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THE EFFICIENCY OF THE SMOKE METER AT CHARACTERIZING ENGINE EMISSIONS

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Summary:

The effectiveness of a smoke meter's ability to characterize the particulate emissions of a jet fuel combustor was evaluated using the University of Missouri-Rolla Mobile Aerosol Sampling System (UMR-MASS). A burner simulating an advanced jet engine combustor design[1] was used to generate typical combustion particulates, which were then analyzed by the smoke meter. The same particulates were then size discriminated to ascertain the effective impact of aerosol diameter on smoke number readings.

Introduction:

For the last several decades, the smoke meter has been the engine manufacturers primary particulate diagnostic tool, as it was a certification measurement on all aircraft engines. The smoke meter was originally designed to aid the engine manufacturers in reducing the undesirable visible smoke emissions from their engines. In recent years, as the role of particulates in the chemistry and dynamics of the upper troposphere and lower stratosphere is coming under closer scrutiny, the smoke meter may no longer be an adequate means of ascertaining the relative magnitude of the role of particulates in an engine's potential impact on the environment.

While these measurements provide an indication of the mass of particulate emissions, and their interdependency with engine thrust setting, these measurements do not address the concerns more crucial to atmospheric assessment, namely the particle density, size distribution, and surface area. Whereas the smoke meter uses the optical degradation of a piece of white filter paper as a means of quantifying an engine's particulate production (smoke number)[2]; the probability of this method quantifying particles of atmospheric significance is small.

Instrumentation:

The jet fuel burner used in these experiments was designed to mimic the aerosol size distribution produced by an advanced combustor concept. Its performance and an analysis of its output aerosol has been described previously.[1]

The smoke meter used in these studies, (Robert Smith Electric Company, Inc Model 473A Engine Smoke Emission Sampler) was configured according to the manufacturer's specification.[3] Essentially, the smoke meter flows a known volume of sample through a piece of white filter paper. A smoke index, or a measure of the optical degradation of the filter paper, is then obtained. A series of smoke indicies allow for the extrapolation of the smoke number, which is the standard industry measurement for particulate production from engines.[2]

Two methods of particulate size discrimination were employed in this study. The first was by inertial impaction where a Casella Impactor (Cascade Impactor, MKIIA) was used to remove the large diameter particles from the sample stream. To obtain the requisite 17 l/m flow through the impactor, a pump was added in parallel with the smoke meter. The instrumental schematic for the experiment is found in Figure I.

To study the smoke meter's ability to characterize particles, the University of Missouri-Rolla Mobile Aerosol Sampling System (UMR-MASS) was used[4,5]. The MASS essentially consists of a series of electrostatic aerosol classifiers (EAC), and condensation nucleus counters (CNC). The sample aerosol is subjected to a bipolar field charging, which is then passed as a charged polydisperse aerosol to the EAC. The EAC then partitions the polydisperse flow based upon the particles electromobility. A narrow sampling slit, at the base of the EAC, allows the selection of a monodisperse portion of the sample. This monodisperse sample can then be passed into a CNC for counting. In this experiment, the MASS was used to obtain the total aerosol concentration by bypassing the EAC, and proceeding directly to the CNC, and to select a monodisperse portion of the sample to be passed either to the CNC, or to the smoke meter. (Figure I)

Experimental:

A series of three experiments were conducted to investigate the impact of particulate size on the resultant smoke number.

Experiment One:

The purpose of the first experiment was to determine whether or not the smoke meter did indeed collect all the particles emitted from the combustion aerosol source. Aside from the nominal losses due to diffusion or impaction, the primary candidate for particle loss is the transmission of aerosol through the smoke meter filter paper itself. Since the smoke number is based on the degradation of the optical reflectance of the filter paper, if the paper does not retain all particles, the smoke number would not accurately account for those size ranges lost through transmission.

To determine the collection efficiency of the filter paper, an EAC was used upstream of the smoke meter to select a monodisperse portion of the aerosol size distribution generated by the jet fuel burner. This monodisperse portion was then sent via path (1) in Figure I, to obtain the total aerosol concentration. The sample gas was then routed via path (2) of Figure I, through the smoke meter filter paper, and then to the CN counter to obtain the transmitted aerosol concentrations. The results of this experiment are presented in Table I.

Table I

Particle Size (nm)	Transmission (%)
10	0.868
50	0.005
100	0.003
150	*
200	*

*Below the limit of detection

Experiment Two:

Having determined that the filter paper was efficient at collecting all particles in the range of detection (>5nm), a smoke number measurement was taken on the jet fuel burner emissions. The smoke number was obtained according to the manufacturer's procedure as outlined in the smoke meter instruction manual.[2] A series of four samples were taken, and the smoke number extrapolated from the sample volume, and the smoke index (the measure of change in optical reflectance of the filter paper). The resulting measurements are presented in the **Total Aerosol Sample** section of Table II, and the graphical analysis of the smoke indices is presented in Figure II.

The sample flow was then directed through the Casella Impactor. The Casella nominally removed all particulates 500nm and greater with a 90% efficiency, degrading to 50% at 350nm at the requisite 17 l/m flow.[6]

Under these impacted conditions, another smoke number measurement was performed, and the resultant data is presented in the **Impacted Aerosol Sample** section of Table II, with the accompanying graph in Figure II.

Table II

	Sample Time (s)	W/A (Sample Volume)	Smoke Index
Total Aerosol Sample	15	0.009	9.22
	20	0.0165	13.3
	50	0.033	18.15
	100	0.07	30.33
Smoke Number			**14.68**
Impacted Aerosol Sample	15	0.011	2.72
	20	0.016	9.22
	50	0.032	12.29
	100	0.063	14.88
Smoke Number			**8.34**

Experiment Three:

The data in Table II clearly demonstrates a reduction in the smoke number with the removal of the numerically inferior large particulates. The impact of particle size on smoke number was investigated more closely.

The sample flow from the burner was size selected in an EAC to a specific particle diameter. Then, for comparative purposes, a constant number of monodisperse particles was deposited on the smoke meter filter paper. This operation was repeated for a series of 5 size ranges. Due to burner conditions, the three larger particle size ranges (116nm, 143nm, 223nm) were collected at a lower particle number than the two smaller size ranges (53nm, 78nm), this was done to avoid exorbitantly long sampling periods. Otherwise, the smoke meter operated exactly in the same manner as a standard smoke number measurement, save the lengthening of the sample times to accommodate the desire to accumulate larger numbers of particulates.

The resultant smoke indicies, total collected aerosol mass, and total collected aerosol surface area are reported in Table III. Additionally, an extrapolated smoke number, based upon the total aerosol sample smoke number regression (Table II and Figure II) was calculated and presented in Table III.

Table III

Particle Size (nm)	Number Collected	Smoke Index	Extrapolated Smoke Number	Total Aerosol Surface Area (cm^2)	Total Aerosol Mass (g)
53	1E+09	0	0	0.352	1.2E-06
78	1E+09	2.27	0	0.764	4E-06
116	1E+09	20.57	0	0.198	1.5E-06
143	1E+09	24.14	2.64	0.301	2.9E-06
223	1E+09	57.34	40.38	0.731	1.1E-05

Conclusions:

As the data in Table I demonstrates, the smoke meter collects virtually all the emitted particles form the combustion aerosol source. However, as the data for the 53nm, 78nm, and 116nm size ranges show, the smoke meter does not accurately reflect their presence in the smoke number measurement. Whereas the size range for atmospherically significant particles is typically less than 500nm[7], the smoke meter is not adequate as a means of assessing their existence, and as a result their potential impact of engine exhaust on the atmosphere.

With the peak in a jet engine emission size distribution typically residing between 30-60 nm[8], the smoke meter clearly does not account for the bulk of the particles emitted, but only reflects the number density of the numerically insignificant large particles. As combustor technology advances, and efficiencies increase, engines are being produced with smoke numbers of 0.[5] This study demonstrates that engines with extremely low smoke numbers are, in fact, producing large numbers of atmospherically significant particles below the cutoff size range of the smoke meter.[5]

While this work focused on constant number accumulation of particles, to the limit of the data in this study, the resultant mass and surface area data hint at the possibility that the smoke meter measurement is not dependant on the mass or surface area of particles collected. Additionally, it is quite possible that the surface of the filter paper itself plays a key role in determining what particle sizes play a role in its own optical degradation. The smaller particles would penetrate deeper into the filter, and contribute less to the surface reflectivity, whereas large particles would impact on the surface, and degrade optical reflectivity.

Further Work:

Additional studies in constant mass, and constant surface area deposition on the smoke meter filter paper should be performed on larger diameter particles to determine what is the defining characteristic of particulates that contributes to the smoke number.

Additionally, since the filter paper itself can be a variable, multiple types of filter papers should be studied to determine whether or not the filter surface plays a role in determining its own particle diameter cutoff size for contribution to the smoke number.

The filter papers should be subjected to surface characterization, like electron microscopy, before and after exposure to the smoke sample to aid in the determination of particle penetration as a factor in smoke number determination.

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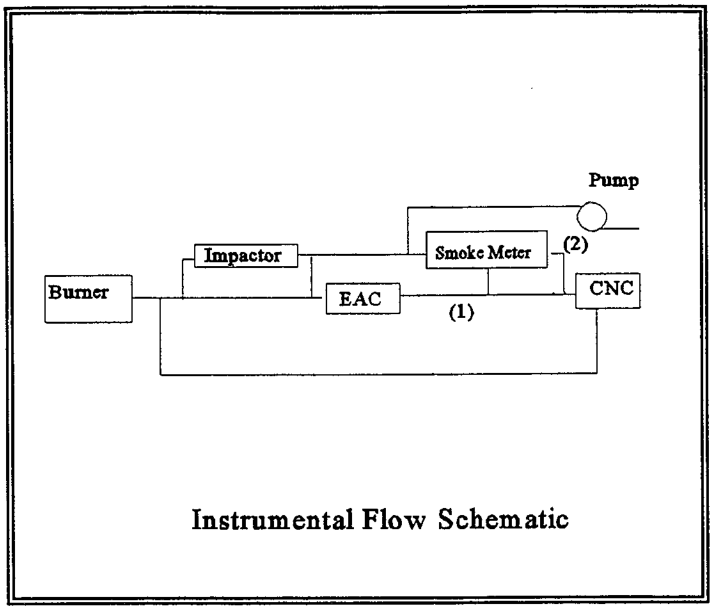
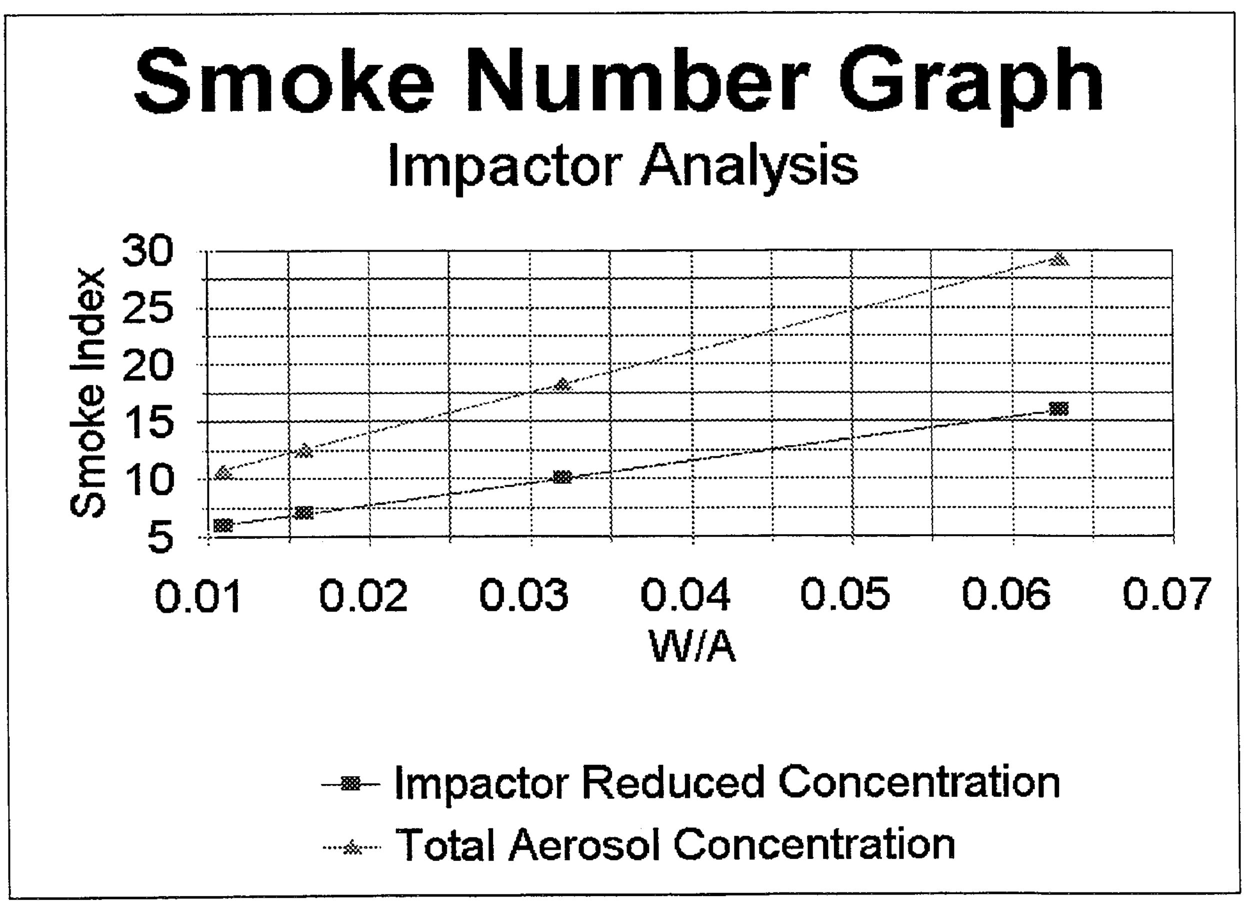
Figure I



Instrumental Flow Schematic

Figure II



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