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DEVELOPMENT OF A PARTICLE MONITOR FOR THE CFFF*

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ABSTRACT

To evaluate and improve the performance of particulate control devices (dry electrostatic precipitator or DESP, wet electrostatic precipitator or WESP, and Baghouse or BH), the entering particle loading, and size distribution if measurable, is needed. Standard extraction methods provide this data but are labor intensive and thus can not provide this data on-line in near-real-time as needed to determine best particulate device settings for changing operating conditions. Furthermore, the extreme particle number density of the solids in the process stream (10^7 particles/cm^3) and the small particle sizes (mass mean diameter 0.5-1.0 μm) are outside the capability of existing near-real-time particle loading and sizing devices. Thus, a particulate sample extraction and dilution system (SEDS) was constructed to allow on-line, near continuous determination of solid particulate size distribution and loading in the flue gas entering the particulate cleanup systems.

The U. S. Department of Energy Coal Fired Flow Facility (CFFF) SEDS was modeled on a Southern Research Institute developed system[1] which dilutes the sampled flue gas to reduce moisture content, acid mist content, temperature and particulate loading as needed to allow direct, near continuous measurement using commercially available instrumentation. Because the 0.25-1.5 μm particles which present the greatest difficulty for successful cleaning by an electrostatic precipitator are difficult to charge[2] and are produced in large numbers by the high temperature MHD combustion, the CFFF SEDS was designed to measure primarily this size particles.

In addition to the measurement uncertainties of the commercially obtained and calibrated particle counting instrument in the SEDS, the dilution process introduces other uncertainties. These uncertainties are being evaluated as the SEDS construction is being completed and as best operating parameters are being determined. Operating conditions to avoid problems such as SEDS orifice plugging and particle counter size range overflow are also being determined.

BACKGROUND

In order for coal fired magnetohydrodynamics (MHD) to become a viable energy generating system, particulate emissions must be environmentally acceptable. Because of the high combustion temperatures MHD system particulates tend to form primarily by vaporization/condensation mechanisms and are thus smaller than typical coal system fly ash which is generally larger than 1 μm, and not smaller than 0.5 μm[3]. The potassium used as seed introduces additional small particulates as it condenses, significantly raising the number density of the small (< 0.5 μm) exhaust particulates in coal-fired MHD. Research at the CFFF confirms that the coal-fired MHD process produces very high loadings of small particles. Standard particulate measurement methods (Method 17 mass loadings and 5 stage cyclone particle size distributions) show that particle densities are greater than 10^8 particles/cc in the diameter range 0.1 to 3 μm, as shown in Figure 1.

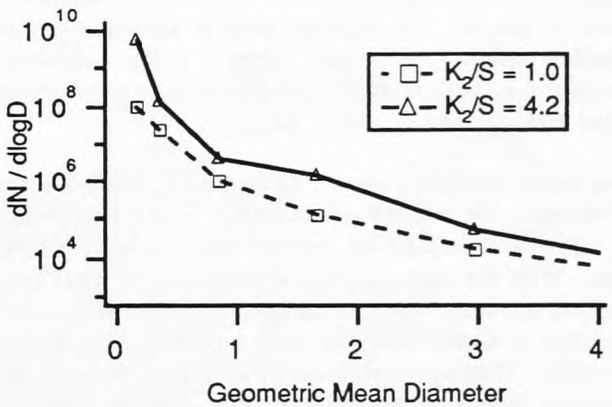

Figure 1. Particle Size Distributions Measured at CFFF for different K_2/S ratios.

The five stage cyclone measurements shown in Figure 1 were acquired over an approximate 90 minute time interval. During a typical 90 minute interval variations occur in coal chemistry and ash content as well as coal flow rate and the particulate and gas flow also change due to events such as thermostatically tripped superheater soot blowing. As a result, Figure 1 must be viewed more as a time averaged particle size

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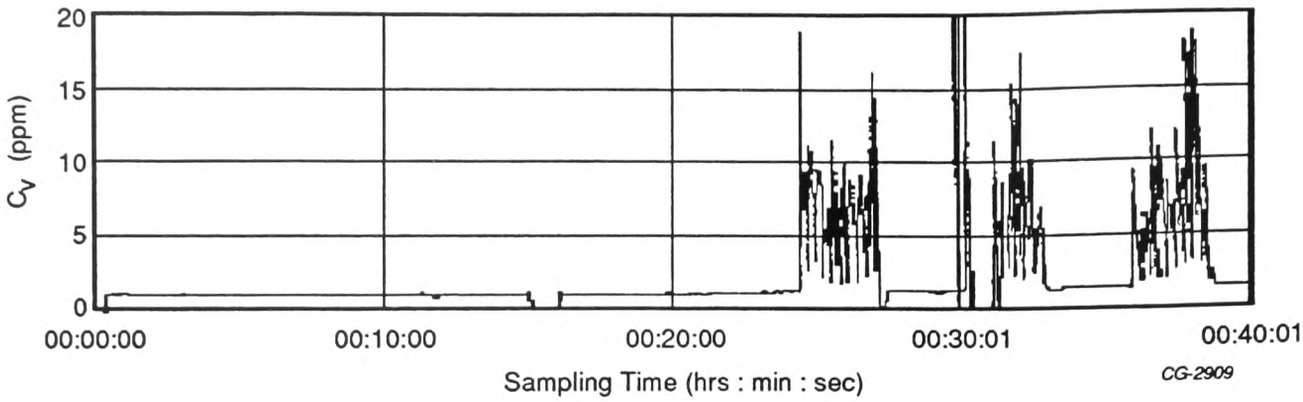


Figure 2. BH, DESP and WESP Inlet Particle Volume Concentration Time Variations[4]

distribution entering the particulate control systems. Indeed, as shown in Figure 2, CFFF in-situ laser scattering measurements made by Insitec, Inc.[4], and 2-color laser transmissometer measurements made by Mississippi State University[5], indicate substantial changes with time in particle volume concentration both upstream and downstream of the particle control systems. Although the particle volume concentration entering the particle clean up system fluctuates, the MHD system particulate emissions must not exceed environmentally acceptable limits whether the entering volume concentration is high or low. Therefore, it is necessary to measure particulate size distributions entering and leaving the particle emission control systems with a sufficiently high frequency response to measure the different particle loading and size distribution levels. As Figure 2 shows, a time resolution measurable in seconds is needed rather than in hours as can be obtained with cyclones or impactors.

Current particle emission control systems being studied at the CFFF include a BH, a DESP, and a WESP. Figure 3 shows the CFFF test train to indicate locations of these particle clean up devices. With the inlet sampling location and all three system outlets, sufficient lengths of straight duct precede the sample location to ensure sampling from a fully developed pipe flow profile. Therefore representative isokinetic samples can be extracted from a known gas mass flow. During different tests, the operation of the particle clean up devices is being altered to determine appropriate operation for MHD system particle emission control. For example, the effects of different bag filter materials, different cleaning cycles, and reverse air flows have been studied with the BH. The electrodes, and the specific collection area have been altered in the DESP, and different spray nozzles are being tested in the WESP. With these changes recent testing has shown particle collection efficiencies at 99.97% on average. However, time resolved collection efficiencies can't be measured until the SEDS is fully operational.

SYSTEM DESCRIPTION

A schematic of the SEDS is shown in Figure 4. A sample is extracted from the flow stream with a heated probe and taken into an oven to prevent acid and water vapor condensation by keeping the sample temperature above the acid and water dew points. In the oven, the particle stream goes through a cyclone to remove the particles larger than 2 μm that are likely to initiate plugging of metering orifices or deposition in the SEDS. Also, particles larger than 2 μm are only a small percentage of the flue gas particles and are easily captured by the BH, DESP or WESP, so their measurement is not important for this instrument. The exhaust from the cyclone pump can be returned to the flue gas downstream of the sampling probe. SO_x is reduced in the sample stream, while it is in the oven, by diffusion absorbers. This helps eliminate acid mist condensation as the sample stream cools in the dilution chamber.

The sample gas is pulled from the oven into a turbulent flow dilution chamber where it rapidly mixes with multiple jets of cool, dry clean flue gas. As the sample is diluted particle charges are neutralized by 500 μc ionizing strips of polonium 210. A small sample of the diluted gas is pulled from the dilution chamber into the particle sizing instrument (Particle Measuring System's [PMS] ASASP-X). The rest of the gas is then dried in a condenser, cooled and filtered with a 0.08 μm filter and returned to the mixing chamber through the dilution flow metering orifice. The sample is thus continuously diluted with flue gas.

All pressure drops across the cyclone and orifices are closely monitored since the accuracy of these flows is an essential component of the measurement uncertainties of the SEDS system. Incorrect pressure drops also may affect the measured size distribution by enhancing particle deposition within the SEDS or by promoting larger particles with more momentum to stay in the center of the sample.

One necessary feature of the SEDS is the ability to change dilution ratios because the adjustability of the PMS spectrometer is very limited. Also, when the particle concentration is too high the spectrometer measurements can be biased to larger particles as illustrated in Figure 5. In this Figure the sharp drop in the small diameters and the shift to larger diameters around 30 and 90 seconds correspond to periods when the particle measuring instrument was overwhelmed with too dense a sample. After about 180 seconds, gradual plugging of the dilution orifice is evident.

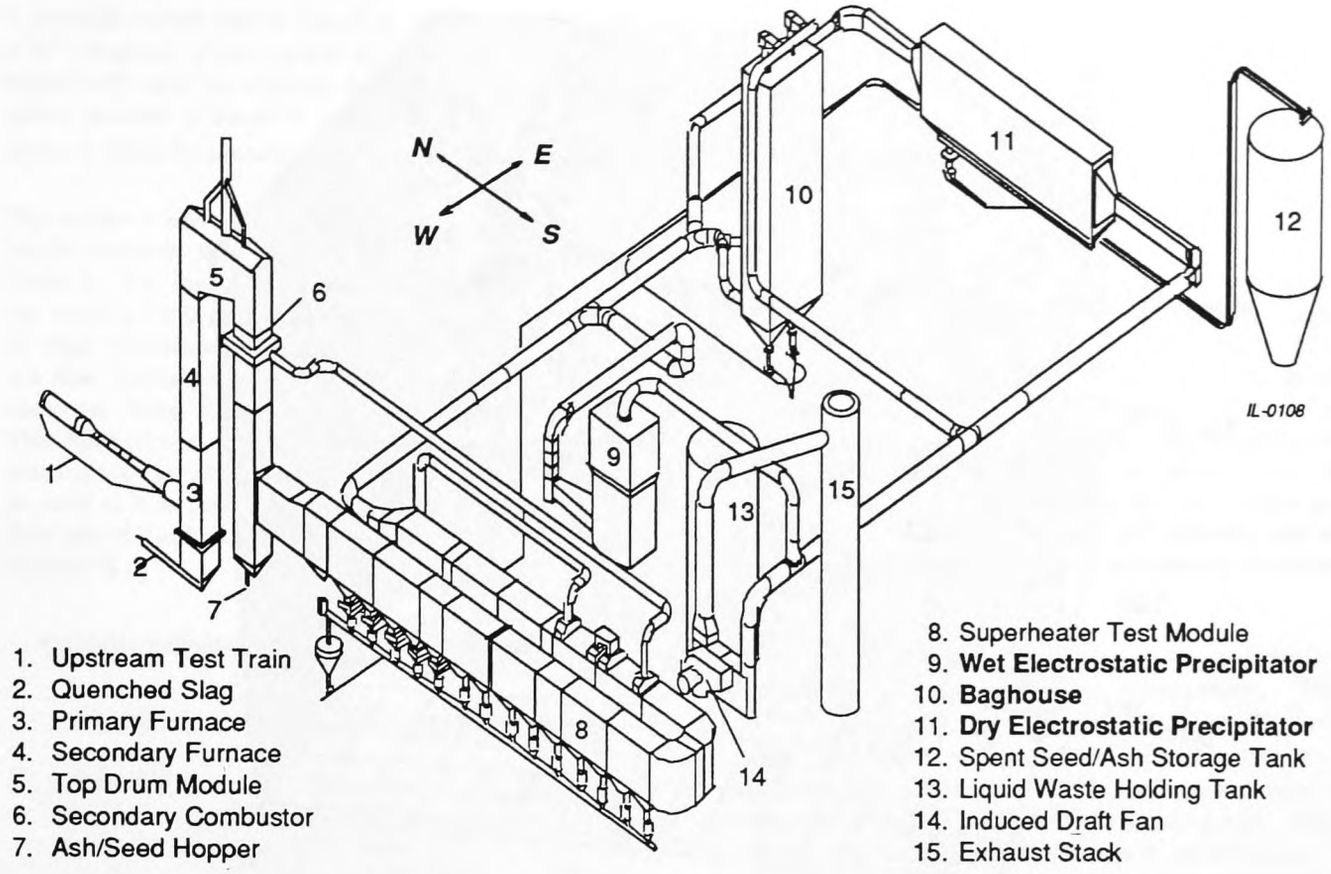


Figure 3. Schematic of CFFF Test Train

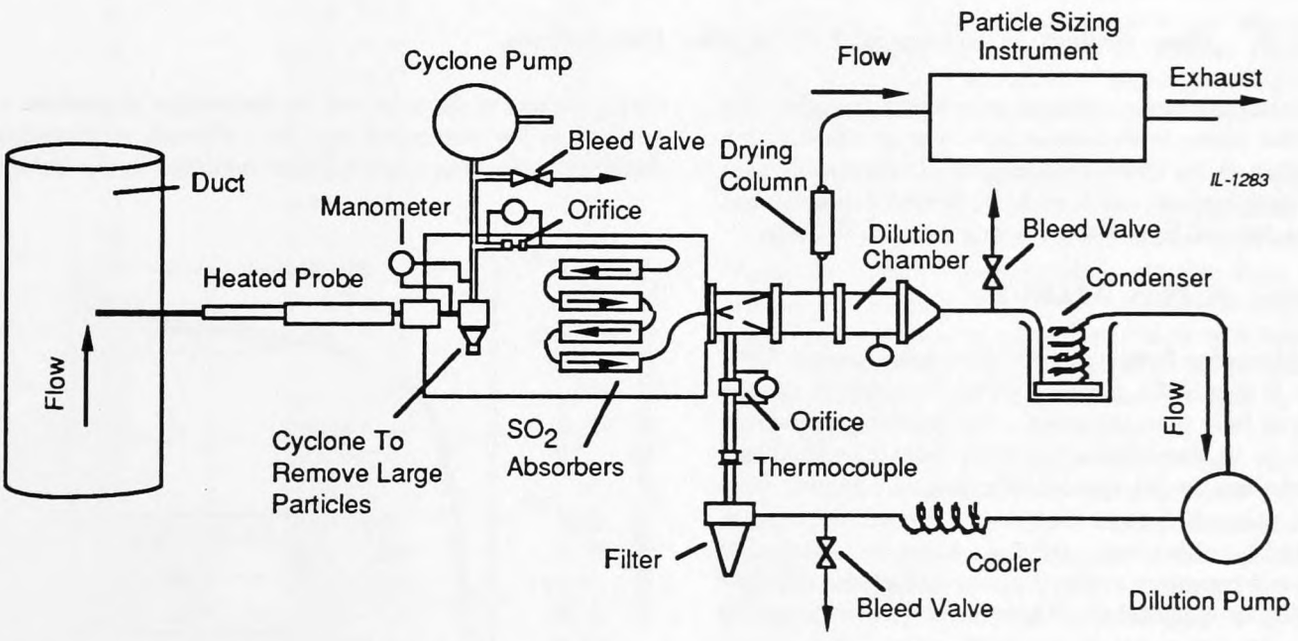


Figure 4. Schematic of the Sample Extraction Dilution System

Another problem encountered during recent tests at the CFFF is that the smallest sample flow orifice, used to obtain the largest dilutions, was plugging with particles in the sample. These problems are being addressed with two system modifications. The first modification is to decrease the PMS spectrometer sample flow. Any significant decrease requires adjustment of the spectrometer aerodynamic focusing jets and an attendant recalibration of the spectrometer. The other system modification involved redesigning the interchangeable orifices to move the downstream pressure tap closer to the orifice

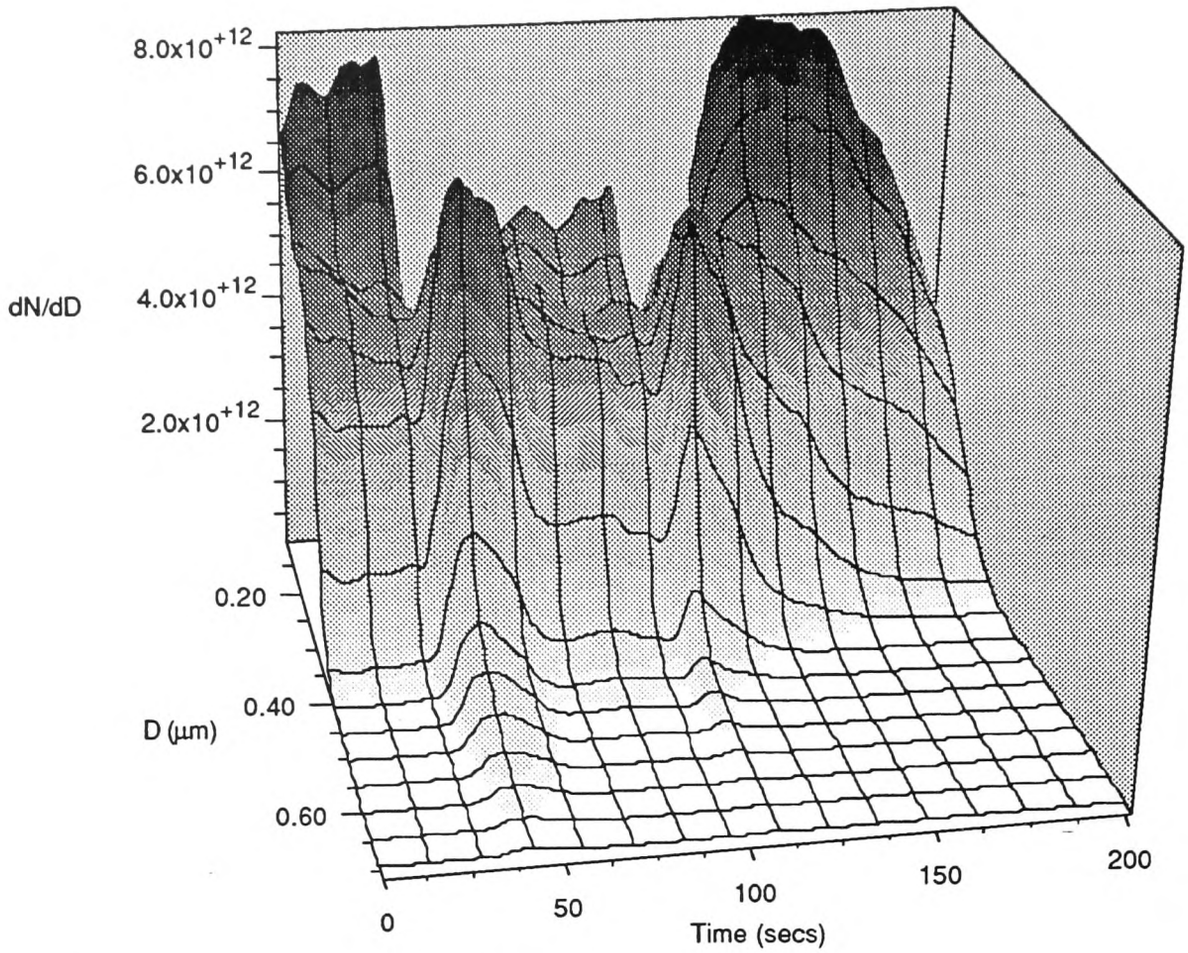


Figure 5. Time changes in Measured Particle Size Distributions

vena contracta where the maximum pressure drop occurs. This modification allows lower sample flow to be measured with a larger orifice at the same pressure drop. Unfortunately tests of these modifications could not be performed during the last CFFF test, but will be conducted during the upcoming test.

Description of PMS ASASP-X[6]

Particle Measuring System's Active Scattering Aerosol Spectrometer Probe (PMS model ASASP-X) operates on the principle of laser light scattering. The particle spectrometer is known to be dependent on particle index of refraction.[7] Thus variations in the spectrometer response curves were expected using Mie scattering theory for the polystyrene latex (PSL) calibration particles, potassium carbonate particles and potassium sulfate particles. (Particles collected at the CFFF are essentially K_2SO_4 for $K_2/S = 1$ conditions and a mixture of K_2CO_3 and K_2SO_4 for $K_2/S = 4.2$ conditions.) As shown in Figure 6 the spectrometer response curves are largely independent of index of refraction of the particles especially for particles smaller than 2 μm.

Particles extracted by the spectrometer are aerodynamically focused through the center of a laser beam (HeNe operating in the TEM_{oo} mode, $\lambda = 632.8$ nm). The laser beam is approximately 0.6 mm in diameter and the focused jet of particles is confined to the center 0.2 mm by a filtered, recirculating sheath gas flow. The scattered light collection optics include

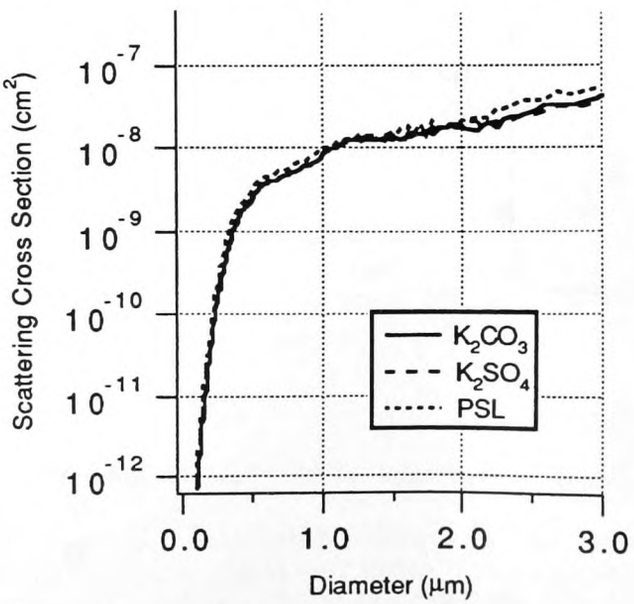


Figure 6. PMS Spectrometer Response Curves

a parabolic mirror (silver coated to provide 95% reflectivity) a 45° diagonal plane mirror (dielectrical coated for 99% reflectivity) and an aspheric lens. Together, the collection optics provide a forward scattering light collection solid angle of about 2π steradians (35° to 120°).[6]

The scattered light pulses are sensed by a 32 channel pulse height analyzer, thus resulting in 32 bin sizes as shown in Table 1. The maximum number of particles the instrument can count is 5000 particles per second due to the particle time of flight in crossing the laser beam and to electronics speed. All data acquisition and analysis was done on a Macintosh computer using National Instrument's LabView® software. This allowed near real time analysis of the samples. Data is read over the serial port every one to ten seconds and analyzed as soon as it is read. At the calibrated spectrometer sample flow rate of 2 cc/sec the maximum measurable particle number density is,

$$\text{maximum particle density } \frac{\#}{cc} = \frac{\text{maximum count rate \#/sec}}{\text{sample flow rate cc/sec}} .$$

Table 1. Spectrometer Size Channels

CHANNEL	SIZE (μm)	INTERVAL
1	0.10 - 0.11	0.01
2	0.11 - 0.12	0.01
3	0.12 - 0.13	0.01
4	0.13 - 0.14	0.01
5	0.14 - 0.15	0.01
6	0.15 - 0.16	0.01
7	0.16 - 0.17	0.01
8	0.17 - 0.18	0.01
9	0.18 - 0.20	0.02
10	0.20 - 0.22	0.02
11	0.22 - 0.24	0.02
12	0.24 - 0.27	0.03
13	0.27 - 0.30	0.03
14	0.30 - 0.35	0.05
15	0.35 - 0.40	0.05
16	0.40 - 0.45	0.05
17	0.45 - 0.50	0.05
18	0.50 - 0.60	0.10
19	0.60 - 0.70	0.10
20	0.70 - 0.80	0.10
21	0.80 - 0.90	0.10
22	0.90 - 1.00	0.10
23	1.00 - 1.20	0.20
24	1.20 - 1.40	0.20
25	1.40 - 1.60	0.20
26	1.60 - 1.80	0.20
27	1.80 - 2.00	0.20
28	2.00 - 2.20	0.20
29	2.20 - 2.24	0.20
30	2.40 - 2.70	0.30
31	2.70 - 3.00	0.30
32	> 3.00	

Following SEDS calibration the second spectrometer was calibrated at a sample flow of 0.2 particle per cc, giving a maximum measurable number density of 2.5×10^4/cc. If the SEDS dilution is set at 5000 to 1, the maximum SEDS measurable number density is 1×10^8/cc.

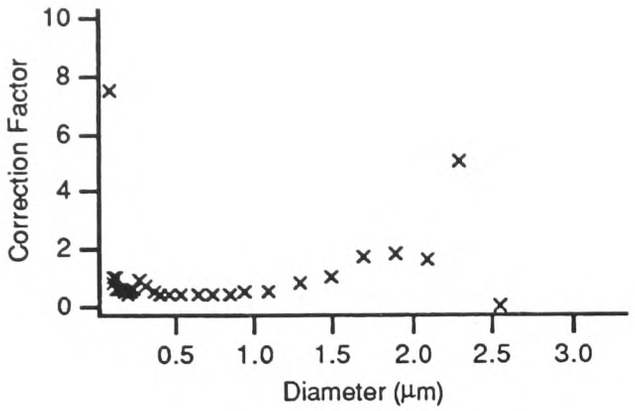
Calibration of the SEDS

Using two different PMS spectrometers, it is possible to calibrate the SEDS by measuring the particle sample both before and after dilution and then comparing results. The particles used for this calibration were made by dripping oil onto a hot element and blowing the smoke through a Tee with valves at each outlet. One valve led to the sampling duct and the other was exhausted. It was necessary to use the two valves to adequately stabilize the flow of smoke particles. The sampling duct was a pipe of 6 inch diameter with a forced draft fan and a honeycomb flow straightener downstream of the particle inlet.

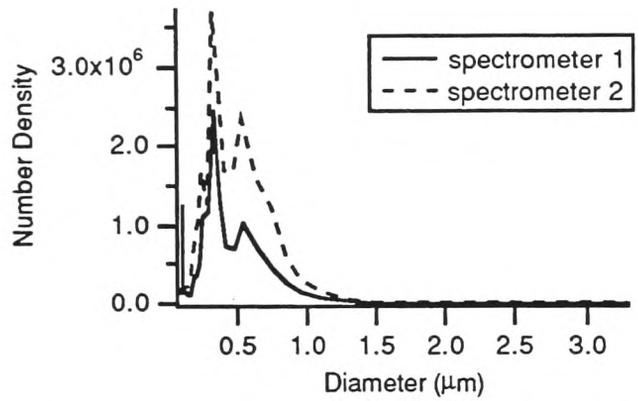
Before SEDS calibration only one of the spectrometers had been recently calibrated by the manufacturer. The other spectrometer had not been calibrated, so the calibrated spectrometer was used to correct the measurements of the uncalibrated spectrometer. With both spectrometers simultaneously sampling from the same place, a correction factor was obtained for the uncalibrated spectrometer. This correction factor, CF, shown in Figure 7, was obtained for each spectrometer size channel by dividing size channel data from the calibrated spectrometer by data from the uncalibrated spectrometer. Except for the smallest size channel, CF is reasonably close to 1 for particles smaller than 1.5 μm. Figure 7 (b) shows the number densities measured by the uncalibrated (1) and calibrated (2) spectrometers.

In order to measure the adjustability of the spectrometer sample flow rates, one spectrometer (uncalibrated) was used to monitor the consistency of the smoke generator and the other spectrometer simultaneously sampled from the same source at different flow rates. The normalized number densities were calculated by taking the ratio of each measurement to a standard measurement (taken to be the measurement at 1.0 cc/s) for the first instrument and dividing by the same ratio measured by the other instrument. This eliminates fluctuations of the smoke generator particle loadings. In Figure 8, the results from these measurements are shown to be varied and inconsistent. Each normalized number density represents the mean number densities of measurements of 5 to 10 minutes, data being taken every 1 second. The variability indicates that the flow rates on these particle spectrometers are not adjustable over the wide sample flow rates tested. The manufacturer indicates a narrow adjustability, and that obviously can not be exceeded, so most adjustments will need to be made with the SEDS.

The SEDS calibration also involved using both spectrometers, one measuring just before dilution and one after. The SEDS and the calibrated spectrometer both sampled



(a). Correction Factor (CF) of the Uncalibrated Spectrometer vs. Particle Diameter



(b). Number Density of Each Spectrometer

Figure 7. Correcting Different PMS Spectrometer Measurements

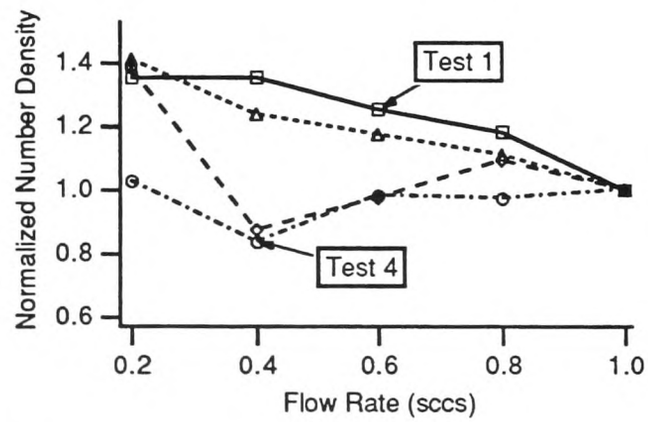
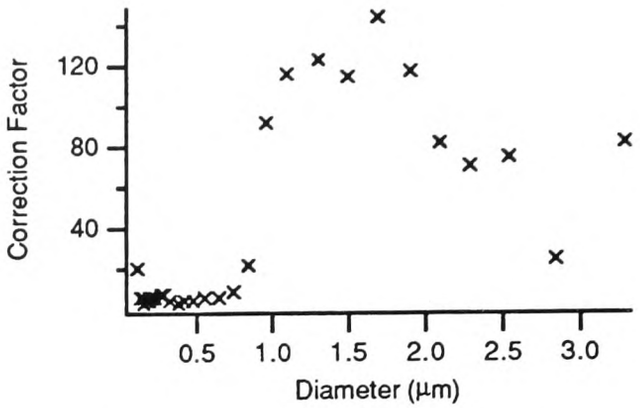
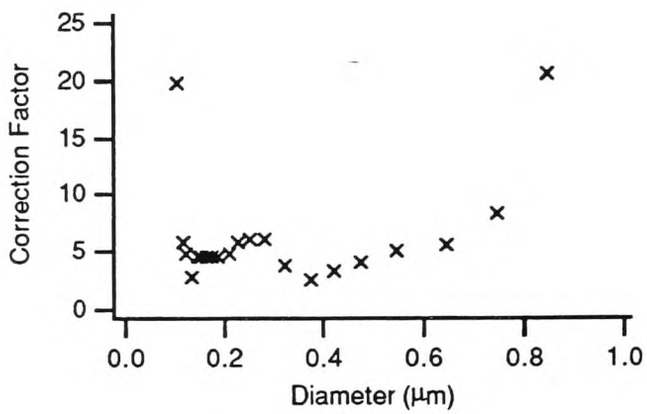


Figure 8. Normalized Number Density vs. Spectrometer Sample Rate

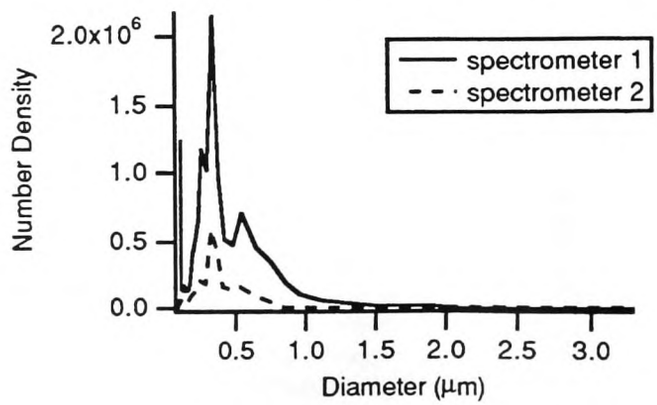
directly from the smoke. The other spectrometer sampled from the dilution chamber of the SEDS at a sample flow of 2.0 cc/sec. The low sample flow setting (0.2 cc/sec.) of the calibrated spectrometer was necessary because of the heavy smoke required to measure a reasonable dilution. Measurements were taken for SEDS dilution rate of 600, 700, 800, 900, and 1000 to one. Figures 9 (a) and 9 (b) below show the ratio of the diluted sample measurements (corrected for dilution rate) to the undiluted sample versus diameter. At larger diameters the correction factor substantially increases



(a). Correction Factors for the SEDS at 600:1 Dilution



(b). Expanded View of Figure 9(a).



(c). Cumulative Number Densities for a Dilution of 600:1.

Figure 9. Correcting SEDS Dilution Ratios

due to the small number of particles seen in that size range as shown by Figure 9 (c). Thus the large correction factors shown for diameters greater than 1 μm do not represent measurements with a high degree of statistical confidence. Overall confidence is low in all correction factors given in Figure 9 since stable operation of either spectrometer at 0.2 cc/s was not possible until a spectrometer was calibrated for this sample flow.

Before the LMF5-I test, we plan to recalibrate the SEDS dilution using 2 calibrated spectrometers. Then we plan to send the SEDS to Insitec, Inc. and perform a separate calibration. During LMF5-I, there will be three independent particle sizing measurements; the 5 stage cyclone and method 5 sample train will be run immediately prior to simultaneous tests with the SEDS and with Insitec's particle sizing instruments. Comparison of these should help to evaluate the performance of the SEDS.

SUMMARY

This paper discusses the development of an on-line near-real-time particle size distribution and loading instrument at the CFFF. All of the current instruments available are insufficient by themselves to meet the demand of high particle concentrations and small sizes found in coal fired MHD. Studies using standard particle methods show that the particle loading approaches 10^8 particles per cc and the great majority of these particles have diameters smaller than 0.5 μm. On-line, near-real-time capability is important so that changes in particle samples can be measured as a result of changes in operating conditions.

A sample extraction and dilution system was designed for operation at the CFFF based on one developed by Southern Research Institute. The SEDS extracts a sample of the flue gas and heats it to prevent condensation of acid mist and water. After the larger particles are removed (> 2.0 μm) the sample is mixed with clean dry flue gas as it is cooled. This diluted sample is then analyzed by a commercial particle sizing instrument (PMS ASASP-X).

In order to calibrate the SEDS, several correction factors are needed. There is a correction factor for the differences between the two instruments, one for the adjustability of the flow rates, and one for the actual dilution of the SEDS. But as we saw, we had problems getting consistent results from measurements with particles that have low flow rates. Problems and inconsistencies arose from measurements at low flow rates, so we will repeat most of these measurements with both spectrometers calibrated at proper flow rates and running at those conditions.

Other uncertainties to be investigated further include those associated with the SEDS dilution ratios, overloading of the particle spectrometers, and operational difficulties such as plugging of the orifice.

Future plans include modifying the orifices to provide larger pressure drops and higher dilutions with larger sized orifices, and replacing the rotometers currently used in the particle sizing spectrometers with electricity controlled flow meters. The current accuracy of the rotometers is ±5%.

Other plans are test comparisons with MSU and Insitec. Their instruments along with the SEDS will be run simultaneously for best comparisons and these will all be matched against the 5 stage cyclone and method 17 measurements. Alternate calibrations at the Insitec test site are also being planned.

ACKNOWLEDGEMENTS

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