DEVELOPMENT OF A VERSATILE LOW COST FRAUNHOFER DIFFRACTION INSTRUMENT FOR PARTICLE SIZE MEASUREMENT

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INTRODUCTION

With the introduction of charged-couple devices (CCD) and significant improvements in personal computers, a Fraunhofer (small angle forward) diffraction (FD) instrument was developed for determining particle size and size distribution of water mist and aerosol particulates using off-the-shelf equipment. The instrument offers the ability to operate single or multiple scanners either consecutively or concurrently. Additionally, the instrument's ability to integrate the information from two different focal length lens and combine the results into histograms covering a significantly larger particle size range than other instruments represents a significant step in analytical capability. *Also* the small lightweight components of the system allows aerosol measurements to he taken in cramped quarters where other instruments would not fit.

DESIGN BASIS

The system is based primarily on off-the-shelf hardware. The minimum operational components required for a system were a 4 mW helium-neon (HeNe) laser, beam expander, spatial filter, collimating lens, focusing lens, HeNe line filter, neutral density filter, and a linear variable density filter. The only specialty item used to develop this system was an over-the-counter hand scanner, that was converted to a CCD detector. The software used to operate the system was Proimage Version 1.10™, a scanning program developed by Prolab Tech Company, a Borland C/C++ Version 3.0™ program custom developed to reduced the raw data to a finished ASCII data file for spreadsheet manipulation, and Microsoft Excel™, a spreadsheet program for graphically manipulating the data.

PRINCIPLES OF OPERATION - FRAUNHOFER DIFFRACTION

A review article by Weiner discusses in detail the theory and practice of the FD method of particle analysis (1). The experimental set up for use of this technique **is** shown in Figure **1.** This method analyzes the small angle forward scattering of light by an ensemble of small particles contained in the volume of an aerosol defined by a parallel beam of optical radiation. **All** particles present in the defined volume contribute to the scattering of the radiation; consequently, the particle size distribution is measured while absolute number density is not he determined. With the addition of precise measurements of the optical energy incident upon and transmitted through the aerosol cloud, additional data manipulation can give absolute number densities.

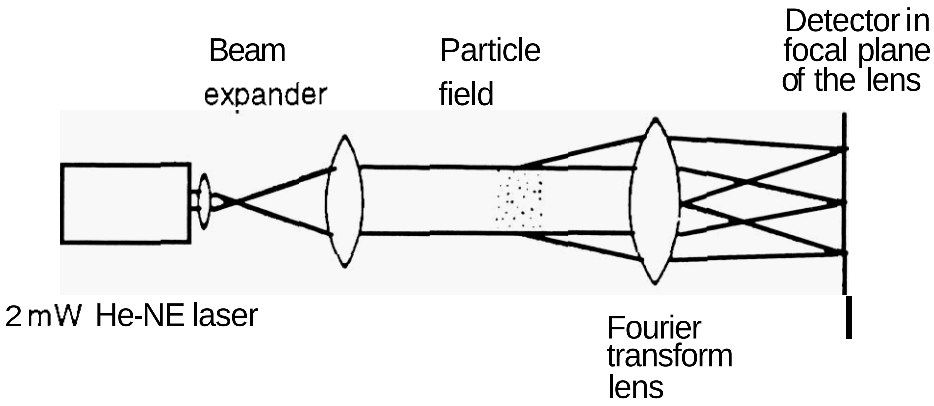

Figure 1. Optical schematic for Fraunhofer apparatus.

In FD measurements the light is scattered by an ensemble of particles into an annulus **as** shown in Figure 2.

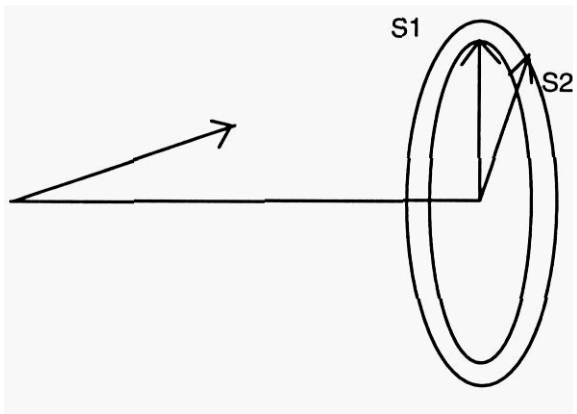

Figure 2. Light scattering geometry.

For this configuration the light energy $L_{S1,S2}$ falling into the annulus is given by

$$L_{S1,S2} = C\pi \sum_{i=1}^{m} N_i \, r_i^2 \left[\left\{ J_0^2(x_i) + J_1^2(x_i) \right\}_{S_1} - \left\{ J_0^2(x_i) + J_1^2(x_i) \right\}_{S_2} \right] \tag{1}$$

Where

$$X_{1,2} = \frac{2\pi}{f\lambda} r_i S_{1,2} \tag{2}$$

C is a constant factor that includes the light intensity, m is the number of annuluses or bins used, r_i is the particle radius, N_i is the number density **of** particles **of** radius r_i, J_0 and J_1 are **Bessel** functions **of** the zeroth and first order respectively, and S is the distance in the detector plane from the unscattered radiation focal position to the detector element being considered (either at S_1 or at S_2). Additionally, f is the focal length of the lens that focuses the radiation onto the detector and λ is the wavelength of the incident radiation.

If the ensemble consists of only a single particle size, then the scattering consists of a **peak** centered on a single annulus where the particle radius and the annulus radius are related by

$$x_i = 1.375 = \frac{2\pi}{f\lambda} r_i S_{1,2} \tag{3}$$

This relationship then is employed to select the values of r_i for various values of $S_{j,k}$. A program was written in Borland C/C++ Version 3.0™ to evaluate Equation 1 directly. The program was directed to permit the determination of a set of particle densities, N_i, which would permit the theoretically determined data set to be brought into agreement with the experimentally determined data set.

To this end, a theoretical data file was calculated directly from Equation 1 using the condition that N_i in Equation 1 was held constant and that the values of λ and f were those of the experimental setup. The incremental steps (r_i) utilized for summation of the detector elements was determined experimentally to be 0.012 mm. Thus Equation 4 becomes:

$$r_i = \frac{(1.375)(0.0006328)(100)}{(2)(3.14159)(0.012)(i-1)} \tag{4}$$

The Bessel functions $J_1(x)$ and $J_0(x)$ were evaluated from their power series expansions and their calculation yielded a value the same as that given in the Bessel function tables within 0.02 percent for all values of x (2). The results of these calculations were then written to a theory data file.

Equation **3** was used to select groupings or bins of particle radii that were used to provide a manageable number of data points for display. The binning method selected contained 36 groupings which were selected so as to replicate a Malvern instrument data set as closely as could be determined. The theory data file was normalized so that the sum of all data elements added to 100.00.

The experimental data sets were collected as two-dimensional bitmap files (400 by 1600) and then reduced to a 1 by 800 file by averaging the successive line scans detector element by detector element. Two scans were made for each experimental determination: (a) a background scan taken with no aerosol particles present and (b) a data scan made with the aerosol present in the beam.

In another Borland C/C++™ program, the data and background scans were subtracted from each other element by element, the resultant file was smoothed by employing a 10-point exponential smoothing function, and the resultant file was binned appropriately for comparison with the theory data file. Then the resultant file was normalized to the total value of 100.00 as was done for the theory file.

Finally, a least squares routine was employed, with the fitting variable being the particle number density, N_i. The value of N_i was changed for each of the bins *so* as to force the theoretical curve to assume the same shape as the experimental data file. The resultant distribution of N_i as a function of r_i, the particle radius, was then written to a final data file for processing in Microsoft Excel™ or some other spreadsheet program.

The calculations for the various diameter means were based on the following standard definitions:

Length-based diameter
$$D_{10} = \sum_{i=1}^{m} N_i D_i \Big/ \sum_{i=1}^{m} N_i \qquad (5)$$

Volume-based diameter
$$D_{30} = \left(\sum_{i=1}^{m} N_i D_i^3 \Big/ \sum_{i=1}^{m} N_i \right)^{1/3} \qquad (6)$$

Sauter Mean Diameter (SMD)
$$D_{32} = \frac{\sum_{i=1}^{m} N_i D_i^3}{\sum_{i=1}^{m} N_i D_i^2} \qquad (7)$$

Surface area-based diameter
$$D_{20} = \left(\sum_{i=1}^{m} N_i D_i^2 \Big/ \sum_{i=1}^{m} N_i \right)^{1/2} \qquad (8)$$

The definition-based equations were directly programmed and were calculated from the number density particle distributions versus particle size.

ADVANTAGES OF A FRAUNHOFER INSTRUMENT

The articles cited provide an extensive description and discussion of the FD technique and discuss its strengths and limitations (1.3 through *6)***.** A summary of conclusions concerning the Fraunhofer diffraction theory method is presented below,

1. The FD instruments are very versatile. They can be used for size distribution analysis of particles or droplets suspended or flowing in any clear liquid, conducting or nonconducting, or when particles or droplets are airborne. By varying the focal length and size of the Fourier transform lens, a large range of particle sizes can be evaluated.
2. The measurement, like most optical measurements, is nonintrusive. No probe disturbs the flow *to* introduce sampling errors.
3. In the range where Fraunhofer diffraction theory is applicable, no calibration is necessary, and the results are independent of refractive index, to an accuracy within 5 percent. Below about 10 µm, however, a systematic error may occur. This does not affect precision or selectivity, both of which are prerequisites for process control.
4. Repeatability is within *3* percent. Resolution is good, provided a lens of the correct focal length is used. In the largest size ranges, resolution is only fair.
5. The Fraunhofer diffraction-based instruments are easy to set up and to operate. Typically, measurements require a few seconds, and results may be obtained in a few minutes at most (fractions of a minute for the instrument described here).
6. Although it is not possible to use the technique when the transmittance is low, the range of concentration over which results are obtainable is comparable with other techniques.
7. The technique is not a single particle counter. It does *not* measure at a single point, rather it measures an ensemble average over a large number of particles rapidly, and over a region of space.
8. Particle shape is not measured. Results are often in terms of an orientation-averaged effective size distribution.
9. Measurements are biased toward slower moving particles. This is true for any instrument sensitive to the number of particles per unit volume of space rather than *to* **flux.** However, for particles moving at the same or nearly the same speed, which is true for the vast majority of liquid-borne particles, the effect is rarely significant.
10. The equivalent depth of field is very large. There is a vignetting problem, which is only significant for the smaller sizes when using very long path lengths far from the receiving lens.
11. In the data analysis, it is assumed that the density is the same for all particles, i.e., independent of size. For a mixture where this is not true, errors will arise.

APPLICATIONS FOR THE FRAUNHOFER INSTRUMENT

The range of possible applications for measuring aerosols with this instrument is only limited by our imaginations. The following list gives some easily identified **areas** of application:

1. Single or multiple scan capabilities
2. Water mist or aerosol *size* distribution changes with distance from the generator
3. Water mist or aerosol/flame interaction - Draft studies
4. Aerosol formation and agglomeration
5. Particulate formation in flames
6. Aerosol or mist reaction with flames

A SAMPLING OF FRAUNHOFER INSTRUMENT RESULTS

Based on the above listed advantages and possible applications for a Fraunhofer instrument, a prototype instrument has been developed for use in measuring aerosols. Tables **1** and 2 show **the** median data, while Figures **4** and ***5*** show the histogram results and reproducibility of the FD instrument on a Malvem Series 2600 calibration reticle, (a glass plate with particles embedded in it) and for a medical aerosol nebulizer. Additionally a histogram of **the** calibration reticle taken with **the** Malvem Series *2600* particle analyzer has been shown for comparative purposes. It should be noted that the Malvem instrument has **31** data bins (points), while the Fraunhofer instrument was designed with **36** data bins (points) for collating and displaying **the** results.

FRAUNHOFER INSTRUMENT - HARDWARE

Since one of the most significant advantages of this instrument is its small size in comparison to instrument presently on the market, a schematic of the largest part of the prototype instrument has **been** include for comparison to other instruments (Figure *6)*. The detector's overall dimension are **25** cm by **13** cm by *20* cm. Improvements in design and construction of a production type instrument should further reduce the detector to approximately half this size. The space needed for the laser and optics will depend upon the focal point of the lens, but should be able to occupy a space similar to that required by the detector, approximately 17 cm by **13** cm by **15** cm.

PARTICLE DATA FOR THE CALIBRATION RETICLE

Malvem Series 2600 particle analyzer — Volume median 46.5 ± 1.9 μm.

TABLE 1 MEDIAN DATA FOR THE CALIBRATION RETICLE ON THE FRAUNHOFER INSTRUMENT

Run Number	Number Median, μm	Surface Median, μm	Volume Median, μm	Sauter Median, μm
1211DT1	45.6	42.1	48.0	45.9
1211DT2	45.6	41.0	48.0	45.4
1211DT3	45.6	41.5	48.0	45.7
1212DT5A	45.6	37.5	48.0	46.5
1212DT5B	45.6	39.4	48.0	47.3
1212DT5C	45.6	40.0	48.0	47.3

DROPLET DATA FOR (MEDICAL) AEROSOL NEBULIZER

TABLE 2 NEBULIZER MEDIAN DATA FOR ND 4.0 AND ND 3.5 FILTERS

Run Number	Number Median, μm	Surface Median, μm	Volume Median, μm	Sauter Median, μm
1212DT2A	4.6	5.2	8.3	6.5
1212DT2B	4.5	5.3	8.3	6.6
1212DT2C	6.1	5.4	8.3	6.9
1212DT5D	4.6	5.1	8.3	6.4
1212DT5E	4.6	5.2	8.3	6.5
1212DT5F	4.6	5.4	8.3	6.8

PARTICLE SIZE DISTRIBUTION - MALVERN SERIES 2600

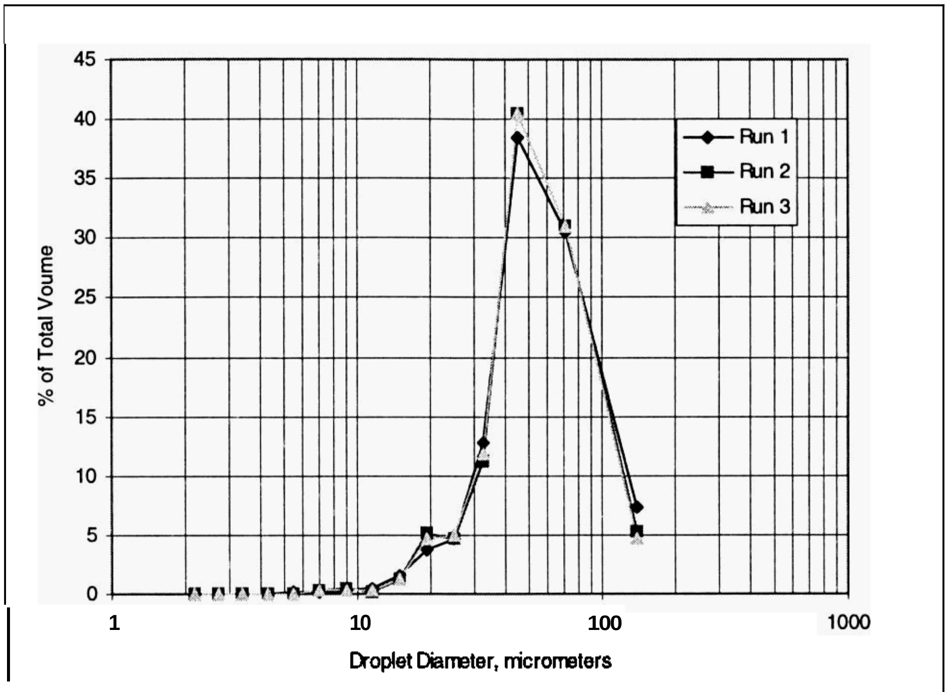

Figure 3. Calibration Reticle on the Malvern Instrument.

PARTICLE SIZE DISTRIBUTION - FRAUNHOFER INSTRUMENT

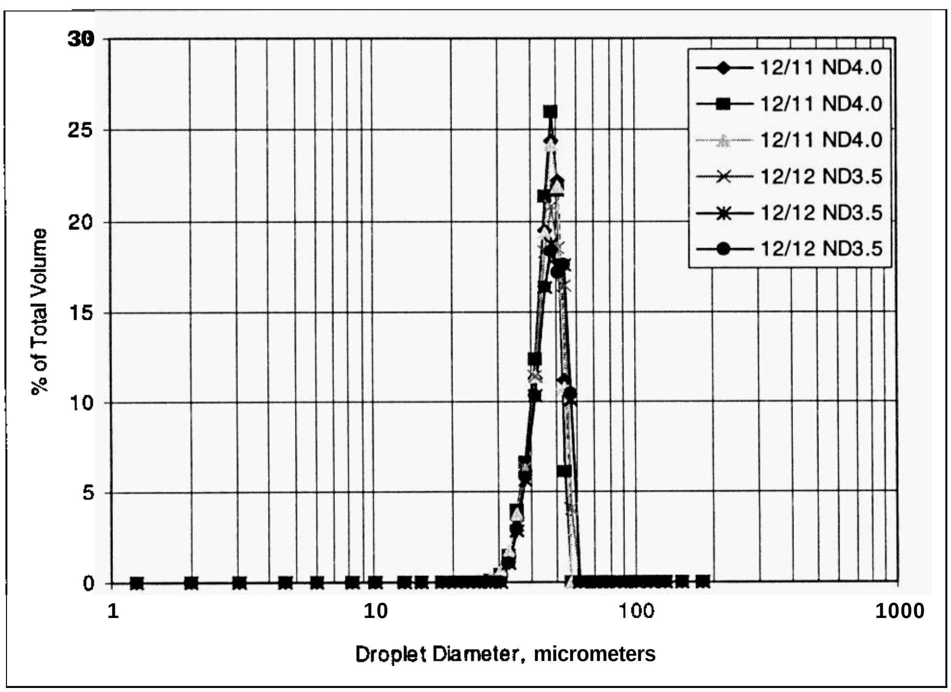

Figure 4. Calibration Reticle on the Fraunhofer Instrument.

DROPLET SIZE DISTRIBUTION- AEROSOL NEBULIZER

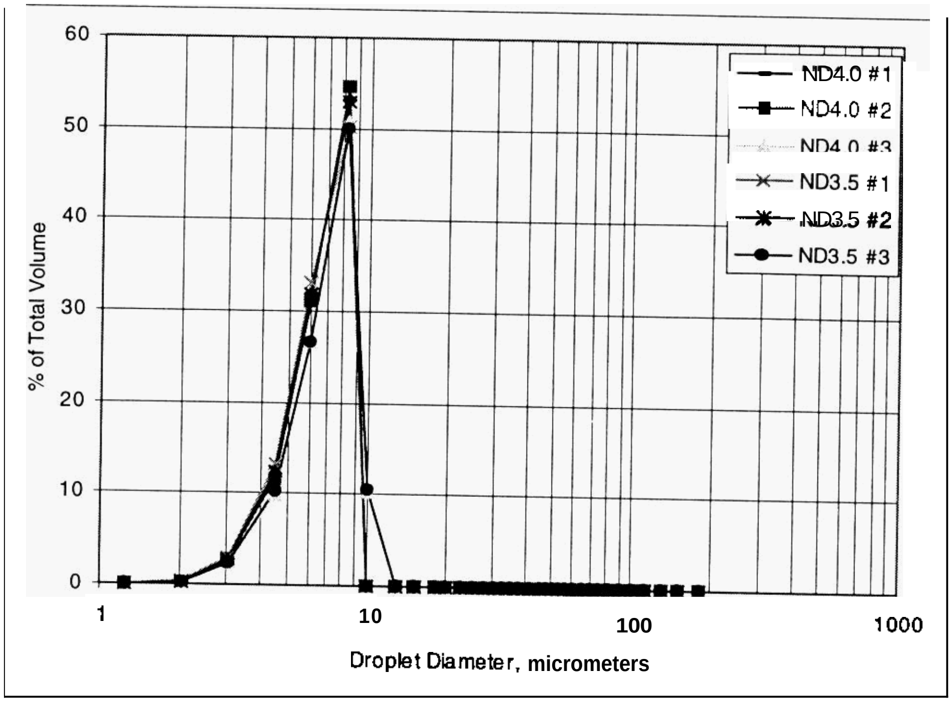

Figure **5.** Nebulizer Aerosol Data from the Fraunhofer Instrument.

FRAUNHOFER DETECTOR SCHEMATIC

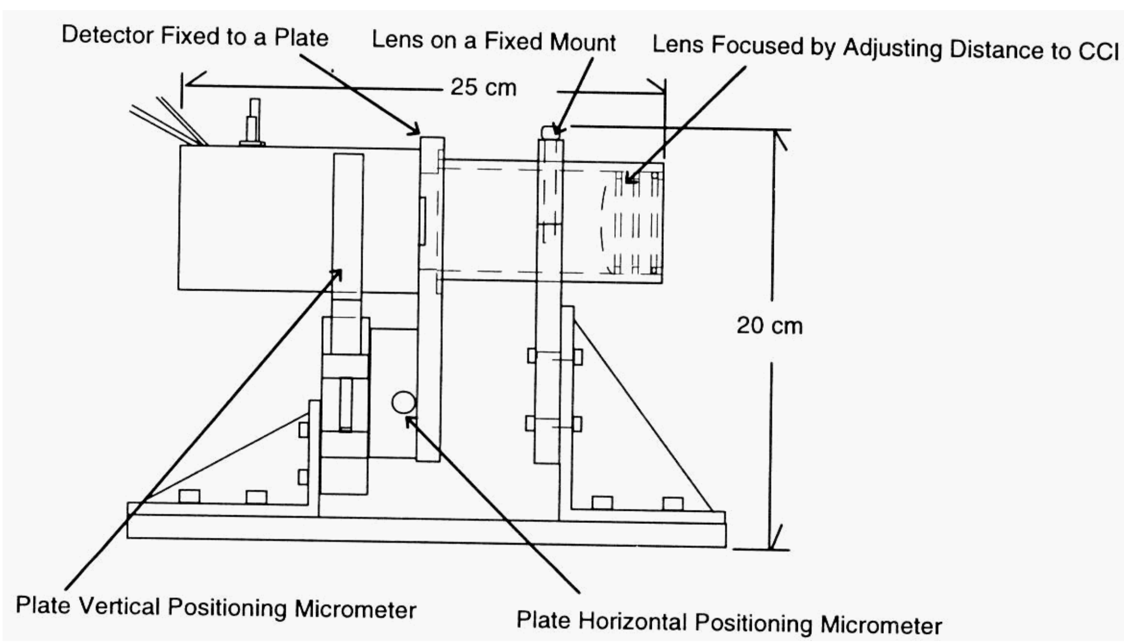

Figure 6. Schematic of the Fraunhofer Detector.

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