"SMOKE:" CHARACTERIZATION OF SMOKE PARTICULATE FOR SPACECRAFT FIRE DETECTION

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INTRODUCTION

The "Smoke" experiment is a flight definition investigation that seeks to increase our understanding of spacecraft fire detection through measurements of particulate size distributions of preignition smokes from typical spacecraft materials. Owing to the catastrophic risk posed by even a very small fire in a spacecraft, the design goal for spacecraft fire detection is to detect the fire as quickly as possible, preferably in the preignition phase before a real flaming fire has developed. Consequently the target smoke for detection is typically not soot (typical of established hydrocarbon fires) but instead, pyrolysis products, and recondensed polymer particles. At the same time, false alarms are extremely costly as the crew and the ground team must respond quickly to every alarm. The U.S. Space Shuttle (STS: Space Transportation System) and the International Space Station (ISS) both use smoke detection as the primary means of fire detection. These two systems were designed in the absence of any data concerning low-gravity smoke particle (and background dust) size distributions. The STS system uses an ionization detector coupled with a sampling pump and the ISS system is a forward light scattering detector operating in the near IR. These two systems have significantly different sensitivities with the ionization detector being most sensitive (on a mass concentration basis) to smaller particulate and the light scattering detector being most sensitive to particulate that is larger than 1 micron. Since any smoke detection system has inherent size sensitivity characteristics, proper design of future smoke detection systems will require an understanding of the background and alarm particle size distributions that can be expected in a space environment.

Prior studies of spacecraft aerosol particulate include (Urban et al. 1997 and Liu et al. 1991). Urban et al. (1997) measured the STS and ISS detector response to various smoke particulate sources. In general the size of the smoke particulate was found to be larger in low gravity and the apparent size of the particles in smokes where the particulate was primarily liquid drops was found to increase to the point that the STS detector was essentially unable to detect the smoke. Liu et al. (1991) measured the mass concentration and particle size distribution of the cabin air on one shuttle flight. Two particle size distributions were measured and were found to have the mass median particle size greater than 100 microns. This is to be compared with their values of about 1 μm to 3 μm for ambient aerosols. The large difference results from the larger particles rapidly settling out at 1 g. The mass concentration of the particulate was found to be approximately 55 $\mu g/m^3$ in the shuttle, versus 11 $\mu g/m^3$ for 1-g ambient conditions.

The ideal approach would be to obtain complete particle size distributions for all of the smokes of interest. Unfortunately, the instruments that provide data of this type (classifiers or impactors) are unsuited for spaceflight experiments either because they are too large or cannot provide real time measurements. The Smoke experiment seeks to work around this problem by measuring three moments of the particle size distribution using instruments that are adaptable to space experimentation. This paper discusses progress toward development of the flight experiment. Progress in the moment method is described below in the first section of this paper. This is followed by the results of detailed characterization of the ISS and STS smoke detectors. Design of the space experiment and generalization of the results requires understanding of the smoke growth process. To develop a predictive understanding of the aerosol growth process, a model is being developed by extending the NIST FDS (Fire Dynamics Simulator) program to model the smoke particle growth process. This work is discussed in the final section below.

MOMENT METHOD DEVELOPMENT

As discussed in more detail by Cleary et al (2001), 5 test smokes were studied using instruments capable of measuring the zeroth, first and third moments. Specifically, the zeroth moment was measured using a condensation particle counter (CPC), the first moment by a measuring ionization counter (MIC) and the third moment by a taper element oscillating microbalance (TEOM). Similar instruments are planned for the smoke experiment for the zeroth and third moments and the third moment will be measured using a light scattering measurement. Figure 1 presents the size distributions for these smokes (determined using a cascade impactor). The slope of the points on the plot increase with the geometric standard deviation. The slopes are very similar with the toast having the lowest slope and therefore the narrowest size distribution. Assuming a log-normal size distribution, the three moments can be used to calculate the geometric standard deviation and the diameter of average mass (Hinds 1999). Assuming unit density spherical particles, the Hatch-Choate relationships can be used to estimate the Mass Median Aerodynamic Diameter (MMAD) which can be compared to the MMAD determined from the impactor data. The results of this comparison can be seen in Table 1. The comparison is very good for the Cotton Wick, Wood and Corn Oil and reasonably close for the polyurethane smoke. In the case of the toast, there was no solution because the count mean diameter was larger than the diameter of average mass which suggests a problem with the measurement system since the moment average should increase with the moment (for the same distribution). In general these results suggest that the moment method can be used to develop a summary description of the particle size distribution.

SMOKE DETECTOR CHARACTERIZATION

To characterize the comparative performance of the STS and ISS detectors, the detectors were exposed to Monodisperse dioctyl phthalate (DOP) aerosols generated using the procedure discussed by Mulholland and Liu (1980). The system is able to develop mono-disperse aerosols with sizes ranging from 0.056 to 1.34 μm although the number concentration decreases strongly with particle size. The results are presented in figures 2-4. The response of the two detector types is consistent with their design. The STS ionization detector is most affected by changes in the number concentration but also shows increasing sensitivity as the particle size increases. The ISS light scattering device, which basically responds to mass concentration, is very strongly affected by the particle size for particle sizes less than 1 μm. Thus, it is able to detect the largest particles even though the number concentration is low.

AEROSOL DYNAMICS MODELING

The modeling effort is based on the NIST Fire Dynamics Simulator (FDS, version 2), which is a CFD code with LES (large eddy simulation) and DNS (direct numerical simulation) options. The code was modified to include homogeneous nucleation and growth to model aerosol dynamics that includes two-phase, momentum, heat and mass transfer. The computational procedure can be briefly summarized as follows. The velocity, temperature, and concentration fields are first determined using DNS mode of the modified code. The saturation ratio field is then computed. Homogeneous nucleation (in this case, condensation) occurs when a critical saturation ratio is reached. Nucleation is modeled using classical homogeneous nucleation theory. The aerosol diameter at nucleation is then calculated, and condensation growth follows and is assumed to be diffusion-limited. Coagulation and agglomeration are not considered in the model. The flow fields are then corrected for interfacial momentum, heat and mass transfer. Droplet number density, size distribution, and the moments are then computed in each grid cell.

Figures 5 and 6 show graphical representations of the results from a simulation. The computational domain, which simulates a flow duct, is 0.2 m in length with a cross section of 0.028 m by 0.028 m. The solid block in the figures simulates an aerosol generator with dibutyl phthalate (DBT) vapor being ejected from four sides (except the two ends). The generator is located 0.05 m downstream from the inlet. A vapor mass flux of 8.55×10^{-4} kg/s m^2 at 200 °C was used in the simulation. The inlet air velocity was set at 0.05 m/s and 25 °C. The calculations were performed using zero gravity and an ambient temperature of 25 °C. In this particular case, 31 x 31 x 700 grids were used in the simulation to ensure convergence. These results are very promising and our current main effort focuses on the validation and improvement of the aerosol dynamics model.

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Table 1. Comparison of Mass Median Aerodynamic Diameter predicted from moment measurements with that from impactor data

Smoke	Mean D_{30} (µm)	Mean σ_g	Predicted MMAD (µm)	Impactor MMAD (µm)	σ_g
Cotton Wick	0.24	1.4	0.28	0.31	1.7
PU foam	1.0	1.6	1.4	2.0	1.6
Wood	0.53	2.25	1.4	1.5	1.9
Corn Oil	0.50	2.5	1.8	1.6	2.2
Toast	0.32	invalid	invalid	0.43	1.6

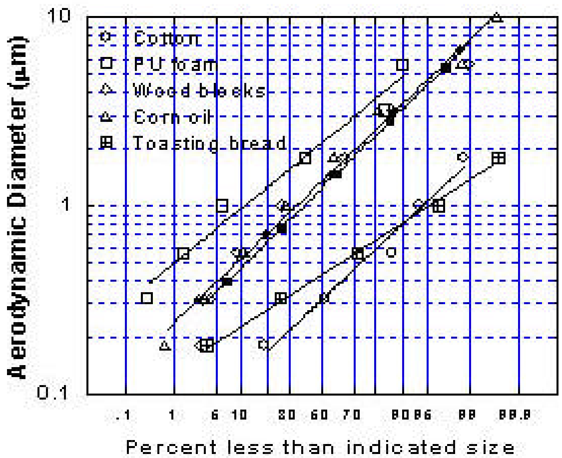

Figure 1. Temperature profile at the mid-plane at 2

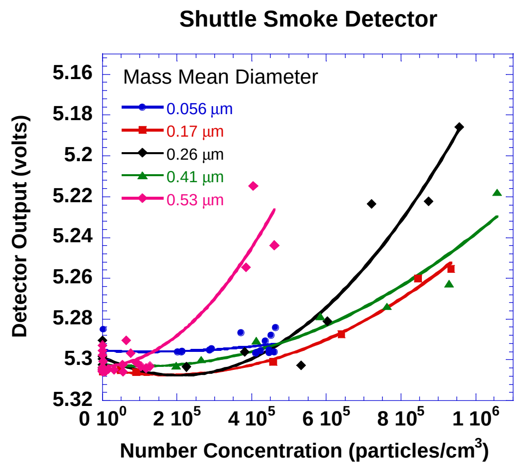

Figure 2. STS detector output versus number concentration.

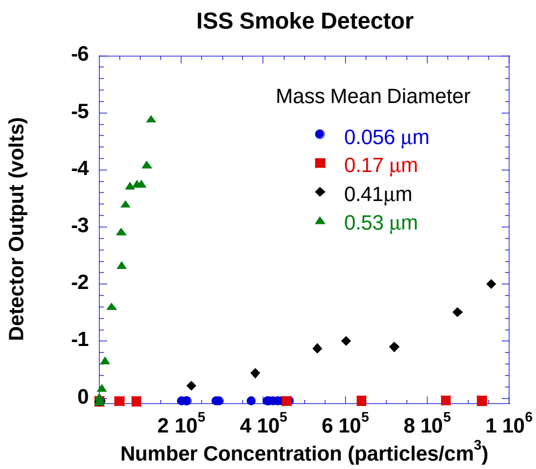

Figure 3. ISS detector output versus number concentration for droplets from 0.056 to 0.53 µm.

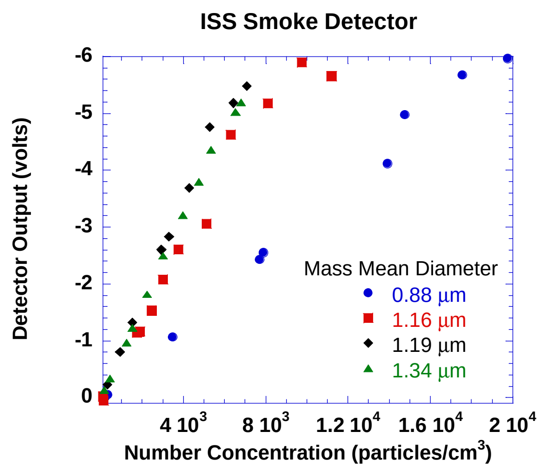

Figure 4. ISS detector output versus number concentration for droplets from 0.88 to 1.34 µm.

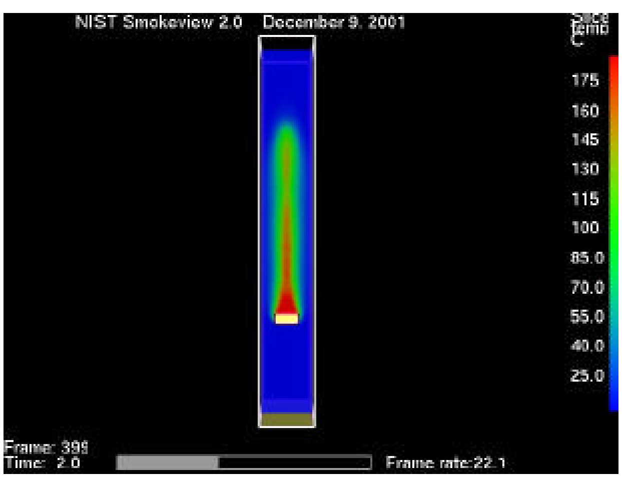

Figure 5. Temperature profile at the mid-plane at 2 s.

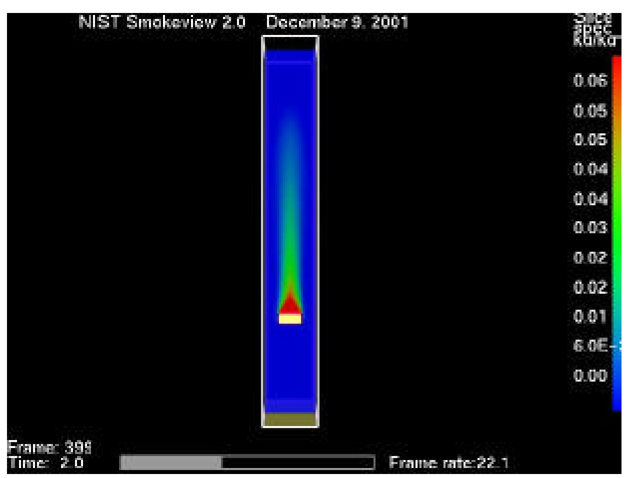

Figure 6. Mass fraction profile of DBT vapor at the mid-plane at 2 s