United States
Environmental Protection
Agency

Environmental Sciences Research
Laboratory
Research Triangle Park NC 27711

Research and Development

EPA-600/S2-81-096 Aug. 1981

EPA

Project Summary

Modification of Optical Instrument for In-Stack Monitoring of Respirable Particle Size

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A light scattering instrument for *in-situ* measurements of particulates in the 0.2 to 20 micrometer diameter size range is described, and field test results are presented. The instrument is a modified version of a prototype built during a prior EPA contract, Number 68-02-2447. The upper limit of the size response has been extended from 10 to 20 micrometers, and several component and packaging changes have been incorporated to make the unit more suited to stack particulate survey applications. Low forward angle and 90° polarization dependent scattering is employed to make the measurements.

The completed instrument was tested at a coal-fired electric power generating facility. During the test a cascade impactor was used as a referee device and both instruments were run side by side in the outlet duct of the electrostatic precipitator.

The results show an excellent correlation between the two instruments with regard to the identification of a 1 μm diameter peak in the particle size distribution. A second peak around 20 μm was defined by the optical instrument, but could not conclusively be confirmed through the impactor data. The optical instrument handled well during the field test and was delivered to EPA for additional testing.

This Project Summary was developed by EPA's Environmental Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

A prototype real-time *in-situ* monitor was developed and constructed on EPA Contract 68-02-2447 to measure particle size distribution of respirable particles in the 0.2 to 10 μm range. The purpose of this project was to add a channel to cover the 15 μm size range so as to include the upper cut-off of the inhalable particulate emissions from stationary sources.

The addition of the large particle channel required a series of changes in the optical and electronic assemblies of the original instrument. In the process of incorporating these changes, the latest available components were selected and packaging improvements were made, resulting in an instrument optimally suited for survey work and stack particulate analyses. The new instrument measures the size distribution in the 0.2 to 20 μm range in five size fractions, using a low power helium neon laser light source.

The modified prototype instrument was tested at a coal-fired electric generating plant. Referee measurements were made with a cascade impactor. Both instruments reported a strong peak in particle size around one μm in diameter.

Procedure

Principles of Operation

The instrument was designed by using simple diffraction theory for the low angle forward scattered light, and rigorous Mie theory for the light scattered at 90° to the probe beam. By adding high angle scattering capabilities, the use of light scattering for particle analysis can be extended to the sub-micrometer size range.

The stack particulate monitor measures the light scattered by particles passing through a 2.5 cm by 36 cm slot at the end of a 152 cm (5 foot) long probe. The light source is a 2 milliwatt helium neon laser, which emits a coherent beam at 0.6328 μmeters. The scattered light signals are proportional to the volumes of particulate material present in each of five size fractions. Six scattered light readings are taken at precisely determined angles. The light signals are acquired through fiber optic cables and transmitted to detectors located in the transceiver. A digital microprocessor calculates a five channel, volume-by-size histogram, covering the size range from 0.2 μm to 20 μm.

Modification of the Prototype

Modification of the original instrument to add a 15μm channel involved a number of significant changes. When appropriate, these changes were made so as to accommodate improvements suggested from field trial experience with the first unit. The pertinent aspects of the new design are discussed in the following paragraphs.

The xenon arc source was replaced by a low power (2 milliwatt) helium-neon laser, which provides better collimation of the source, and eliminates a troublesome electrical transient starting problem. A slightly larger collection lens system was designed to accommodate a wider range of forward scattering angles. However, the 90° collection system used in the earlier unit remains the same.

A beam alignment sensor was added to the tip of the probe to monitor any thermally induced shifts. Through ports accessible from the rear of the probe, the beam can be aligned in or out of the stack by maximizing the reading on a meter adjacent to the adjustment ports.

A Z-80 microprocessor system replaced the original 8008 based electronics. The new system allowed for rapid and efficient implementation of the hardware and software changes required in modifying the unit. The new electronics is much more compact than the earlier version, and is combined with a small digital printer in a 20 pound transportable electronics console. A second, smaller box, contains the electronics power supply, packaged separately to avoid heat build-up on the control console box.

A summary of operational characteristics of the prototype is shown in Table 1. The measurement time can be set by the user and ranges from 5 seconds to 12 minutes. Immediately following the data collection, the size distribution is printed out at the console.

Calibration

The calibration process involved several steps and used a variety of materials. To properly fill the sample slot region under operating conditions simulating a flowing gas stream, an aerosol test chamber was constructed in the laboratory.

The major steps of the calibration process are outlined here.

(1) During assembly, the light collecting apertures were checked for alignment and adjusted to insure that the correct angles were being measured.

(2) Di-octyl phthalate (DOP), a transparent liquid with an index of 1.49, was dispersed as a droplet suspension in the aerosol test chamber by a Phoenix Precision Aerosol Generator. This created a well-controlled size and loading of particles in the 0.2 to 3 μm size range. From the measured signal levels and knowledge of the loadings, detector gain adjustments were made to accommodate a uniform distribution of particles at 40 parts per billion.

(3) The collection geometry and fiber transmission product at each angle was determined by measuring fresh, filtered cigarette smoke. Because the majority of the particulate volume is well below one μm in diameter, the forward scattering pattern does not change with particle size. A correction constant is thus defined for each scattering angle, based on th difference between scattered light strengths observed and those predicted by theory.

Results

Laboratory Tests

As a check for consistency, the instrument was then used to measure the aerosol distributions employed to calibrate it. Figure 1 shows the filtered cigarette smoke distribution, indicating a large percentage of the material in the 0.3 μm size channel, while Figure 2 shows the measured and manufacturer's specifications for the DOP aerosol suspension. In both cases, agreement between expectation and observation is quite good.

To further check the performance and calibration, two other materials were run, burning red phosphorous, and solid glass spheres. The red phosphorous is used for tactical smoke screens, but no referee data was available. The instrument readings indicated roughly equal amounts of material in the 0.3 and 1.0 μm size channels. This is consistent with its intended tactical use since particles in this size range are the most efficient scatters per unit volume and thus provide good obstruction.

The solid glass spheres, from Potters Industries, Inc., were used to check performance of the larger size channels. The spheres are specified as "3 to 10 micron" size, but no additional data was provided or available. No material is reported in the 0.3 μm channel, as expected, and most of the material is in the 3.5 or 7.5 μm region. The material reported in the 15 μm channel may be caused by clumping of the beads due to electrostatic charges introduced in the suspension process. Microscopic examination of a bead sample collected during the test confirmed this, showing occasional clumping.

Field Test Performance

During July, 1980, the prototype instrument was tested at an east coast coal-fired electric power generating station. L&N personnel used the prototype instrument to measure particle size distribution in a duct leading to the smoke stack. Personnel from Northrop Services, Inc., Environmental Science (NSI-ES), participated in the tests, taking data with a cascade impactor, and provided the necessary data analysis

Table 1. Operational Characteristics of Stack Particulate Monitor

Size Range (Particle Diameter)	*0.2 to 20.0 μm*
Size Discrimination	*Five volume fractions with centers at 0.3, 1,0, 3.5, 7.5, 15 μm*
Mode of Operation	*Low angle forward scattering and 90° polarization dependent scattering*
Loading Range	*0.01 to 1.0 grams of material/meter^3 (.023 to 2.3 grains/ft^3) or 4 to 400 parts/billion by volume (with s.g. of 2.5)*
Measurement Time	*Signal integration time selectable from 5 seconds to 12 minutes (including a 6-minute position)*
Duct Velocity	*1.5 to 18 meters/second (5-60 feet/second)*
Duct Temperature	*260° C maximum (500° F)*
Instrument Temperature	*2° C to 43° C (35 to 110° F)*
Power Requirements	*One 20A, 115 volt, 60 Hz outlet*
Physical Specifications	
Probe Dimensions	*152 cm long (60 inches) by 9 cm diameter (3¼ inches)*
Sample Slot Dimensions	*2.5 x 36 cm (1 x 14 inches)*
Transceiver-Probe Assembly	*203 x 25 x 25 cm, 31.8 kg (80 x 10 x 10 inches, 70 pounds)*
Control Console	*38 x 41 x 25 cm, 9.1 kg (15 x 16 x 10 inches, 20 pounds)*
Electronics Power Supply	*23 x 41 x 25 cm, 6.4 kg (9 x 16 x 10 inches, 14 pounds)*
Blower	*74 x 48 x 43 cm, 22.7 kg (29 x 19 x 17 inches, 50 pounds)*
Probe Material	*Type 316 Stainless Steel (except for optical components)*

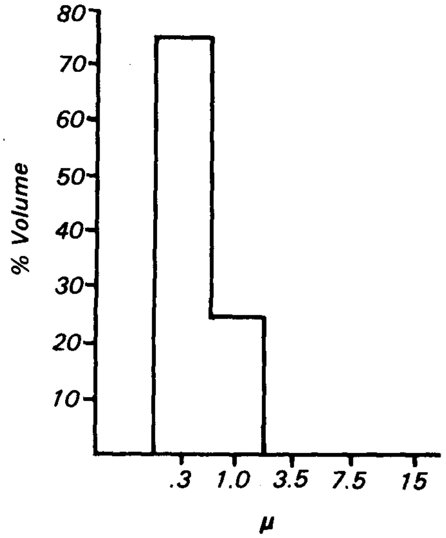

Figure 1. *Calibration run using cigarette smoke.*

for that method. Six separate data sets were collected over two days. One set of data from each day is presented here.

All testing was performed at the outlet of the electrostatic precipitators and prior to the final exhaust fan. The testing section was a vertical flow duct, approximately 32 1/2 ft. wide by 7 ft. deep. Sampling ports are located horizontally across the wide side of the duct. Each port is a 6-inch diameter flanged pipe, approximately 14 in. long. Two adjacent ports were selected as test points. A summary of the stack conditions appears in Table 2.

All aerodynamic particulate sizing was performed using a University of Washington Mark III Cascade Impactor and necessary support equipment. Prior to actual source testing, all in-stack atmospheric measurements necessary for isokinetic and other calculations were recorded. Velocity head and stack differential pressure measurements were peformed using a type "S" pitot. In-stack temperatures were measured using a thermocouple system attached to the end of the pitot tube. Velocity profile measurements were made up to 4.5 ft. into the duct at both test ports, with the impactor sampling conducted at the point of both average velocity and close proximity to the optical instrument. The point used for sampling was approximately the mid-point of the duct or 4 ft. from the lip of the port flange.

The impactors were preheated to stack temperature before sampling to avoid moisture condensation within the impactor body. The duration of each test was varied according to the stack opacity, knowledge that this coal unit was within particulate emissions standards, and the visual inspection of the previous impactor test. Sample runs varied from 20 to 40 minutes in length.

Several hours were required to make the preliminary measurements before the impactors were inserted.

The prototype optical particle size monitor was prepared within approximately one hour. All electrical cables were connected and the instrument was turned on to warm-up the electronics. The optical alignment of the unit was adjusted using the external meter. The stack velocity, measured for the impactor runs, was used to set the purge flow rate on the blower. To facilitate insertion and removal from the stack during the tests, a suspension rail designed and built previously for this unit by NSI-ES was erected. A typical sample run lasted 6 minutes, and several runs were made during the impactor sample collection period.

On the first sampling day the boiler unit was operating at maximum output. On the second day, the boiler was operating at reduced output, and the particulate emissions were distinctly lower, dropping from around 0.02g/Nm^3 the first day, to 0.007g/Nm^3 the second, as measured by the impactor.

Results for both optical and inertial instruments are shown in Figures 3 and 4, plotted as histograms of volume fraction per unit log interval of particle size. The optical data in each figure are indicated by the cross hatched histogram, while the impactor data are shown as the heavier outlined histogram. Variations in the individual channel widths

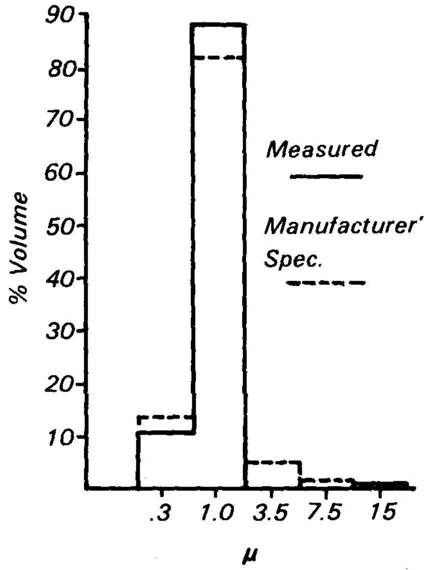

Figure 2. *Calibration using dibutyl phthalate aerosol from Phoenix generator.*

are due to the different principles involved in measuring the particle distribution.

The impactor data, provided by NSI-ES, were derived by plate weighings and computer assisted data reduction. A material density of 2.5g/cm^3 was assumed, and the channel edges were based on the aerodynamic separation properties of the individual stages of the impactor.

During each impactor run, continuous optical data measurements were made. The histograms shown are compiled from the time weighted average of the sequential optical data, which involved from 5 to 8 optical runs, depending on the length of the impactor run. The boundaries of the optical histogram are determined by the instrumental response, as calculated from scattering theory.

Discussion

The optical and inertial measurements agreed in some significant respects. In all runs both instruments reported a significant size fraction to be around one μm in diameter with, in most cases, substantial reductions in the amount of material above the one μm size. The optical instrument consistently indicated a good deal of material in its largest size channel, which made the distribution appear bimodal. This could not be definitely confirmed by the impactor data available, although impactor runs from some tests show a leveling off of the distribution, and run 4 does indicate a secondary peak in its largest particle channel.

Table 2. *Stack Conditions During Field Test*

Stack gas velocity:	*45 to 50 feet/second*
Stack gas temperature:	*230 to 300° F*
Gas pressure:	*-2 inches of Hg*
Direction of flow:	*Vertical downward*

The general agreement between the two methods is good. The size response question could well be resolved through further testing at other sites. There were some relatively minor technical problems, but none that should prevent the optical instrument from being used in other field tests. At the conclusion of this test, the prototype stack particulate monitor and its associated equipment were turned over to the EPA.

Conclusions and Recommendations

The primary goal of this work was to modify and test a prototype optical stack particulate monitor by the addition of a channel responding to particles in the 15 μm size range. This was successfully accomplished. Tests in the laboratory showed results that agreed with expected size distributions of several sample materials which were in the 0.2 to 20 μm size range of the instrument. The field tests, conducted at a coal fired electric utility plant, provided size distribution data which were in excellent agreement with results reported by a referee inertial impactor. An additional advantage with the optical instrument is that size distribution data are computed and displayed immediately upon the conclusion of the signal collection sequence.

A secondary goal of this project was to improve the reliability and portability of the instrument to make it more suitable for stack survey work. The modified prototype unit is lighter and smaller than the original, and the operational improvements, such as ease of alignment and reliability of operation, were demonstrated during the field trial.

There may be some value in developing an on-site technique to provide the operator with a quick means of checking the calibration of the unit. Although

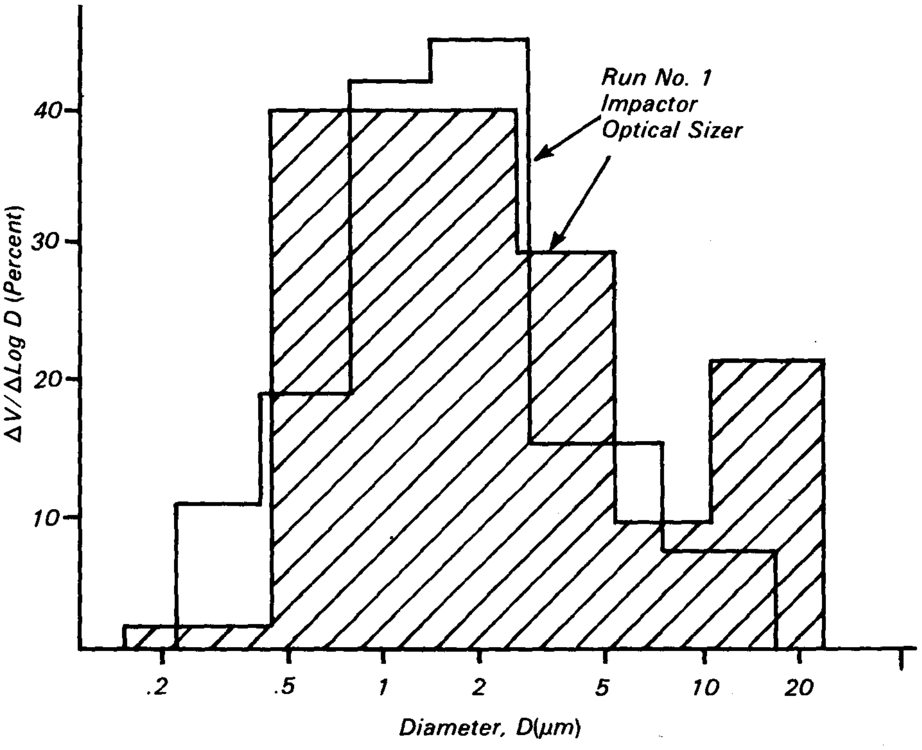

Figure 3. *Particle size vs. volumetric concentration distribution during Day 1 of the field test.*

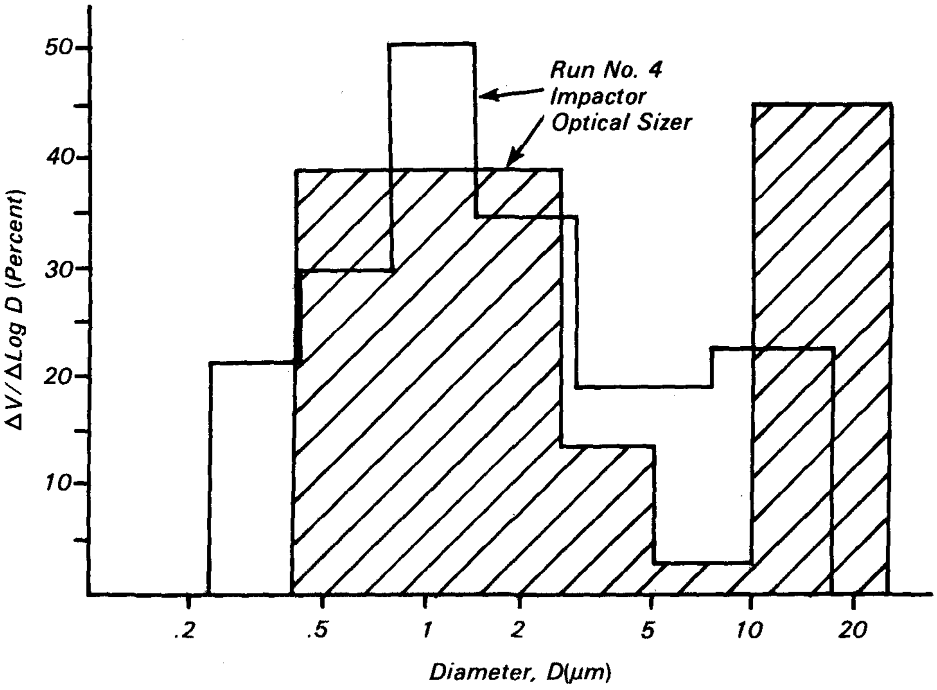

Figure 4. *Particle size vs. volumetric concentration distribution during Day 2 of the field test.*

there are no moving parts in the prototype which would affect the calibration, some form of indicating calibration status is desirable.

Another area for future consideration is modification of the electronics to optimize the gain for loadings at or below the originally specified range of 0.01 to 0.1 grams/meter^3. This could be done by changing the feedback resistors at the detector board and trimming the electrical offsets to lower values.

In its present form, however, this type of instrument should prove to be very useful for field survey work for analysis of size distributions from stationary sources. Recommendations for future work involve additional field trials at sites with different types of fuel, cleanup devices, and loading conditions. To gain confidence in this type of instrumentation, measurements with referee sizing instruments should be taken in parallel.

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