Direct-reading Instruments for Aerosols*,† A Review

P. A. Baron

US Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, 4676 Columbia Parkway, Cincinnati, OH 45226, USA

Direct-reading instruments for aerosols have not had the popularity within the industrial hygiene community that similar instruments for gases and vapours have enjoyed. There are several reasons for this: aerosols have complex properties that are difficult to characterize with a single measurement, commercial instruments often do not provide an accurate measure of a useful aerosol property and aerosol instruments are relatively expensive for industrial hygiene use. A variety of instruments are commercially available and are briefly reviewed. Two general classes of instruments used for industrial hygiene measurements are covered: field instruments and research instruments. The International Symposium on Air Sampling Instrument Performance held in Research Triangle Park, NC, USA, in October, 1991 included a workshop on direct-reading aerosol instruments that produced several recommendations to advance the state of the art. The two primary recommendations approved by the symposium attendees were to develop voluntary consensus standards for aerosol mass measuring instruments and optical particle counters and to develop an accurate, portable, direct-reading aerosol mass monitor. Some progress is being made on the latter recommendation through a project supported by the US Bureau of Mines. Other instruments have found specific application in industrial hygiene measurements. A miniaturized condensation nucleus counter is being used to estimate fit factors for respirators. A fibre monitor is used for monitoring asbestos, especially in asbestos abatement operations. Optical particle counters are used for low-concentration aerosols, especially in clean rooms. Aerosol research instruments are being used to evaluate and improve field instrumentation, such as respirable, thoracic and inhalable samplers and cascade impactors. Several such direct-reading instruments are now commercially available that can rapidly measure aerosol concentration and size distribution. These instruments can also be used to make field measurements. Accurate aerosol sampling is often difficult in uncontrolled atmospheres; many direct-reading instrument manufacturers have paid little attention to inlet characteristics of their instruments. Errors due to sampling and internal instrument losses can be large.

Keywords: *Direct-reading instruments; aerosols*

Introduction

There are many aerosol contaminants in workplace environments that can cause detrimental health effects. Monitoring techniques for estimating aerosol contaminant concentrations frequently require that a sample be taken and sent to a laboratory for analysis. However, it is often desirable to obtain concentration information rapidly in order to estimate hazard levels, to evaluate control systems or to provide feedback so that exposed persons can modify behaviour and thus reduce health risk. These instruments can also allow the laboratory-analysed samples to be taken in an efficient manner, *e.g.*, in the most appropriate location and for an optimum duration. Direct-reading instruments can fulfil these needs and portable instruments of this type are often the most convenient to use.

Some areas related to direct-reading aerosol instruments are surveyed. Several commercially available portable instruments are discussed briefly, as these are generally of most interest to industrial hygienists, and some directions of current research will be indicated. A discussion of some aerosol research instruments is included. These discussions do not attempt to be comprehensive, as there are publications available on measurement techniques.[1,2]

A recent workshop on air sampling instruments, held at a symposium sponsored by the American Conference of Governmental Industrial Hygienists (ACGIH),[3] produced a set of recommendations regarding direct-reading aerosol instruments. These recommendations will be summarized. The full set of recommendations from all the workshops at this symposium has been published.

The last area of interest is peripheral to direct-reading instruments, but can significantly affect measurement accuracy. Sampling efficiency, internal instrument losses, and instrument calibration are all important factors in this regard.

Direct-reading Instrumentation

Different types of instruments are used for making workplace measurements of aerosols. These instruments are used to obtain specific information about the aerosols. The most common type of measurement is to determine the mass concentration of the aerosol. Many regulatory exposure limits are based on mass concentration, as the health effect due to exposure is proportional to aerosol mass. Within this category, several types of mass measurements are made, including those for respirable mass (representing particles that reach the alveolar region), thoracic mass (particles reaching the thoracic region) and inhalable (or total) mass.[4] For direct-reading instruments, a pre-classifier is often used to remove non-respirable or non-thoracic particles, so that the instrument only detects the desired fraction. Respirable mass measurements are perhaps the most common type of aerosol measurement because insoluble particles reaching the alveolar region of the respiratory tract are removed from the lung relatively slowly and have the greatest time to induce adverse health effects. Many of the instruments that purport to measure mass are unsatisfactory because of a lack of accuracy, portability or ease of use. In addition, the specific requirements of some applications may preclude the use of certain collection or detection techniques, *e.g.*, explosive

* Presented at the Conference on Modern Principles of Workplace Air Monitoring: Pumped and Diffusive Sampling for Contaminants, Geilo, Norway, February 15–18, 1993.

† Mention of a product or company name does not constitute endorsement by the Centers for Disease Control and Prevention.

atmospheres in coal mines necessitate the use of spark-free (intrinsically safe) instruments.

For certain types of measurements, the number concentration of an aerosol is useful. One such measurement is the leakage rate of respirators. At low aerosol concentrations, measurement of the number concentration of particles inside and outside the respirator is a useful way of determining penetration of an aerosol through and around the respirator. Number concentration is also a useful measure of low-concentration aerosols, such as in clean rooms.

The behaviour of aerosols often measured in the workplace is largely governed by the particle aerodynamic diameter. For instance, the settling and impaction of particles within the respiratory system can be explained using the aerodynamic diameter. Measurement of the aerosol aerodynamic diameter size distribution is therefore useful in understanding aerosol behaviour.

With the variety of chemicals to which workers can be exposed, it is often useful to determine specific components of an aerosol. Thus, instruments that measure only particles with a certain chemical, element or shape can be useful. There have been several attempts to make field analytical instruments specific for certain elements, *e.g.*, lead[5] and other elements,[6] but none of these are portable instruments.

There are several particle properties that are important in different applications. In monitoring for the control of detrimental health effects, the toxicity of individual particles is clearly important. Health effects from aerosol exposure often depend directly on particle chemistry, although in certain instances they may depend on particle size (*e.g.*, respirable) and shape (*e.g.*, asbestos fibres). Unfortunately, there are very few direct-reading aerosol instruments capable of providing qualitative analysis. It is difficult enough to perform such analyses, especially for multiple analytes, on collected samples in a laboratory. However, for some specific chemicals, the development of such instruments may be warranted.

Light-scattering Instruments

Photometers or nephelometers are perhaps the most commonly used direct-reading aerosol instruments. These have been commercially available for over 20 years and are available in a variety of configurations.[7] The detection mechanism is depicted in Fig. 1. A light source illuminates the detection volume through which the aerosol passes. Light scattered from the particles is collected and detected. The angle of light detection relative to the direction of illumination will determine the relative detection efficiency for small and large particles. Large particles are detected more efficiently at small scattering angles, while sub-micrometre particles scatter more uniformly in all directions. Many of the particles of interest are in the Mie scattering range. For simple geometric shapes such as spheres and rods, the Mie scattering pattern can be predicted theoretically.[8] However, for most dust particles, the complex and varied shapes do not warrant even attempting the difficulties of predicting their scattering patterns.

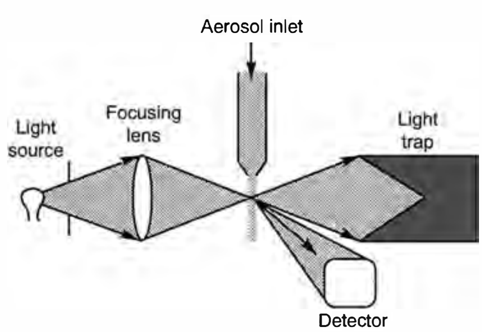

Fig. 1 Optical detector for aerosol particles

Each instrument uses a specific range of scattering angles. In addition to size, particle refractive index and shape also play an important role in the direction and intensity of scattering. Particles smaller than 0.3 μm in diameter are detected very inefficiently, if at all, as scattering decreases as the fourth power of particle diameter in this size range. Large particles scatter light proportionally to their cross-sectional area. Maximum detection efficiency generally occurs in the 0.5–2 μm particle diameter range. The shape of the particle volume (or mass) response curve is indicated in Fig. 2. The fall-off in the 1–10 μm range is approximately similar to the respirable dust curve,[9] so these instruments are often used as indicators of respirable dust concentration. Of course, the calibration of the instrument for this purpose is important, because the calibration will change with particle size distribution, refractive index and shape.

The instrument measures the light scattered from all particles present in the detection volume and, therefore, is fairly sensitive to low concentrations of aerosol. The aerosol can be measured on a continuous basis, and the components of the detection system are relatively common and inexpensive. The measured concentration is independent of the flow rate through the sensing volume. Hence the instrument can be used at a variety of flow rates; some instruments use 'passive sampling', *i.e.*, the natural convection in the environment, to push the aerosol through the sensor. Hence the photometer is useful as a relatively inexpensive, approximate, real-time indicator of aerosol concentration.

Improvements to photometers are not likely to make these instruments more useful than current instruments for typically desired measurements of workplace aerosols, such as mass, respirable mass or other particle properties. The intrinsic response to scattered light depends in a complex way on particle shape, refractive index and size. For instance, changes in particle size distribution or chemistry can readily cause changes of 50% or more in the detected light scattering signal for the same particle mass.

These instruments, because of their relative simplicity, can be made small and portable. Hence they are convenient for sniffers in providing approximate indications of aerosol concentration. In this vein, they can be used for locating aerosol sources, evaluating respirators, evaluating control systems or determining approximate concentrations of respirable dust.

Optical particle counters (OPCs) are very similar to photometers in principle (Fig. 1), except that the detection volume is much smaller and the aerosol flow rate through the detection volume is carefully controlled so that particle

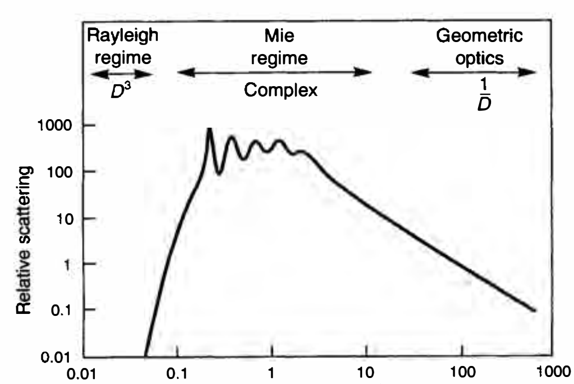

Fig. 2 Light scattering per mass of aerosol as a function of particle diameter

concentration can be determined.[7] The signal from each particle generally increases with increasing particle size, so that some size distribution information can be obtained from these instruments. These instruments may be used for low-concentration measurements, since single particles are counted. They have been used for clean room measurements.

OPCs are generally more sophisticated than photometers, requiring better control of airflow, including a sheath air system and more complex electronics. A great deal of literature and many commercial OPC instruments exist, indicating a mature technology. As with photometers, it is unlikely that there will be any real breakthroughs in improvements for specific measurements. However, the light-scattering detection principle is very sensitive and well understood, so that it is possible to combine the OPC principle with other detection or particle separation mechanisms to produce an instrument responsive to some desired particle property. Examples of such an approach include aerodynamic particle sizers, which use nozzle acceleration, and fibrous aerosol monitors, which use electrostatic alignment. These instruments are discussed further below.

Detection of light transmission is another approach to aerosol particle detection. However, the sensitivity is not as high as for light scattering and this approach is used for high-concentration aerosols, such as in smoke stacks, or in environmental measurements, where long measurement path lengths can be used.

Piezoelectric Microbalance

The piezoelectric balance consists of a piezoelectric crystal on which particles are deposited by electrostatic precipitation or impaction (Fig. 3).[10] The collected mass is measured from the change in resonant frequency of the crystal. Because the particles must couple to the crystal surface, the surface must be frequently cleaned. Some particles may not couple well to the surface. One end of a chain or fibre may attach to the surface while the other end moves freely and does not couple to the crystal surface; large particles may not adhere sufficiently to the crystal surface to change the resonant frequency, and some collected liquids may flow to the nodes of vibration, also resulting in reduced sensitivity. A recent evaluation of a piezobalance-based cascade impactor found that highly charged particles can cause measurement biases.[11]

These instruments are available in both a single-stage, hand-portable instrument (Model 8510, TSI, St. Paul, MN, USA) and multiple-stage, cascade impactor instruments (Model C-1000A, QCM Research, Laguna Beach, CA, USA; PC-2, California Measurements, Sierra Madre, CA, USA). The hand-portable instrument can be used with reasonable accuracy for certain types of aerosols that are primarily respirable. This instrument uses an electrostatic precipitator and is not designed to be safe for use in explosive atmospheres.

Condensation Nucleus Counters

There is a commercially available portable condensation nucleus counter (Portacount, TSI) that has been used primarily for quantitative fit testing of respirators.[12] This device uses an ambient aerosol as a challenge aerosol. The condensation nucleus counter (CNC) works by passing the aerosol through a supersaturated vapour (Fig. 4). The vapour condenses onto the particles so that they grow to a uniform size. The particle concentration is determined by counting with an OPC or measuring with a photometer. These instruments are in relatively common use and have been accepted by the Occupational Safety and Health Administration as an alternative technique for quantitative fit testing. There are also miniature, fixed-location versions of the condensation nucleus counters that have been used for clean-room monitoring because of the CNC's ability to detect sub-micrometre particles.

Oscillation Microbalance

The tapered element oscillating microbalance (TEOM) (Rupprecht and Patashnick, Albany, NY, USA)[10] currently belongs in a class by itself, as there are no other commercially available instruments that use a similar sensing element. It is not available as a portable instrument, but is included here as the general technique shows promise and is in an area of current development. The TEOM uses the resonant frequency of a tapered oscillating tube, on the end of which is a particle collection element, to determine the mass of the collected particles (Fig. 5). The principle is the same as that of a pendulum, with the collected mass decreasing the resonant frequency of the sensor. The collection element is typically a

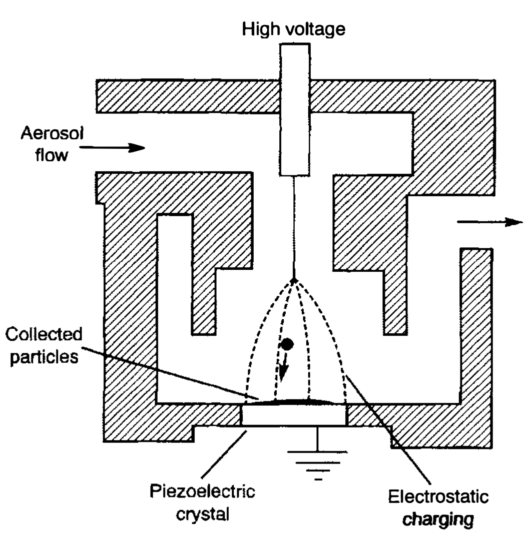

Fig. 3 Piezoelectric detector with electrostatic precipitator for particle collection (Model 8510, TSI)

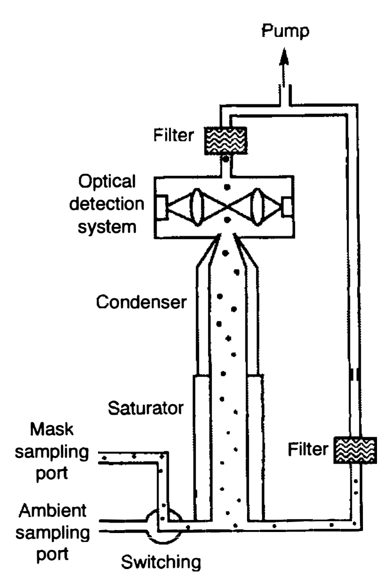

Fig. 4 Condensation nucleus counter (PortaCount, TSI) sensor

small filter. At a sampling rate of 3 l min^{-1}, the manufacturer estimates the mass resolution to be ±15 µg m^{-3} for a 2 min measurement. The coupling of the particles to the filter surface is usually much better than that for the piezoelectric crystal since the resonant frequency is much lower and the vibrational motion is parallel to the surface rather than perpendicular. Particles also adhere to the rough surface of a filter better than the smooth surface of a crystal. Hence these instruments are probably the most accurate direct-reading instruments for particulate mass. One version of this instrument has been certified for PM-10 ambient air monitoring by the Environmental Protection Agency.

However, the instrument cannot be used as a portable monitor. Although the sensor is relatively compact, it is sensitive to temperature changes and vapour (*e.g.*, water) condensation, so the air entering the sensor must be conditioned to a constant, higher than ambient temperature. The conditioning system makes the instrument large, expensive and relatively immobile.

There was a development programme some years ago to build a device based on the TEOM sensor that could provide a respirable dust mass readout at the end of a work shift.[13] This device worked successfully, but was not commercialized. With some additional research and development, a device based on the TEOM or similar oscillating sensor principles would be a very useful tool for compliance and research in the occupational and indoor environment.

Another instrument based on the oscillation of filter-collected aerosol was marketed for some time by Hund (Model MESA, Helmut Hund, Wetzlar, Germany). This device was based on a filter tape collection system that combined both mass measurement (from the resonant oscillation frequency of a clamped section of tape) and photometer measurement. The oscillating mass measurement was subsequently removed from the MESA instrument because of the cost and complexity of the mass detection mechanism.

A device now under development by MIE (Bedford, MA, USA) is based on a circular filter clamped in a holder. The mass collected on the filter is sensed by the change in resonant frequency of the filter, which is made to vibrate like a drum. This effort is being supported by the US Bureau of Mines and is currently in its initial phase, so no further information is available.

β-Radiation Attenuation Monitors

Several devices have been developed that use the attenuation of β-radiation to indicate particle mass collected on a thin film or filter. The mass is approximately proportional to the difference in attenuation of β-radiation before and after the particles are collected. The radiation counting process limits the precision with which mass measurements can be performed, thus limiting the sensitivity of the instrument. The radiation scattering that produces the observed attenuation is a function of electron density within the particles.[10] For example, hydrogen-containing materials tend to have a lower attenuation than higher atomic mass elements. Several portable instruments of this type were marketed in the 1970s and early 1980s (GCA, now MIE), but are no longer available. These instruments required sampling periods from 1 min to hours, depending on concentration. There are several commercial fixed-location tape samplers that are used to monitor environmental concentrations of aerosol. In this application, the instrument response time is not as critical, so sampling times of ≥1 h are acceptable.

Aerodynamic Particle Sizers

There are several commercial instruments based on the detection of particles with scattered light combined with particle acceleration. These instruments attempt to measure a useful parameter of aerosol behaviour directly, namely the aerodynamic diameter. These are basically research instruments that can be used for size distribution measurement in the field. The most common instrument of this type is the aerodynamic particle sizer (APS3300, TSI).[14] It uses the accleration of particles through a nozzle and measurement of particle velocity to estimate aerodynamic size (Fig. 6). A computer provides a sophisticated display of size distribution (0.5–30 µm) and allows the calculation of a number of other parameters. The acceleration field of this instrument is high enough that true aerodynamic diameter is not measured directly and adjustments have to be made for particle density and shape. Liquid particles may also distort in the acceleration field and appear smaller. Because of the more complex detection system, coincidence artefacts can appear in the detected size distribution. Phantom particles are produced throughout the detected size range, mainly as a result of partially detected small particles.

Another instrument that uses a similar detection system is the Aerosizer (Amherst Process Instruments, Amherst, MA, USA).[14] This device uses a critical flow nozzle as the particle accelerating device, resulting in sonic flow. This higher velocity requires even larger corrections to be made for calculating aerodynamic diameter. The Aerosizer has a larger measurement size range (0.2–200 µm) than the APS and can be used at higher concentrations.

Another instrument, developed in Russia, is marketed by GIV (Breuberg, Germany). There have been no published evaluations of this instrument, so it is difficult to assess its utility. The instrument is currently being improved by GIV in

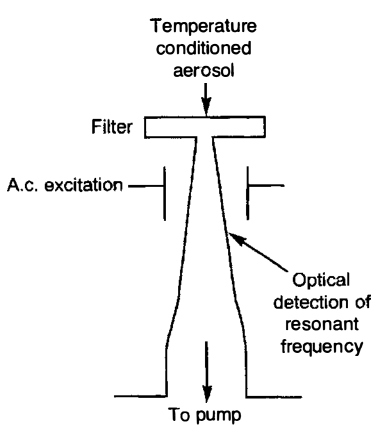

Fig. 5 Tapered element oscillating microbalance (TEOM, Rupprecht and Patashnick) sensor

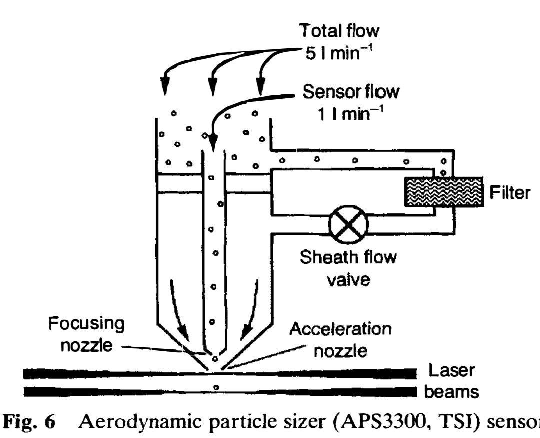

Fig. 6 Aerodynamic particle sizer (APS3300, TSI) sensor

cooperation with the developers. This device uses an accelerating nozzle, but measures the particle acceleration in front of the nozzle. The acceleration is lower and an improved detection system reduces coincidence problems. The lower acceleration also has the advantage of reducing correction factors for particle density and shape. The low flow rate through the small sensing volume allows measurements of high aerosol concentrations, as in powder analysis, but may make it difficult to measure low concentrations.

Another instrument, the electric single particle aerodynamic relaxation time analyser (ESPART, Hosakawa Micron International, Osaka, Japan),[14] accelerates particles by using either an acoustic or an electric field (for charged particles). The commercial version of this device is expensive and large and is primarily intended for measuring the size and charge of toner dust particles. However, there are several research versions in use that are more mobile. As the particle velocity relative to the surrounding air is relatively low, only small corrections are needed to estimate aerodynamic diameter. At a single operating frequency, the instrument has a sizing range of about 1.5 orders of magnitude. The frequency can be changed to extend the range, but this requires recalibration of the system.

Fibrous Aerosol Monitors

The fibrous aerosol monitor (Models FAM-1 and FM7400, MIE) was developed primarily to measure asbestos fibres.[14,15] The instrument operates by aligning fibres in a high-voltage oscillating electric field. The oscillation rotates the fibre in a plane perpendicular to the illumination from a laser beam. A detector senses the scattered light at right-angles to the laser beam (Fig. 7). The scattered light is sensed as a series of pulses for fibres and a relatively constant signal for compact particles. Hence fibres are preferentially detected and counted.

The fibrous aerosol monitor has been widely used for monitoring asbestos removal operations. It provides a real-time indication of fibre concentration to evaluate the controls used to contain the asbestos aerosol. The instrument has not been demonstrated to be sufficiently accurate to replace the standard filter collection/phase contrast light microscope method for fibres.

Another instrument operating on similar principles, but using a multidetector light-scattering system rather than fibre rotation, is under development by Hygenius (FACT-1000, Hygenius, Mississauga, Ontario, Canada). The instrument uses a high-speed data processing system to analyse scattering patterns in real time and classify particles according to length and diameter. The classified particle data are stored for readout and further analysis.

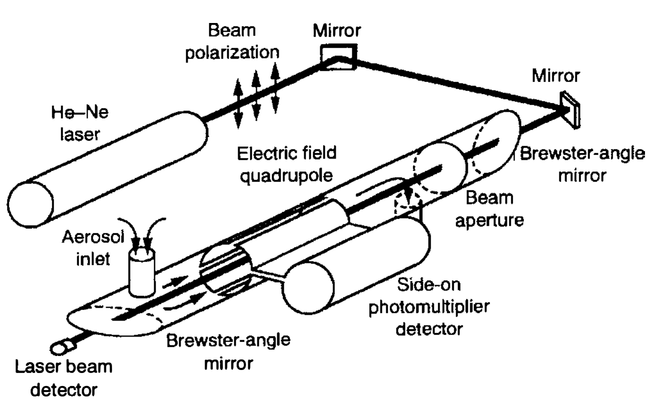

Fig. 7 Fibrous aerosol monitor (FAM-1, MIE) sensor

Recommendations of ACGIH Workshop

There is clearly room for improvement of direct-reading aerosol instruments for use in industrial hygiene. A recent workshop on direct-reading aerosol instruments, sponsored by the ACGIH,[3] produced a series of recommendations addressing some areas of improvement. The recommendations are being made to instrument manufacturers and to various national and international groups, including national industrial hygiene organizations, the American Society for Testing Materials (ASTM), American National Standards Institute (ANSI), the European Standards Organization (CEN) and the International Standards Organization (ISO).

The first recommendation was to develop voluntary consensus standards on specifications, calibration and operation of direct-reading aerosol instruments. The standards should be developed for two specific types of instruments: those measuring number concentration and those measuring mass concentration. Part of this recommendation is to develop guidelines for manufacturers on how to present data on their instruments. This part could be implemented as a separate effort, as a full consensus standard usually takes many years. Such standards would reduce some of the confusion that results when comparing instrument manufacturers' specifications for their products.

The second recommendation focused on the need for an accurate, portable, direct-reading aerosol mass monitor. A variety of instruments are commercially available, but they measure a surrogate parameter for mass, *e.g.*, photometers measure light scattering. These instruments need calibration for the specific aerosol size and material being measured. Microbalances are available, some based on piezoelectric crystals and others based on the tapered element oscillator. The piezobalances have problems with non-uniform sensitivity on their surface, frequent cleaning requirements and adequate coupling of collected particles to the crystal surface for various types and sizes of particles. The tapered element oscillating microbalance (TEOM) meets most of the requirements, but is not available in a portable instrument.

This recommendation has already been acted upon. As mentioned previously, the US Bureau of Mines, responding to a request by the US Mine Safety and Health Administration, has funded the development of a direct-reading mass monitor based on an oscillating filter membrane.

Another recommendation was to provide additional education and promotion in the industrial hygiene community to utilize more fully the capabilities of direct-reading aerosol instrumentation. Some possible mechanisms for providing this education could be through development of video training tapes, short courses and improved instructional materials.

Finally, it was recommended that manufacturers follow quality assurance guidelines for the manufacture of their instruments, *e.g.*, Guides 9000–9004 produced by the International Standards Organization. Such an approach might remove some of the problems that have been observed in the past when instruments were produced that were unreliable. Marketing of such instruments resulted in users being discouraged from using similar instruments.

Sampling Issues

Although sampling efficiency is a more general aerosol measurement issue, it also applies to direct-reading instrumentation. Because of the ease with which numbers can be obtained with direct-reading instruments, sampling issues are often overlooked. The sampling biases produced at the inlet of an aerosol measuring system can be as great as or greater than some of the biases noted in the discussion of various instrument sensors. The inlets of many instruments consist of a tube protruding from the side of the box enclosing the sensor. Little guidance is given to the user with regard to sampling arrangements or an indication of potential losses under various wind conditions. Recent work on thin-walled inlets has resulted in empirical algorithms for calculating sampling efficiencies.[16] The situation with the sampling inlet projecting slightly from the surface of the instrument is represented better as a blunt sampler. This is an area of active research, so there is not a great deal of guidance for instrument users.[17]

Many of the instrument sensors require that aerosol entering the instrument be uniformly distributed in the flow stream. If there is a pre-classifier upstream of the sensor, this may not always be the case. For instance, a cyclone will create a vortex in the exit stream. The aerosol in this stream is likely to be non-uniformly distributed. Similarly, aerosol passing through an impactor is also non-uniformly distributed. For instruments that use impactors to deposit the detected aerosol on a surface, the deposit may not be uniform. Recent work indicates that larger particles sampled with a circular nozzle impactor will be deposited in a ring, while smaller particles will be deposited with something approaching a normal distribution.[18] Such deposits may have important consequences for instruments that assume uniform sample deposition.

Further, aerosol losses may occur within the instrument by various mechanisms. If the instrument inlet and sample handling lines are not properly designed, particles smaller than about 0.1 μm may diffuse to the inlet and sample line walls; particles larger than about 3 μm in diameter may exhibit significant settling and impaction. In small-diameter sample handling lines, electrostatic losses may occur with charged particles, especially if the inlet and lines are non-conductive.[19,20] Particles larger than 15 μm typically exhibit order-of-magnitude or greater biases during aspiration into the inlet. In addition to losses, particle deposition on sensor surfaces may produce biases that increase with measurement time. For instance, some simple photometers expose the light source and detector windows to the aerosol stream, resulting in increased light scattering detected by the instrument. A detected increase in signal level occurs with aerosol exposure, biasing the measurement.[21]

Conclusions

A variety of aerosol instrumentation for monitoring in the workplace is available and new instruments are being developed. However, further work is needed, not only to improve the accuracy of these instruments but also to ensure that they are being used properly. This requires efforts by both the instrument manufacturers and the industrial hygiene community to provide proper information and education in the use of these instruments.

References

1 *Aerosol Measurement: Principles, Techniques, and Applications*, ed. Willeke, K., and Baron, P., Van Nostrand Reinhold, New York, 1993, p. 876.
2 *Air Sampling Instruments*, ed. Hering, S. V., American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 7th edn., 1989, p. 612.
3 Baron, P., *Appl. Occup. Environ. Hyg.*, 1991, **8**, 405.
4 Soderholm, S. C., *Ann. Occup. Hyg.*, 1989, **33**, 301.
5 Smith, W. J., Dekker, D. L., and Greenwood-Smith, R., *Am. Ind. Hyg. Assoc. J.*, 1986, **47**, 779.
6 Baron, P. A., in *Symposium—Advances in Air Sampling*, ACGIH, Asilomar, CA, 1988, p. 205.
7 Gebhart, J., in *Aerosol Measurement: Principles, Techniques, and Applications*, ed. Willeke, K., and Baron, P., Van Nostrand Reinhold, New York, 1993, p. 313.
8 Kerker, M., *The Scattering of Light and Other Electromagnetic Radiation*, Academic Press, New York, 1969, p. 666.
9 American Conference of Governmental Industrial Hygienists, *Ann. Am. Conf. Gov. Ind. Hyg.*, 1984, **11**, 23.
10 Williams, K., Fairchild, C., and Jaklevic, J., in *Aerosol Measurement: Principles, Techniques, and Applications*, ed. Willeke, K., and Baron, P., Van Nostrand Reinhold, New York, 1993, p. 296.
11 Horton, K. D., Ball, M. H. E., and Mitchell, J. P., *J. Aerosol Sci.*, 1992, **23**, 505.
12 Cheng, Y. S., in *Aerosol Measurement: Principles, Techniques, and Applications*, ed. Willeke, K., and Baron, P., Van Nostrand Reinhold, New York, 1993, p. 427.
13 Patashnick, H., and Rupprecht, G., *Personal Dust Exposure Monitor Based on the Tapered Element Oscillating Microbalance*, Rupprecht and Patashnick, Albany, NY, 1983.
14 Baron, P. A., Mazumder, M. K., and Cheng, Y. S., in *Aerosol Measurement: Principles, Techniques and Applications*, ed. Willeke, K., and Baron, P. A., Van Nostrand Reinhold, New York, 1992, p. 381–409.
15 Lilienfeld, P., Elterman, P., and Baron, P., *Am. Ind. Hyg. Assoc. J.*, 1979, **40**, 270.
16 Hangal, S., and Willeke, K., *Environ. Sci. Technol.*, 1990, **24**, 688.
17 Vincent, J. H., *J. Aerosol Sci.*, 1987, **18**, 487.
18 Sethi, V., and John, W., *Aerosol Sci., Technol.*, 1993, **18**, 1.
19 Liu, B. Y. H., Pui, D. Y. H., and Szymanski, W., *Ann. Occup. Hyg.*, 1985, **29**, 251.
20 Baron, P. A., and Deye, G. J., *Am. Ind. Hyg., Assoc. J.*, 1989, **51**, 51.
21 Willeke, K., and DeGarmo, S. J., *Appl. Ind. Hyg.*, 1988, **3**, 263.

Paper 3/03212D
Received June 4, 1993
Accepted September 3, 1993