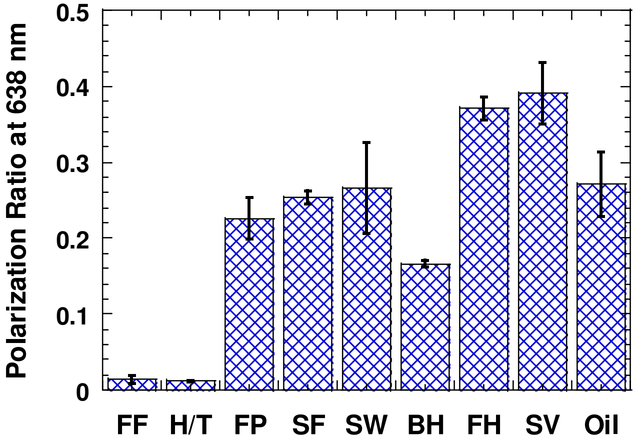

Figure 7. Polarization ratios for various sources, error bar indicates standard deviation.

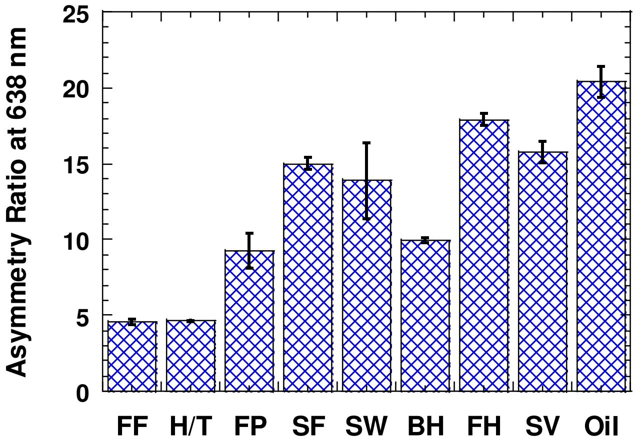

Figure 8. Asymmetry ratios for various sources, error bar indicates standard deviation.

Conclusions

The results show a high degree of discrimination between flaming soot and other smoldering and cooking aerosols considering a 90^o polarization ratio, and a lesser degree of discrimination considering forward scattering and asymmetry ratios at the chosen angles similar to measurements conducted by Weinert.

Acknowledgements and Disclaimer

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References

[1] Weinert D., [2003] *Light Scattering by Smoke and Nuisance Aerosols*, Ph.D., Victoria University of Technology, Australia.

[2] *ANSI/UL 217-2015: Standard for Safety for Smoke Alarms*, Underwriters Laboratories Inc., Northbrook, IL, 2015.

[3] 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

[4] Cleary, T.G., and M. Zarzecki, "*A Nephelometer/Polarimeter for Characterizing Smoke and Nuisance Alarm Sources*," Proceedings of the 15th International Conference on Automatic Fire Detection AUBE '14, Duisburg, Germany, October 14-16, 2014.