Characterizing Smoke Generator Smoke Transport for Aircraft Cargo Smoke Detection Certification

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Abstract

Artificial smoke generators are used in the certification of aircraft smoke detectors. However, there is currently no standardization concerning the use of these generators and their smoke transport. 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. There is ongoing work led by the FAA to define a set of requirements for smoke generator qualification. 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 the ambient environment is necessary to ensure the reliability and integrity of the inflight smoke detection certification test. It was found that changing the gas propellant pressure, the gas propellant, and the heater wattage affected the smoke generator volumetric flow rate. The heater wattage was the most significant easily adjustable parameter in the volumetric flow rate. Large-scale tests inside an aircraft cargo compartment showed increasing the volumetric flow rate decreased detection time. The small-scale measurements of the volumetric flow rate can help determine the smoke transport and detection time.

A comparison of four major airframe manufacturers' smoke generators and settings identified their performance. Aircraft Certification Offices have approved these smoke generators and settings as acceptable means of compliance for smoke generation methods for certifying cargo smoke-detection systems. Large-scale tests showed that different settings of smoke generators could significantly affect detection time for in-flight smoke detection certification testing. The standardization attempt serves to equalize the settings and performance.

Keywords: Smoke generator, smoke detection, smoke transport, aircraft cargo compartment, AC 25-9A

Introduction

Federal Aviation Administration (FAA) regulations require that a commercial aircraft's cargo compartment smoke detection system must provide a visual indication to the flight crew within one minute after the start of a fire [1]. Further FAA guidance states that the design of the inflight smoke detection certification testing is to demonstrate that the smoke detection system will detect a smoldering fire that produces a small amount of smoke [2]. Currently, there are no objective parameters to quantify smoke generator artificial smoke production for certification testing. Therefore, this study's design was to create a framework for potential guidelines for standardizing smoke generator artificial smoke properties. However, this paper does not reflect the FAA policies or position. Standardizing the smoke properties and characteristics resulting from artificial smoke generators is necessary to ensure the reliability and integrity of cargo compartment smoke detection system certification testing on a global scale.

The smoke generators detailed within this report are specialist units designed to produce temperature-resistant artificial smoke. Smoke generators use inert gas to propel mineral oil into a heat exchanger. The heat exchanger vaporizes the mineral oil and creates a nontoxic fog similar in appearance to smoke. The smoke exits through a chimney incorporated with heaters to create a thermally buoyant plume.

The detection time is dependent on multiple variables. These variables include thermal buoyancy, the density of artificial smoke production, artificial smoke particle size, the volume and ceiling height, the number of smoke detectors and their locations, and other contributing factors [3]. This study reveals ranges of these variables used by different aircraft manufacturers. Beyond that, it was determined how smoke generator parameters affect the volumetric flow rate.

Experimental

Smoke Generator Parameters

The environmental test chamber was 93 inches x 72 inches x 70 inches and was capable of simulating ambient conditions that may occur during a typical flight profile. It was equipped with a blue and IR detector (BIRD) that measures the light scattering intensity response to blue (470 nm) and infrared (850 nm) wavelength light, a scanning mobility particle sizer (SMPS) that characterizes particle size, and six light obscuration meters aligned vertically above the smoke generator or smoke source.

Four major airframe manufacturer's smoke generators and settings were tested and compared. One manufacturer uses a Siemens Cerberus device, two manufacturers use the Aviator 440, and one manufacturer uses a modified Aviator 440.

For anonymity purposes, the smoke generators 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 the certification regulation. Light obscuration and light scattering measurements were acquired every second throughout the entire test. The SMPS measurements began 210 seconds after the smoke generator was turned on (150 seconds after the smoke generator was turned off) with 90-second scan times. Size distributions and light scattering characteristics of smoke were measured for the following: smoldering foam, smoldering wood, and lithium-ion battery thermal runaway vent-gas. These measurements were then compared to particles produced by the smoke generators. The SMPS measurements occurred in 90 seconds increments starting 60 seconds after ignition with 60 seconds scan times.

Volumetric Flow Rate Variation

Volumetric flow rates exiting out of a Concept Aviator UL smoke generator chimney were determined. The tests sought to determine the effect of three parameters on the volumetric flow rate. The considered smoke generator parameters were the chimney heater wattage, gas propellant, and its pressure. The assumption is that the data and conclusions can extrapolate to other smoke generators that operate under similar principles. The heater wattage varied between 160 W and 640 W. The gas propellant pressure varied between either 15 psig, 30 psig, or 50 psig. The gas propellant varied between helium and carbon dioxide.

At the exit of the smoke generator chimneystack was a reducing square to round cone. At the exit of the cone was a 2.75-inch vane anemometer. The vane anemometer measured the volumetric flow rate. A one-minute average determined the volumetric flow rate.

Large Scale Testing

Large-scale tests were conducted in a 2,000 ft^3 McDonnel Douglas DC-10 aft cargo compartment to determine if the volumetric flow rate would affect the smoke transport and detection time. The cargo compartment was not ventilated during the test. This test also used the Concept Aviator UL under the assumption that the data and conclusions can be extrapolated to other smoke generators that operate under similar principles. The smoke generator was located in the forward left corner of the cargo compartment and the smoke detector was located at the aft centerline of the ceiling. The horizontal ground distance between the smoke generator and the smoke detector was 19.5 ft. The vertical ceiling height was 66 inches. The intention was to determine the correlation between volumetric flow rate and smoke detection time.

Results

Smoke Generator Parameters

Important parameters for the standardization of artificial smoke generators are particle size (especially in the context of false alarm resistant smoke detectors), initial transient rate of aerosol production, total aerosol production, and vertical and horizontal smoke velocity. The repeatability of aerosol production plays an important role in assessing the reproducibility of certification testing.

Particle Size

The main nuisance sources present in commercial aircraft are fog, dust, and insecticides. Particle sizes of those nuisances are generally above 1000 nm. With the aviation standard AS8036, a means has been created to qualify smoke detectors according to their response behavior to nuisance sources [4]. Smoke detectors that pass the tests described in this standard demonstrate the ability to detect real fires whilst being resistant against false alarm sources, up to a certain degree. However, this can be problematic for the smoke-detection certification test that typically uses artificial smoke generators; if the particle size and light scattering characteristics of the aerosol from artificial smoke generators are similar to false alarm nuisances and dissimilar to actual smoke sources the false alarm resistant smoke detectors may not alarm. Therefore, smoldering fire smoke was compared to smoke generator aerosol by measuring the particle size distributions with a SMPS and comparing the light scattering response with the BIRD.

The measurements of geometric mean diameter for smoke generator aerosols ranged from 167 nm to 293 nm with an overall average of 223 nm and a standard deviation of the means of 56 nm (Table 1) [5]. These measurements are similar to Palas-Welas measurements, which found the mode of aerosol particle sizes from two smoke generator suppliers to be approximately 300nm [6]. The geometric mean diameter measurements for lithium-ion batteries thermal runaway vent gas, smoldering foam, and smoldering wood ranged from 130 nm to 209 nm with an overall average of 173 nm and a standard deviation of the means of 40 nm, as measured by the SMPS (Table 2) [5].

The average percentage of blue to blue-and-IR light scattering intensity measurement for smoke generator aerosols ranged from 29 % to 56 % with an overall average of 40% and a standard deviation of the means of 12 % (Table 1) [5]. The lithium-ion batteries thermal runaway vent gas, smoldering foam, and the smoldering wood average percentage of blue to blue-and-IR light scattering intensity measurements ranged from 39 % to 62 % with an overall average of 48 % and a standard deviation of the means of 15 %, as measured by the BIRD (Table 2) [5]. This demonstrates that smoke generator aerosols and real smoke sources can vary in particle diameter and light scattering properties. Furthermore, it shows 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 Percentage of Blue Signal (BIRD)
MFR 1	240	56
MFR 2	192	34
MFR 3	167	29
MFR 4	293	40
Average	223	40
Standard Deviation	56	12

Table 2. Smoke particle size.

Smoke Source	Average Particle Size (SMPS), nm	Average Percentage of Blue Signal (BIRD)
Lithium-Ion Battery	209	62
Smoldering Foam	130	39
Smoldering Wood	182	51
Average	174	51
Standard Deviation	40	12

Aerosol Production and Light Obscuration

Standardizing artificial smoke generators for the rate of aerosol production, the total quantity of aerosol production, and the repeatability of aerosol production is necessary to ensure the reliability and integrity of the inflight smoke detection certification test. The transient obscuration phase characterizes the rate of smoke production. This phase occurred during the initial 60 seconds of testing and was the only period that the smoke generators produce an aerosol. After the aerosol was fully mixed and the light obscuration became quasi-steady, the steady-state obscuration was measured. This typically occurred 150 seconds from the start of the test and characterized the total smoke production [5]. The average particle sizes were less than 1000 nm. Therefore, the aerosols took multiple hours to settle after diffusion and did not affect the steady-state obscuration measurements. Fig. 1 shows how the transient obscuration and the steady-state obscuration developed for multiple smoke sources [5].

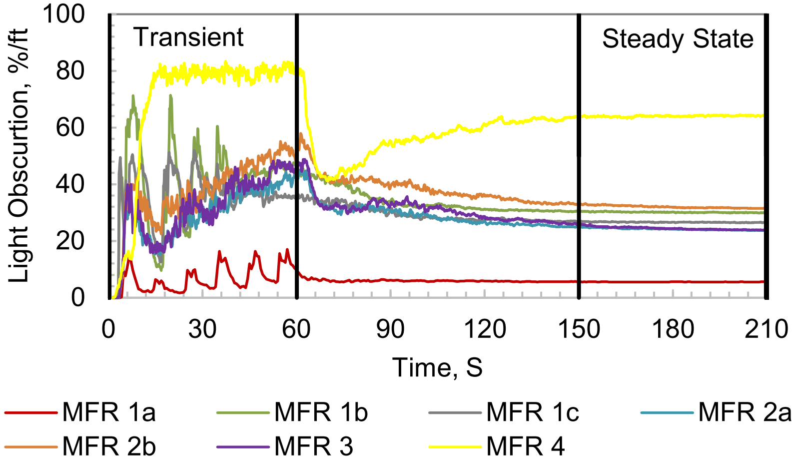

Fig. 1. Light obscuration vs time of individual tests.

The initial rate of rise of smoke production in the transient obscuration phase can influence the smoke detection time. If the rate of rise is fast, quicker smoke detection is foreseen. The data points in Fig. 2 represent the time required to reach the respective light obscuration (y-axis) [5]. Two important indicators from the graph are the smoke production rate and the maximum light obscuration. The slope of the curve represents the smoke production rate. Fig. 2 displays that there is a relatively wide range of aerosol production rates used for inflight smoke detection certification testing [5]. There is one standout point for MFR 2a at 40 s and 40 %/ft not shown in Fig. 2 [5].

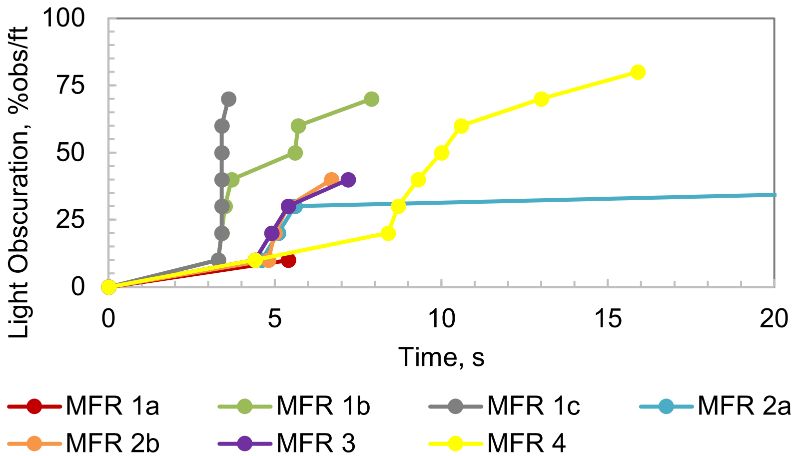

Fig. 2. Light obscuration vs time for transient light obscuration.

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 [5]. Fig. 3 shows that there is a relatively wide range of total aerosol production used for smoke detection certification testing [5]. However, it should be noted that this wide range is partly due to adjusting the aerosol production depending on the volume of the tested compartment.

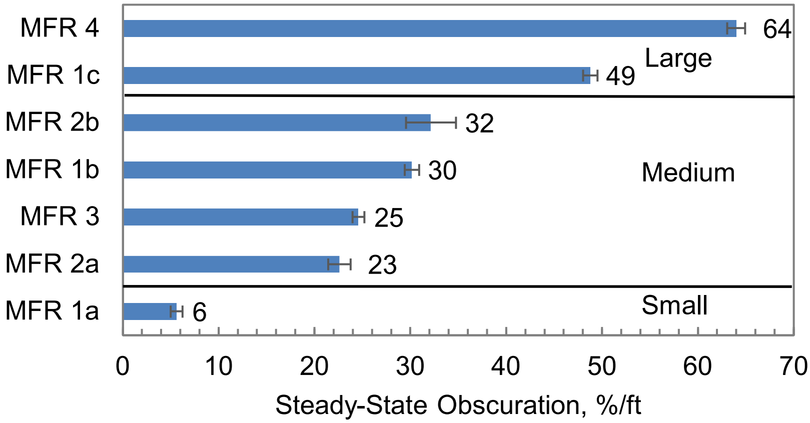

Fig. 3. Steady-state light obscuration by manufacturer.

The relative percent deviation of light obscuration per foot between a minimum of three tests per smoke generator over 10-second periods was calculated. This parameter helped determine the variability of each smoke generator's aerosol production throughout the 60-second test and overall repeatability. The smoke-detection certification test is time-dependent; therefore, the initial seconds are the most critical. Fig. 4 shows that the variability between tests decreases with time [5]. There was an average of 24 % deviation between tests from an individual smoke generator during the first 10-second period [5]. The second and third 10-second periods had an average of 15 % and 9 % deviation between tests, respectively [5].

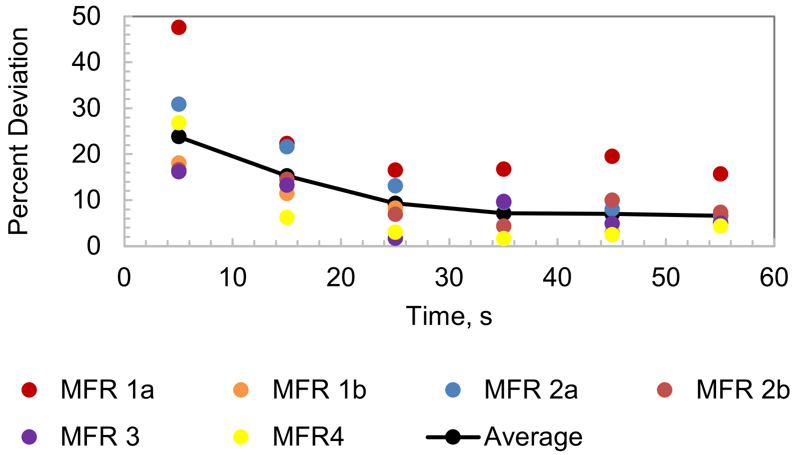

Fig. 4. Percent deviation vs time for repeatability.

Volumetric Flow Rate (Vertical Velocity)

The volumetric flow rates for the smoke generators under investigation ranged from 13.0 ft^3/min to 19.4 ft^3/min (Fig. 5). The average volumetric flow rate was 15 ft^3/min with a standard deviation of 2.6 ft^3/min. There was a 39.5 percent difference between the lowest and highest volumetric flow rate. Although MFR1a had less chimney heater wattage than MFR2a, MFR2b, and MFR3, it still had a greater volumetric flow rate.

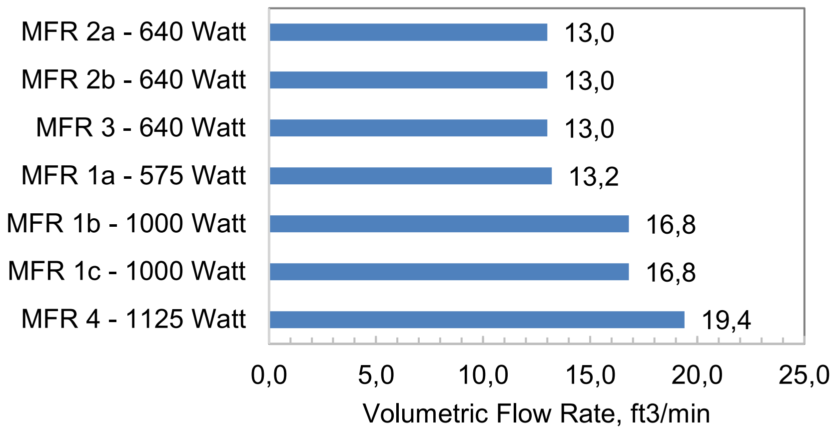

Fig. 5. Volumetric flow rate for smoke generators.

Volumetric Flow Rate Variation

Three separate control and experimental groups provided insight as to the impact of varying parameters on the resulting volumetric flow rate. The first control group had the heater wattage and gas propellant pressure as the constants and varied the gas propellant between helium and carbon dioxide (Fig. 6). While the use of helium as a gas propellant for smoke detection certification testing is uncommon due to its availability and cost, it has unique buoyancy properties that can make it an attractive option for this particular use. Changing the gas propellant pressure from carbon dioxide to helium caused an average of 4.8 ± 0.7 percent increase in the volumetric flow. Helium created a slightly higher volumetric flow rate than carbon dioxide because it is more buoyant.

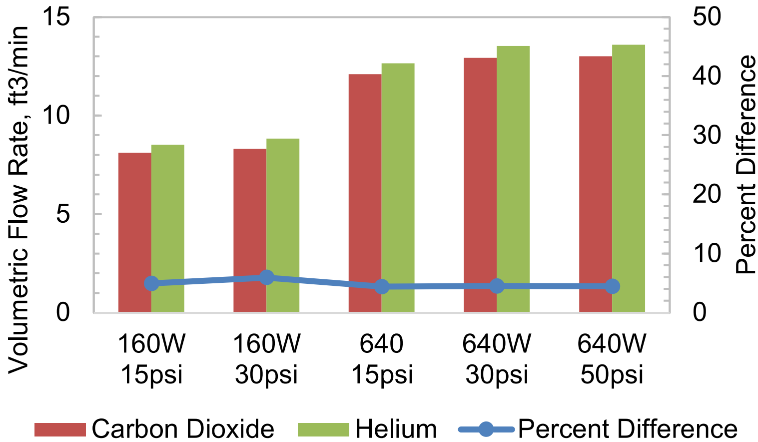

Fig. 6. Varying gas propellant.

The second control group maintained a constant heater wattage and gas propellant while varying the gas propellant pressure (Fig. 7). The range of gas propellant pressures commonly used for cargo smoke detection certification is between 10 psig and 26 psig. The selection of the bounds of 15 psig and 50 psig for the gas propellant pressure emphasized the effect that the gas propellant pressure could have on the volumetric flow rate. Changing the gas propellant pressure from 15 psig to 50 psig caused a percent increase of 6.5 ± 1.2 in the volumetric flow. The increased volumetric flow rate was a result of increased momentum.

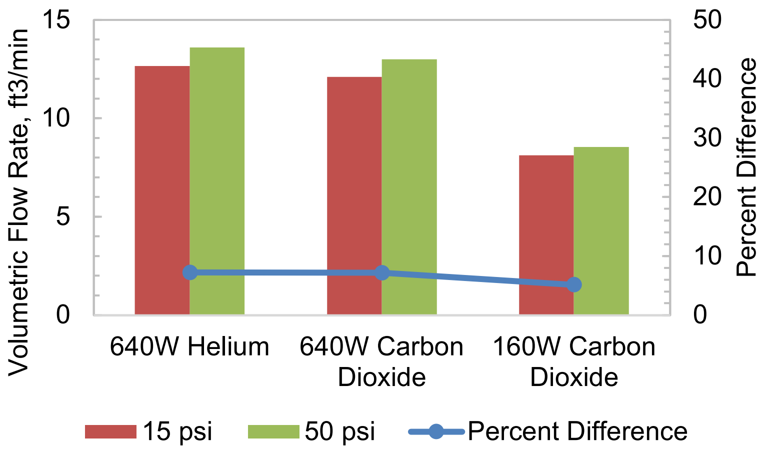

Fig. 7. Varying propellant pressure.

The third control group maintained the gas propellant and pressure as the constants and varied the heater wattage (Fig. 8). The Concept Aviator UL smoke generator that was used in this study has four 160 W heater bars inside of its chimneystack. The selection of the bounds of 160 W and 640 W heaters in the chimneystack emphasized the effect that the chimney heater wattage could have on the volumetric flow rate. Changing the heater wattage from 160 W to 640 W caused a percent increase of 41.1±1.9 in the volumetric flow rate. The increased volumetric flow rate was a result of the increased thermal buoyancy.

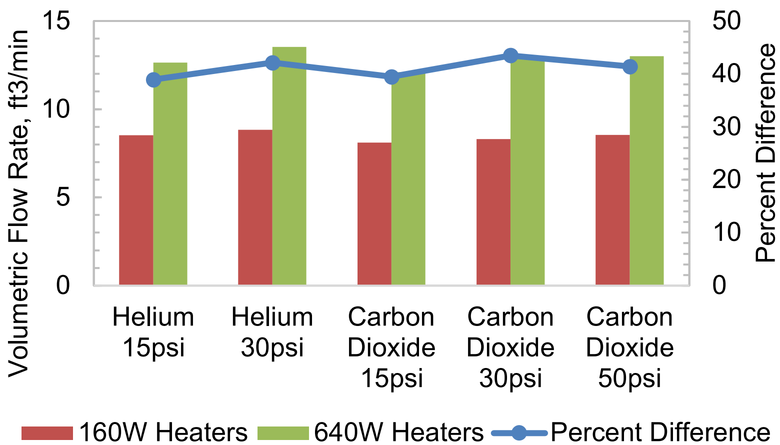

Fig. 8. Varying heater wattage.

The three separate control groups showed varying amounts of impact to the volumetric flow rate, as shown in Fig. 9. The volumetric flow rate was largely dependent on the chimney heater wattage.

Additionally, the volumetric flow rate is moderately dependent on the gas propellant and its pressure. This demonstrates that the heater wattage is the most significant adjustable parameter in the volumetric flow rate for smoke generators. However, this also demonstrates that the volumetric flow rate is dependent on multiple variables. Since the volumetric flow rate accounts for all three variables, it is a potential measurement to characterize the smoke transport of artificial smoke generators.

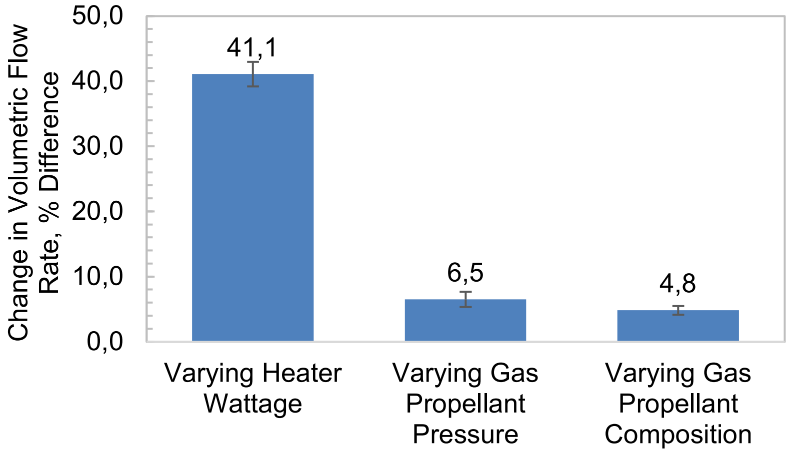

Fig. 9. Percent difference by variable.

The chimney heater wattage for the smoke generators under investigation ranged from 575 W to 1125 W (Table 3). However, other contributing factors asides from chimney heater wattage affected the volumetric flow rate from smoke generators. Large-scale tests (see the following section) showed that this magnitude of difference in volumetric flow rate could significantly affect detection time for inflight smoke detection certification testing.

Table 3. Smoke generator information.

Manufacturer Symbol	Chimney Heater Wattage	Smoke Generator Manufacturer
MFR 1a	575	Siemens Cerberus
MFR 1b	1000	Siemens Cerberus
MFR 1c	1000	Siemens Cerberus
MFR 2a	640	Concept Aviator 440
MFR 2b	640	Concept Aviator 440
MFR 3	640	Concept Aviator 440
MFR 4	1125	Modified Concept Aviator 440

Large-Scale Results

Large-scale tests showed that increasing the volumetric flow rate decreases the smoke detection time and increases the horizontal ceiling jet flow. Fig. 10 separates the tests by gas propellant and pressure to isolate the volumetric flow rate from the production of artificial smoke. An increase in gas propellant pressure increases the total quantity of artificial smoke production and typically decreases the detection time. The volumetric flow rate is varied by using either 160W or 640W chimney heater bars. The cargo compartment volume and ceiling height were constant control variables. Changing these variables could affect the results. However, one can infer that the correlation between volumetric flow rate and smoke transport is not limited to this one scenario.

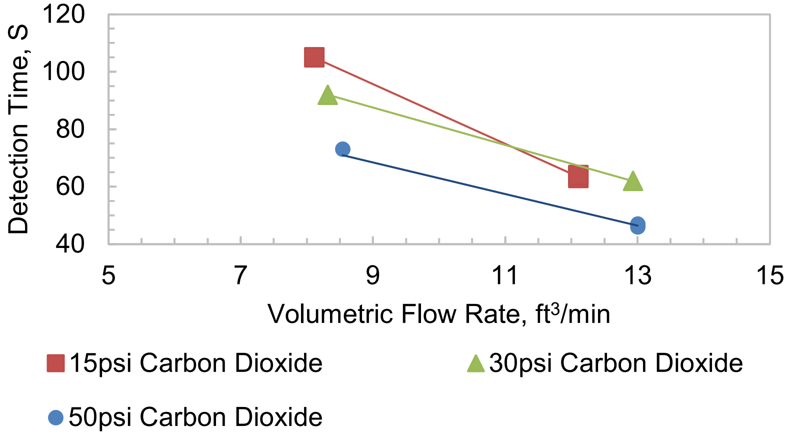

Fig. 10. Detection time versus volumetric flow rate.

Summary and Conclusions

Four major airframe manufacturers' smoke generators and settings were tested and compared. Airworthiness Authorities have approved these smoke generators and settings as an acceptable means of compliance for smoke generation methods for certifying cargo smoke detection systems.

Relevant parameters for an internationally standardized smoke generator performance qualification have been identified. Those are particle size, volumetric flow rate, and transient and steady-state light obscuration. The values of these parameters vary depending on the smoke generator model and its operation.

The gas propellant, gas propellant pressure, and the heater wattage affect the smoke generator volumetric flow rate.

Large-scale tests showed that increasing the volumetric flow rate decreases the detection time by increasing the horizontal ceiling jet velocity. Increasing the gas propellant pressure can also decrease the detection time by increasing the total quantity of artificial smoke production. Changing the compartment volume or ceiling height would likely change the detection times. However, the assumption is that the correlation between volumetric flow rate and smoke transport will remain. Therefore, the small-scale measurements of the volumetric flow rate can help determine the smoke transport and detection time.

A comparison of four major airframe manufacturer's smoke generators and settings quantified their volumetric flow rates. The volumetric flow rates ranged from 13.0 ft^3/min to 19.4 ft^3/min. The average volumetric flow rate was 15 ft^3/min with a standard deviation of 2.6 ft^3/min. There was a 39.5 percent difference between the lowest and highest volumetric flow rate. Large-scale tests showed that this magnitude of difference in small-scale volumetric flow rates could significantly affect detection time for inflight smoke detection certification testing.

Outlook

There is ongoing work within an international working group (Cargo Smoke Detection Task Group), involving the major airframe manufacturers and Airworthiness Authorities, to create a handbook to outline a qualification procedure for artificial smoke generators. The goal of the group is to define values and tolerances for the parameters that have been investigated in this study so that an international agreement on the performance of smoke generators for aircraft use is achieved.

Future work

It is under discussion in the Cargo Smoke Detection Task Group if a test procedure to quantify the horizontal smoke velocity, shall be added to the smoke generator performance qualification. The purpose of this test would be to simulate a real aircraft environment, reproduce the large-scale test results, and anticipate on-aircraft testing.

The dimensions of the apparatus represent the order of magnitude that can be found on an aircraft (Fig. 11). The smoke generator would be placed under a funnel opening so that the whole amount of smoke that the generator is producing would be captured and introduced into the apparatus. The position of the funnel would allow air to ingress to provide the respective buoyancy, which is required for the smoke to develop its vertical dynamics. The smoke would be guided from its vertical chimney outlet into a horizontal smoke tunnel. Within the smoke tunnel, at least two reference measurement devices for light obscuration would be located to identify the speed at which the smoke spreads. To simulate a ventilated compartment, a fan could be located at the far end of the horizontal smoke tunnel producing a "headwind" against the direction of smoke movement.

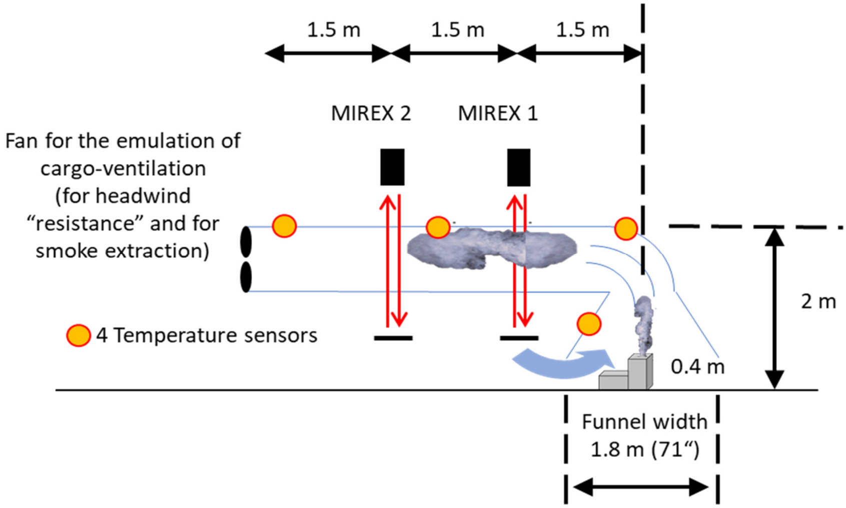

Fig. 11. Horizontal velocity test apparatus.

It will be evaluated if this approach brings additional information about the vertical smoke velocity which is described in this paper and which is determined using anemometers above the smoke generator chimney.

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