Methods for Characterizing Artificial Smoke Generators for Standardizing Inflight Smoke Detection Certification

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Abstract

False alarm resistant smoke detectors must pass the inflight smoke detection certification test in order to be implemented in aircraft[1,2,3]. Due to health and safety concerns – artificial smoke generators are used for inflight certification testing. Aerosols created by artificial smoke generators must be similar to smoke in order for the false alarm resistant smoke detectors to alarm. Therefore, verifying which artificial smoke generators produce an aerosol with similar particle characteristics to smoke is essential for the implementation of false alarm resistant detectors in aircraft. Furthermore, standardizing the artificial smoke generators for the total quantity of aerosol production, rate of aerosol production and repeatability of aerosol production and quantifying the effects of ambient environment is necessary to ensure the reliability and integrity of the inflight smoke detection certification test.

This study indicates artificial smoke generators are capable of producing an aerosol with similar particle size distributions and light scattering characteristics to smoke created by smoldering foam, smoldering wood, and lithium-ion battery thermal runaway vent-gas. Measurable differences in the total quantity of aerosol production and the rate of aerosol production are found between four separate smoke generators that are used by major airline manufacturers for the inflight smoke detection certification testing. In addition, changes in ambient temperature and pressure that may occur during a typical flight profile can measurably affect an individual smoke generator's production of aerosol.

Keywords: Smoke generator, aerosol, smoke detection, fire detection, nuisance aerosols, forward scattering, blue light, IR light, light obscuration, SMPS, size distribution, aircraft cargo compartment, 14 CFR 25.858, TSO-C1E, AC 25-9A

Introduction

Federal Aviation Administration (FAA) regulations require that a commercial aircraft cargo compartment smoke detection system must provide visual indication to the flight crew within one minute after the start of a fire[1]. Further FAA guidance states that the smoke detection certification test is designed to demonstrate that the smoke detection system will detect a smoldering fire that produces a small amount of smoke[2]. In an attempt to eliminate the frequency of false alarms, the FAA issued a Technical Standard Order[3] to adopt the Minimum Performance Standards of smoke detector equipment, which includes criteria for resisting alarms from nuisance sources such as water vapor, insecticide aerosols, dust and light.

On average, there are 70 fire or smoke detector events of inaccessible cargo areas for passenger and freighter aircraft annually[4]. The typical procedure of an inflight warning from fire detection systems is to discharge the fire suppression system into the cargo compartment and divert the aircraft to the nearest suitable airport[1]. Approximately 1% of flight deck warnings of smoke or fire in inaccessible cargo areas are a result of actual fires[4]. This can result in a loss of faith in the fire detection system, inconvenience passengers and financially burden the airlines.

In this study, methods for characterizing theatrical smoke for inflight certification of cargo compartment smoke detection systems are considered. Theatrical smoke generators use an inert gas to propel mineral oil into a heat exchanger, where the solution is vaporized and a fog similar in appearance to smoke is created. The theatrical smoke exits through a chimney incorporated with heaters to create a thermally-buoyant plume. Smoke from smoldering fires are compared to theatrical smoke by measuring the particle size distributions with a scanning mobility particle sizer (SMPS) and comparing it to the light scattering characteristics response to blue (470 nm) and an infrared (850 nm) light. Smoke generators from four major airline manufacturers are compared by measuring the total quantity of smoke, the rate of production and the repeatability. Varying ambient conditions are evaluated to determine the effect on the production of aerosol by smoke generators. During inflight certification process, the cargo compartment temperature can range from 10-30°C and the pressure can range from 101kPa, while on the ground, to 69.7kPa while inflight.

Experimental

Tests were conducted in a 236cm x 183cm x 180cm environmental chamber that is capable of simulating ambient conditions that may occur during a typical flight profile. The environmental chamber is equipped with a blue and IR light scattering intensity measurement (LSM), SMPS, and six obscuration meters aligned vertically above the smoke generator or smoke source. Four major aircraft manufacturer's smoke generators and settings are tested and compared. One manufacturer uses a Siemens Cerberus, two manufacturers use an Aviator 440, and one manufacturer uses a modified aviator 440. The smoke generator setups are annotated as MFR 1a, MFR 1b, MFR 1c, MFR 2a, MFR 2b, MFR 3, and MFR 4. For testing, a smoke generator is turned on to produce an aerosol for 60 seconds to best represent the test procedures outlined in 14 CFR 25.858. Light obscuration and light scattering measurements are taken throughout the entire test, while SMPS measurements are taken incrementally at 10, 90 and 210 seconds. Additionally, size distributions and light scattering characteristics from smoke created by smoldering foam, smoldering wood, and lithium-ion battery thermal runaway vent-gas are measured and compared to particles produced by the smoke generators.

Mie Scattering Theory governs light scattering by sub-micron particles where scattering intensity is a function of the wavelength of the incident light, refractive index and radius of the particle. In theory, the smoke particle size can be determined by measuring the scattering intensity from known multi-wavelength light sources. The theory is tested by comparing simultaneous measurements of multi-wavelength light scattering intensities with a LSM and particle size distributions with a SMPS. As shown in figure 1, the LSM main components consist of two LEDs, a blue LED 470 nm wavelength and an IR LED 850 nm wavelength and two sensors, a blue sensor and an IR sensor. The LEDs face the center and the corresponding sensors are at a forward scattering angle of 135 degrees. The SMPS is a submicron sizing instrument that uses electrical mobility to characterize particle size. It has a measurement range of 10 nm to 1 µm.

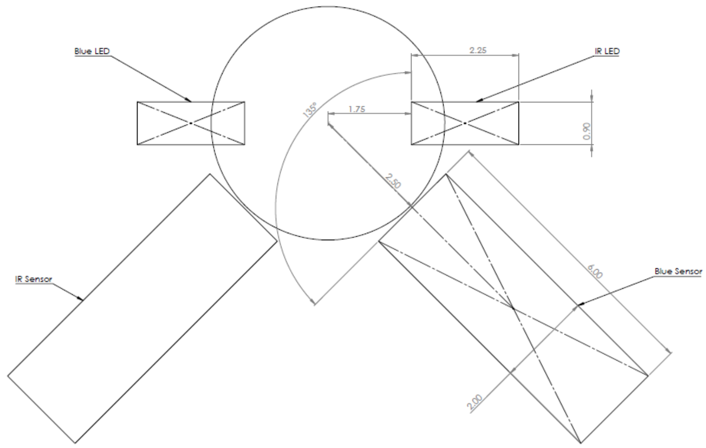

Figure 1. Schematic of LSM

Results

The van de Hulst approximation of the Mie Scattering Theory works well for characterizing very small particles of the order of 100 nm – 500 nm, where the equation is mostly linear. Due to the nonlinear nature of the equation, there can be multiple solutions over a larger range of particle sizes. The mostly linear range is dependent on the refractive index of the particle, where increasing the refractive index will increase the linearly measurable range.

The Mie Scattering Theory is best for generally characterizing the particle size of smoke sources with similar refractive indexes and does not give a full indication of the particle-size distributions like the SMPS does. This is demonstrated in figure 2, where LSM and SMPS measurements of smoke generator aerosols and smoke from smoldering foam, smoldering wood, and lithium-ion battery thermal runaway vent-gas are displayed. There is a strong negative correlation between the percentage of blue to blue and IR light scattering intensity measured with the LSM and the geometric mean diameter measured with the SMPS within individually sourced particles. However, the strong correlation diminishes to no correlation when comparing particles from multiple sources with varying refractive indexes.

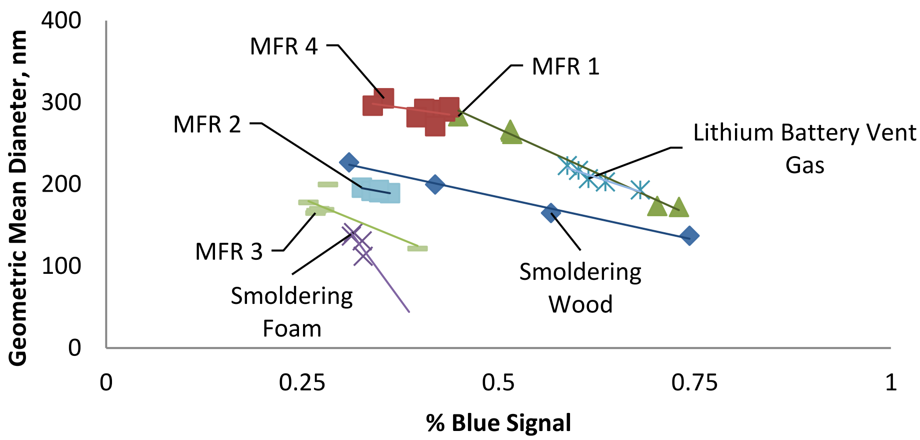

Figure 2 LSM %Blue Signal vs SMPS Diameter

The geometric mean diameter for smoke generator aerosols range from 167 nm to 293 nm with an overall average of 223 nm and a standard deviation of 56 nm, while the geometric mean diameter for lithium ion batteries thermal runaway vent gas, smoldering foam, and smoldering wood range from 130 nm to 209 nm with an overall average of 173 nm and a standard deviation of 40 nm, as measured by the SMPS (Table 1 and 2). The average percentage of blue to blue and IR light scattering intensity measurement for smoke generator aerosols range from 29% to 56% with an overall average of 40% and a standard deviation of 12%, while for lithium ion batteries thermal runaway vent gas, smoldering foam, and smoldering wood the range is from 39% to 62% with an overall average of 48% and a standard deviation of 15%, as measured by the LMS (Table 1 and 2). This demonstrates that smoke generator aerosols and real smoke sources can vary in particle diameter and light scattering properties. Furthermore, that the smoke generators used by major airline manufacturers for the inflight smoke detection certification test are capable of producing an aerosol that is comparable to particles from some smoke sources.

Table 1. Artificial Smoke Generator Particle Size

Smoke Source	Average Particle Size (SMPS), nm	Average % Blue Signal (EMRSM)
MFR 1	240	0.56
MFR 2	192	0.34
MFR 3	167	0.29
MFR 4	293	0.40
Average	223	0.40
Standard Deviation	56	0.12

Table 2. Smoke Particle Size

Smoke Source	Average Particle Size (SMPS), nm	Average % Blue Signal (EMRSM)
Lithium Ion Battery	209	0.62
Smoldering Foam	130	0.39
Smoldering Wood	182	0.51
Average	174	0.48
Standard Deviation	40	0.15

Standardizing artificial smoke generators for the rate of aerosol production, total quantity of aerosol production and repeatability of aerosol production is necessary to ensure the reliability and integrity of the inflight smoke detection certification test. The transient obscuration phase occurs during the initial 60 seconds of testing. This is the only period that the smoke generators produce aerosol. The transient obscuration characterizes the rate of smoke production. After the aerosol fully mixes and the light obscuration becomes quasi steady, the steady state obscuration is measured. This typically occurs after 120 seconds and is used to characterize the total smoke production. Both the transient obscuration and the steady state obscuration are shown in figure 4. Lastly, the repeatability is the relative deviation between individual tests over 10 second increments and is used to show consistency of light obscuration measurements.

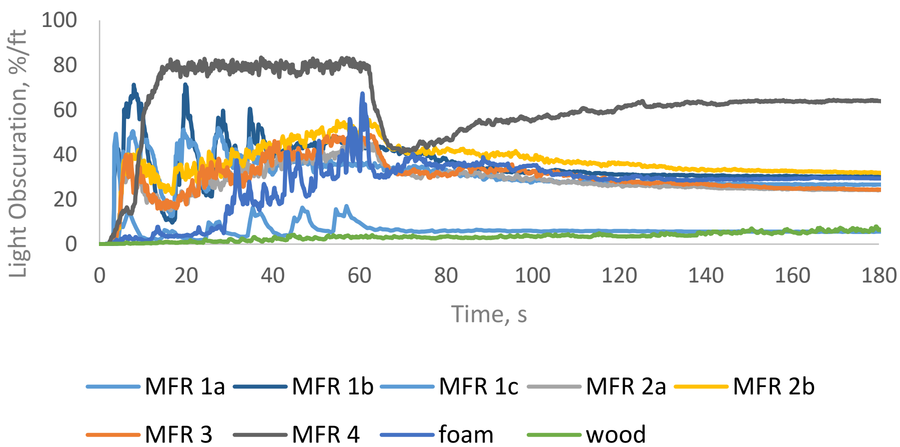

Figure 3 Time vs Light Obscuration of Individual Tests

Commercial aircraft cargo compartment smoke detectors must provide visual indication to the flight crew within one minute after the start of a fire to be implemented in aircraft. This time dependency infers the significance of the transient light obscuration, because the transient light obscuration represents the rate of aerosol production in respect to time. The data points on figure 5 represent the time required to surpass the marked light obscuration threshold. Two important indicators from the graph are the steepness of the curve and the highest point on the graph. The smoke production rate is represented by the steepness of the curve while the maximum light obscuration reached is represented by the highest point on the graph. Figure 5 displays that there is a range of smoke production rates used for inflight smoke detection certification testing.

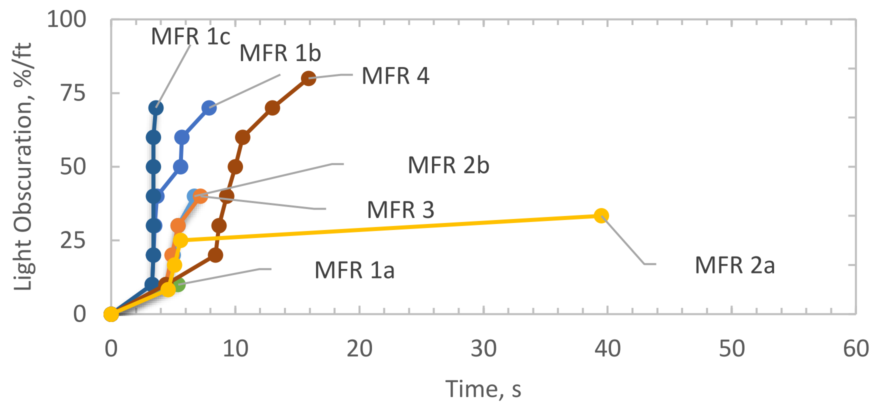

Figure 4 Time vs Light Obscuration for Transient Light Obscuration

Another important parameter for the certification of cargo compartment smoke detection systems is the total smoke production. The steady state light obscuration is calculated by averaging the percent light obscuration per foot over a 60 second period of a well-mixed smoke or aerosol within a known control volume. The overall average steady state light obscuration of the tested aerosols is 32%/ft with a standard deviation of 17%/ft. Figure 6 shows that there is a range of total aerosol production used for smoke detection certification testing.

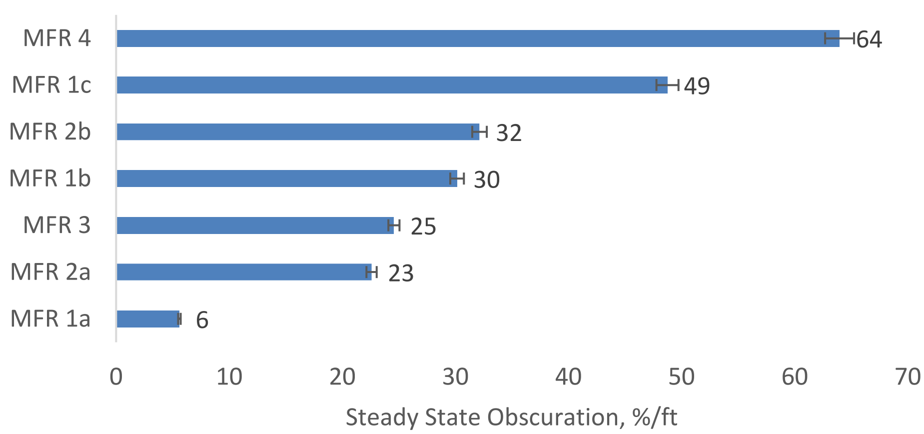

Figure 5. Time vs Light Obscuration for Steady State Light Obscuration

The percent deviation of light obscuration per foot between a minimum of three tests over 10 second increments are calculated to determine a smoke generator's repeatability. The smoke detection certification test is time dependent, therefore the initial seconds are the most critical. Figure 7 shows that the initial 10 seconds are the least repeatable. There is an average of 24% deviation between tests from an individual smoke generator. The second and third 10 second period have an average of 15% and 9% deviation between tests, respectively.

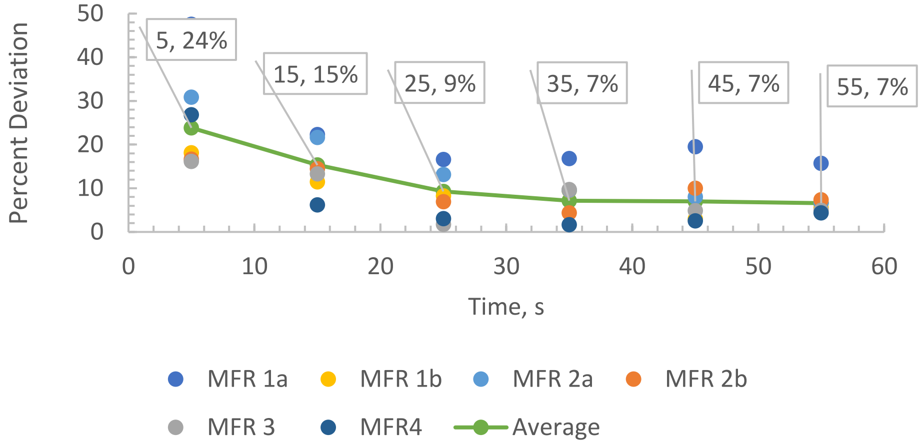

Figure 6. Time vs Percent Deviation for Repeatability

The temperature inside of a commercial aircraft cargo hold can vary by day, location and throughout the flight profile. Testing is conducted to determine if and how the ambient temperature affects a smoke generator's overall production of aerosol (figure 7). Testing shows a correlation between ambient temperature and the total smoke production, where increasing the ambient temperature can increase the total aerosol production. The significance of the ambient temperature on a smoke generator's aerosol production varies by smoke generator and setting.

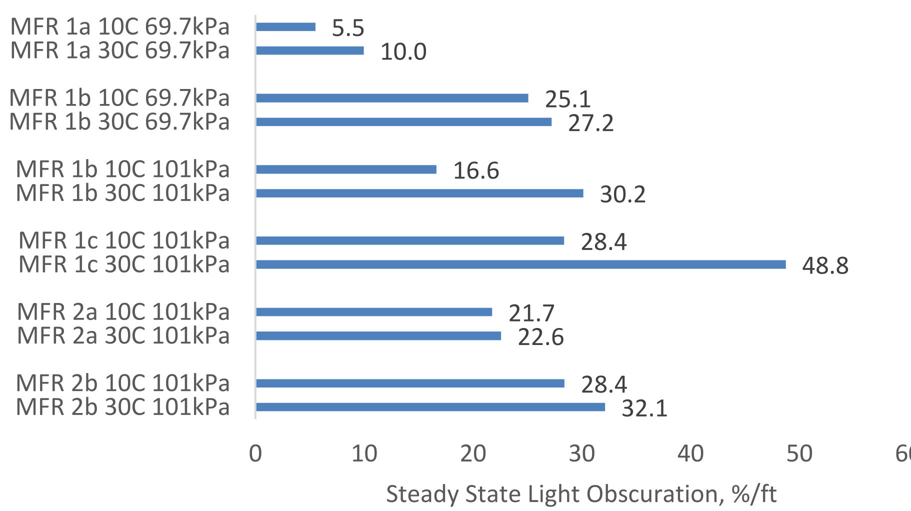

Figure 7. Varying Ambient Temperature and Smoke Generator Aerosol Production

The pressure inside a cargo hold of an aircraft varies throughout flight. Testing is conducted to determine if and how the ambient pressure affects a smoke generator's production of aerosol. Testing shows a weak negative correlation between ambient temperature and the total smoke production, where increasing the ambient pressure can, but does not always, decrease the total aerosol production (figure 8).

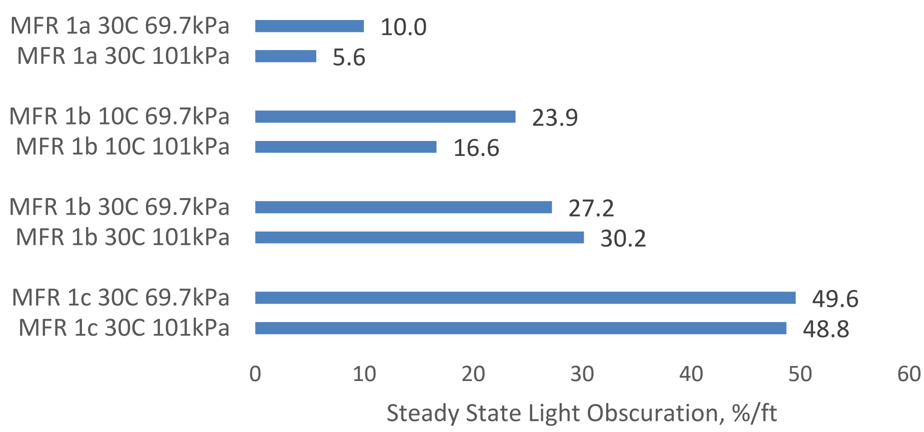

Figure 8. Varying Ambient Pressure and Smoke Generator Aerosol Production

Conclusions

The above results show that smoke generators are capable of producing an aerosol with a similar particle size distribution and light scattering characteristics to real smoke sources. Therefore, aerosol from smoke generators can effectively alarm smoke detectors that utilize light extinction and light scattering methods. The current FAA guideline requires that the smoke detection system will detect a smoldering fire that produces a small amount of smoke[2]. The ambiguity of wording has allowed a measurable difference between the total aerosol production and the rate of aerosol production between smoke generators used for certification testing. Furthermore, this study shows that a smoke generator's aerosol production can vary with the ambient temperature range associated with a typical aircraft flight profile.

References

[1] Title 14 Code of Federal Regulations (CFR) Part 25.858, 2/10/1998
[2] Federal Aviation Administration Advisory Circular 25-9A
[3] TSO C1e, 8/19/2014
[4] R.G.W. Cherry, "Research into Fire, Smoke or Fumes Occurrences on Transport Airplanes," FAA Report DOT/FAA/TC-16/49, March 2017