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Evaluation of spacecraft smoke detector performance in the low-gravity environment

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ABSTRACT

In the interest of fire prevention, most materials used in the interior construction of manned spacecraft are non-flammable, however, they do produce smoke when overheated. Spacecraft smoke detectors will ideally detect smoke generated by oxidative pyrolysis (such as smoldering) in order to allow the maximum time for the crew to respond before a larger flaming fire develops. An experiment on the International Space Station (ISS) was performed to characterize smoke particles generated from the oxidative pyrolysis of five common spacecraft materials. The following parameters were controlled: heating temperature, air flow past the samples and duration of aging. Two different spacecraft smoke detectors were included in the instrumentation and their performance with different smoke types has been evaluated. Additional equipment in the experiment included a thermal precipitator to sample particles for microscopic analysis upon return to Earth, and two commercial-off-the-shelf real-time instruments to measure particle mass and number concentration, and an ionization detector calibrated to estimate the first moment of the size distribution. Results from the ISS experiment show that smoke particles vary in morphology and average diameter, however, they are not significantly different from smoke particles generated in equivalent experiments performed in normal gravity. The two spacecraft smoke detectors did not successfully detect every type of smoke, which demonstrates that the next generation of spacecraft fire detectors must be improved and tested against smoke from relevant space materials.

1. Introduction

All existing spacecraft smoke detectors have been designed based on fire data from experiments in normal gravity for example as described in Bukowski and Mulholland [1] and Bukowski et al. [2]. Many materials of interest for the terrestrial fire detection community are found in residential and commercial buildings, and represented in standard test fires encompassing smoldering wood, shredded paper and polyurethane foam, and flaming fires of wood, heptane/toluene liquid mixtures and polyurethane foam [3]. This body of knowledge is not directly applicable to spacecraft fire safety for several reasons. First of all, the spacecraft environment is a fixed volume of air with very limited evacuation options. Therefore, a fire must be detected in its very early stages, as materials are being heated beyond their safe use temperatures, making pre-ignition oxidative pyrolysis rather than combustion the relevant mode of smoke generation to characterize. Secondly, in the absence of buoyant flow in low gravity, smoke does not rise to the ceiling, but instead can either concentrate at the source, causing the particles to grow by agglomeration as time progresses (referred to as aging) and/or be dispersed throughout the spacecraft by the mixing induced by the ventilation system. The former increases the smoke particle sizes which influences detector performance and the latter rapidly reduces the concentration, making detection particularly challenging. Finally, the materials used in the interior of spacecraft are very different from the Underwriters Laboratory (UL) [3] standard fire fuels. For these reasons, the Smoke Aerosol Measurement Experiment (SAME) was devised to create and characterize smoke in low gravity. This experiment was flown twice on the International Space Station (ISS), in 2007 and 2010, and a series of ground-based tests with the identical smoke generation and measurement hardware were performed concurrent with and after the

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flights. Once it was established that the smoke produced in low gravity did not differ substantially from what was produced in normal gravity, the SAME hardware was used in additional ground-based tests with a research-grade aerosol instrument to measure the particle size distributions of smoke from the five spacecraft materials [4,5].

1.1. Spacecraft fire detector background

Prior spacecraft fire detection systems have been discussed in detail in papers by Friedman and Urban [6,7]. In the early years of manned space flight, the Mercury, Gemini and Apollo missions had small crew habitable volumes and mission durations were short, consequently the fire detection design depended upon human senses of the crew to detect fires. The Skylab module in the 1970s, used approximately 30 UV-sensing fire detectors [6] which were limited to line-of-sight and were reported to have difficulties with false alarms. In subsequent decades, the Space Shuttle detectors were based upon ionization fire detector technology, which was the most advanced technology available at the time. An inertial separator was designed to eliminate particles larger than 1–2 μm from entering the particle sensing volume. The International Space Station (ISS) smoke detectors use near-IR forward light scattering, which is more sensitive to particles larger than 0.3 μm.

As described by Friedman [6], there were six overheat and failed component events in the NASA Space Shuttle fleet during its operational lifetime. Several similar incidents have occurred on the ISS, which are briefly described here. An electrical ‘odor’ was traced to lamp on Service Module (ISS Expedition 10, March 2005), a smoke and solvent smell reported caused by smoldering polymeric bushing (ISS Expedition 18, September 2006), the crew reported a burning odor and smoke from the water recovery system (twice), and most recently, the crew reported a burning odor and smoke coming from a failed micro-pump at the back of a pressure suit [8,9]. None of these events spread into a real fire but as mission durations increase, the likelihood of failures increases. The worst fire event was the solid-fuel oxygen generator malfunction on Mir in 1997, which sprayed molten flaming metal and filled the cabin with smoke. Fortunately, no flaming fire has happened in a spacecraft cabin since that time, but there is still a critical need for improved understanding of spacecraft fires and improved detection [10].

2. Methods

An experiment was developed specifically to increase knowledge of the types of smoke that might occur in spacecraft and the effects of low gravity on smoke generation: the Smoke Aerosol Measurement Experiment (SAME). The goal of SAME was to generate repeatable smoke and obtain particle size statistics on-orbit without relying exclusively upon sample return to Earth. This is challenging because existing aerosol instruments are typically large and incompatible with spacecraft experiment constraints. As will be described below, an alternative approach was employed that used three discrete instruments to measure separate moments of the size distribution. When combined, these moments provide useful aggregate statistics of the size distribution. The measurements were made using smoke generated by overheated spacecraft materials with rigorously controlled sample temperature, flow field, and particle aging time. The experiment flew twice, the first time in 2007 (SAME-1) and the second (SAME-2) in 2010. When discussion applies to both flights, this paper will refer to “SAME.” If the discussion is specific to a particular flight, the flight number will be identified e.g., “SAME-2.”

2.1. Moment method

The approach used by the SAME experiment is termed the ‘moment method’ for convenience [11]. As will be described below, the approach consists of measuring three moments of the size distribution (zeroth, first and third) and using the properties of the lognormal distribution to estimate the geometric mean diameter and the standard deviation.

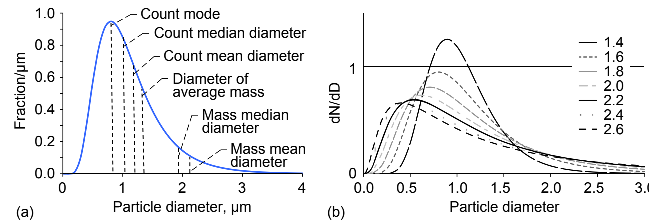

Fig. 1. (a) Diameters for a lognormal distribution with $D_g = 1.0$ and $\sigma_g = 1.6$. (b) Number distributions for lognormal distributions with $D_g = 1.0$ and values of σ_g ranging from 1.4 to 2.6.

The average particle size and an estimate of the width of the size distribution will be estimated from various moments of the size distribution. The number distribution, $f_N(D)$, is defined as

$$f_N(D) = \frac{dN}{dD} \tag{1}$$

where dN is the number of particles per cm^3 with diameter between D and $D + dD$. The moments of interest consist of the number concentration, M_0, the first moment M_1, and the volume or mass concentration moment, M_3 and are defined as

$$M_i = \int D^i f_N(D) dD \quad i = 0, 1, 3 \tag{2}$$

when $i = 0$, the zeroth moment of the distribution, M_0, equation (2) is simply the number of particles per unit volume. In the SAME experiment, this was measured using a condensation nuclei counter. The first moment, $i = 1$, can also be thought of as the “diameter concentration” or integrated diameter per unit volume and is approximately proportional to the ionization detector moment (signal). For particles in the Mie scattering regime, particles sizes from 0.3λ to about 3λ (~0.2–2.0 μm for a red laser, where λ is wavelength), the light scattering signal is approximately proportional to the third moment, $i = 3$ [12]. From these moments, and a measurement of M_0 using a condensation nuclei counter, two mean diameters can be computed: the count (arithmetic) mean diameter $D_{0.5}$ or $\overline{D}$, which is equal to M_1/M_0 and the diameter of average mass $D_{1.5}$ or $D_{\overline{m}}$, which is proportionally equal to $(M_3/M_0)^{1/3}$. These calculations do not depend on any assumed type of size distribution, lognormal or otherwise. (The basis for the subscript naming convention for $D_{0.5}$ and $D_{1.5}$ will be discussed later). The lognormal size distribution is widely used for describing aerosols including non-flaming smoke particles because for most aerosols; the bulk of the number concentration is associated with smaller particles [13,14]. The number distribution $f_N(D)$ for the lognormal distribution is expressed as follows:

$$f_N(D) = \frac{N_t}{(2\pi)^{1/2} D \ln \sigma_g} \exp\left(- \frac{(\ln D - \ln D_g)^2}{2 \ln^2 \sigma_g} \right) \tag{3}$$

where N_t is the total number concentration of the aerosol (=M_0), and D_g and σ_g are the geometric mean diameter and geometric standard deviation defined by

$$\ln D_g = \int_0^\infty \ln D f_N(D) dD \bigg/ \int_0^\infty f_N dD \tag{4}$$

$$\ln \sigma_g = \left[\int_0^\infty (\ln D - \ln D_g)^2 f_N(D) dD \bigg/ \int_0^\infty f_N(D)\, dD \right]^{1/2} \tag{5}$$

For the lognormal distribution, one finds that the various diameter definitions given above are related to the geometric mean diameter, D_g, via the equation [13,14].

$$D_p = D_g \exp(p \ln^2 \sigma_g) \tag{6}$$