Aerosols I & II

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Objectives

– Know aerosol terms
– Describe commonly used techniques for aerosol sampling and size analysis
– Select appropriate aerosol sampling devices
– Explain the size distribution concept
Introduction

• Particulate sampling is different compared to gas sampling. Particle sampling methods must consider physical as well as chemical properties
  – Particle behavior and toxicity depends on size, shape, and density, as well as chemical makeup
  – Often specific particle sizes must be collected
  – Particles are difficult to capture

• Aerosols
  – Solid or liquid particles dispersed in a gaseous medium
  – Classically, a 2 phase flow problem

Definitions

• Dusts
  – Dry particulate matter
    • < 1 μm to 1 mm
    – Formed by grinding, crushing, etc.
• Fumes
  – Fine solid aerosol particles
    • 0.01 μm primary particles to 1 μm agglomerates
    – Formed by condensation of vaporized solid material
      • Welding, smelting, etc.
• Mists
  – Spherical droplet aerosols
    • From a few microns to over 100 μm
    – Produced by mechanical processes like splashing, bubbling, spraying, etc.
• Fogs
  – Droplet aerosols, 1 to 10 μm
  – Produced condensation from vapor phase
• Smokes
  – Complex mixtures of solid and liquid aerosol particles, gases, and vapors
    • 0.01 to 1 μm in diameter, with larger agglomerates
    – Caused by incomplete combustion.
• Fibers
  – Elongated particles
    • length to width ratio > 3:1

• Polydispersed
  – Wide range of particle sizes
• Monodispersed
  – Narrow range of particle sizes
Particle formation mechanisms:

*Primary particle formation* results from mechanical disruption of the earth’s surface.
- Direct generation of sand/dust aerosols
- Sea-spray aerosols resulting from bursting bubbles of entrained air.

*Secondary particle formation* results from Gas-to-particle conversion

----- Homogeneous nucleation
- $N$ molecules form a stable cluster by diffusion induced collisions
- Cluster continues to grow
- Typically, a stable cluster is ~1 nm and contains 10’s of molecules
- Aqueous phase chemical reactions (oxidation of SO$_2$ to aerosol SO$_4$)

----- Combustion particle formation
- Results from the incomplete combustion of fuel (soot carbon etc)

Particle Composition

Primary aerosols: soil dust – iron, calcium, silicates; Sea-spray: sodium, chloride, calcium, sulfate, potassium, etc

Secondary aerosols: sulfates, nitrates, organics, halogens,
- Combustion aerosol: sulfates, nitrates, elemental carbon, organic carbon, soot
- Sulfates are derived from oxidation of SO$_2$
- Nitrates are derived from oxidation of NOx
- Organic (acids) derived from oxidation of VOC’s from plants, cars, etc.
### Particle Characteristics of Particles

<table>
<thead>
<tr>
<th>Equivalent Mass</th>
<th>0.0001</th>
<th>0.001</th>
<th>0.01</th>
<th>0.1</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1,000</th>
<th>10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle (°)</td>
<td>0.0001</td>
<td>0.001</td>
<td>0.01</td>
<td>0.1</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td>1,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Stokes Diameter</td>
<td>100,000</td>
<td>100</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td>1,000</td>
<td>10,000</td>
<td></td>
</tr>
<tr>
<td>Aerodynamic Diameter</td>
<td>1000</td>
<td>100</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td>1,000</td>
<td>10,000</td>
<td></td>
</tr>
</tbody>
</table>

#### Particle Diameters

- **irregular particle**
  - \( d_s = 5.0 \mu m \)
  - \( \rho_p = 4000 \text{ kg/m}^3 \)
  - \( \phi = 1.36 \)

- **Stokes' equivalent sphere**
  - \( d_s = 4.3 \mu m \)
  - \( \rho_p = 4000 \text{ kg/m}^3 \)

- **Aerodynamic diameter**
  - \( d_a = 8.6 \mu m \)
  - \( \rho_p = 1000 \text{ kg/m}^3 \)

\[ V_{TS} = 2.2 \text{ mm/sec} \]

Comparison of equivalent volume diameter, Stokes diameter, and aerodynamic diameter.
Aerodynamic diameter

Aerodynamic diameter \( d_a \) is the diameter of a spherical particle of density \( \rho_0 = 1 \text{ g/cm}^3 \) which has the same terminal settling velocity in air as the particle of interest.

\[
d_a = d_p \left( \frac{\rho_p}{\rho_0} \right)^{1/2}
\]

Stokes diameter \( d_s \) is the diameter of a spherical particle that has the same density and terminal settling velocity in air as the particle of interest.

\[
d_s = d_s \left( \frac{\rho_b}{\rho_0} \right)^{1/2}
\]

where \( \rho_b \) is the bulk density.

PM2.5 = particles with aerodynamic diameters < 2.5 microns

PM10 = particles with aerodynamic diameters < 10 microns

Motion of Airborne Particles

- Particles (aerosols) tend to remain suspended in the air until attractive forces act on them.
  - Settling velocity for small particles is less than ordinary air currents
  - Attractive forces cause particles to adhere to each other and to surfaces, causing them to be removed from the air
  - Smaller particles are more difficult to dislodge
Motion of Airborne Particles

- Sampling methods capture particles by various aerosol deposition mechanisms
  - Sedimentation (gravity)
  - Impaction
  - Interception
  - Diffusion
  - Other
    - Electrostatic attraction
    - Thermal deposition
    - Etc.

Motion under gravity

\[ F_D = \frac{3\pi \eta D_p u_x}{C_c} \]

- \( F_D \) — Drag force
- \( F_B \) — Bouyance force
- \( mg \) — Gravitational force
**Settling Velocity**

\[
\ln(\text{Vts}) = -8.799 \times 10^{-3}x^3 - 2.024 \times 10^{-2}x^2 + 2.337x - 6.278
\]

where \(x = \ln(\text{diam})\) in microns; \(\text{Vts}\) in cm/s

Unit density spheres, sizes from 0.1 to 1000 um

**Particle Removal mechanisms**

- Sedimentation
- Impaction
- Interception
- Diffusion
- Electrostatic

These mechanisms can act together and strongly depend on the particle size
Sedimentation

- Larger particles can be captured by sedimentation (gravity)
- Note, primary (smaller) particles form larger agglomerates, with much faster settling times

Impaction

- Larger particles can be captured by impaction
  - Particle inertia carries it across flow streamlines
Interception

- Particles can be captured when the airstream carries them to within $\frac{1}{2}$ diameter of a surface
  - For larger particles

Diffusion

- Brownian motion causes particles to contact surfaces
  - Capture method for small particles
Electrostatic attraction

- Particles can be captured by electrical charge
  - Good for small particles

- Thermal deposition and other methods (magnetic attraction) also may be used

Particle capture by size

- The “most penetrating” particle (most difficult size to filter out) is ~0.3 micrometers in size:
Particle retention on surfaces

- Particles are strongly attracted to surfaces
  - van der Waals forces, electrostatic attraction, capillary forces, etc.
  - Smaller particles are more difficult to dislodge

Deposition of Inhaled Particles

- Size selective sampling relies on principles of particle physics to collect samples of different size particles.
- For industrial hygiene, particles are classified according to where they deposit in the respiratory tract:
  - Inhalable
    • Up to 50 µm
  - Thoracic
    • < 10 µm
  - Respirable
    • < 5 µm
Collection efficiency for particle aerodynamic diameter

END Part 1

- Questions?

- Part 2 covers aerosol sampling methods
Filter-Based Technologies

- Filtration is the most important method used to collect aerosol samples
  - Easy, inexpensive, widely used
  - Variety of filter media and sampling devices

Filter Media

- Fiber filters
  - Cellulose, glass, or quartz fibers
  - Low pressure drop, high loading capacity, inexpensive
  - May not be adequate for sub-micron particles
  - Water absorption problems may interfere with gravimetric analysis
Filter Media

• Porous membrane filters
  – Cellulose ester, PVC, PTFE, etc.
  – Porous mesh microstructure, convoluted flow path
  – Available in pore sizes of 0.1 to 10 µm
    • 5 µm pore size = 98% efficient for sub-micron particles
  – “Depth” filters
    • Particles are deposited within the filter structure, not just on the surface
    – Higher flow resistance, lower loading capacity

Filter Media

• Straight-through (capillary) membrane filters
  – Polycarbonate or polyester with uniform size pores
  – High-pressure drop, low loading capacity
  – Susceptible to static electricity and particle loss
  – Used for electron microscopic analysis
Filter Media

- Polyester foam
  - “Emerging technology”
  - Used for simultaneous sampling of multiple aerosol fractions
  - Foam plugs with final filter

Filter Media

<table>
<thead>
<tr>
<th>Filter media</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed cellulose ester (MCE)</td>
<td>Metals, welding fumes, asbestos, etc</td>
</tr>
<tr>
<td>Polyvinyl chloride (PVC)</td>
<td>Total or nuisance dust, silica</td>
</tr>
<tr>
<td>Teflon (PTFE)</td>
<td>Paraquat, organic arsenic, PM mass, organics</td>
</tr>
<tr>
<td>Glass fiber</td>
<td>Polynuclear aromatic hydrocarbons, strychnine</td>
</tr>
</tbody>
</table>
Filtration-Based Techniques

• Basic 37 mm Filter Cassette
  – Plastic cassette w/plugs
    • Filter paper
    • Backup pad
    • Outlet has air-distribution channels ("wagon wheel")
  – 2- or 3-pieces
    • 3-piece unit can be used “open-faced”, when an even distribution of particulate is needed
      – Chemically treated filters (i.e., glutaraldehyde, isocyanates)
      – Microscopic analysis (asbestos)

Filtration-Based Techniques

• Gravimetric analysis
  – Known volume of air drawn through a filter
  – Final weight - initial weight (tare) = mass of contaminant on filter
  – Concentration (exposure) = mass on filter / air volume = mg/m³
  – Filters usually must be pre-weighed
    • Laboratories provide pre-weighed, numbered filters
    • The industrial hygienist can weigh filters
    • Requires analytical balance, drying chamber, and good lab technique
Filtration-Based Techniques

• Gravimetric analysis
  – “Matched weight” filters are convenient, as the need to pre-weigh is avoided
    • Two “matched weight” filters are placed into the cassette
    • The upper filter = final weight
    • The lower filter = tare weight
    • The less tolerance in the “match”, the more the cost and the lower the detection limit

• Chemical analysis (various NIOSH and OSHA methods)
  – Known volume of air is drawn through the filter
  – For metals, the filter paper is dissolved, diluted, and analyzed (usually ICP or FAA)
  – For organics, the filter paper is extracted, concentrated, and analyzed (GC, HPLC, MS)
    • Contaminant mass is determined
    • Mass of contaminant/air volume = mg/m³
Filtration-Based Techniques

- Microscopic analysis (asbestos)
  - Asbestos cassette is designed for fiber-counting accuracy
    - Conductive plastic minimizes static electricity
    - Cowl to promote even fiber distribution
    - 25 mm diameter improves fiber density on filter
    - “Plenum” back to avoid “wagon wheel” deposition pattern
    - Mixed cellulose ester (MCE) filter recommended (two filters for TEM)
    - Sampling is “open face”, with the cassette pointed downward

25 mm cowled cassette, for asbestos
Filtration-Based Techniques

• Microscopic analysis (asbestos)
  – Phase Contrast Microscopy (PCM) analysis (NIOSH 7400)
    • Required for OSHA work
  – Transmission Electron Microscopy (TEM) required for “clearance sampling” in schools (EPA AHERA method, NIOSH 7402)
    • TEM is preferred by EPA
    • OSHA accepts NIOSH 7402 method

• Microscopic analysis (asbestos)
  – Transmission Electron Microscopy (TEM) required for “clearance sampling” in schools (EPA AHERA method, NIOSH 7402)
    • TEM is preferred by EPA
      – Fiber types identified
      – Smaller fibers can be seen
      – Unfortunately, there is no corresponding epidemiology, so the results cannot be interpreted properly
    • OSHA accepts NIOSH 7402 method
      – Fiber counting is by PCM
      – TEM is used to identify fibers for a more accurate count
Filtration-Based Techniques

- Inhalable samplers
  - “Traditional” cassettes under-represent the amount of inhalable particulate, especially for larger-sized particles (open-face collects more than closed-face)
  - Institute of Occupational Medicine samplers (IOM)

- IOM sampler (cont.)
  - Designed for “inhalable” particulate
    - 2 lpm, 25 mm filter
    - Removable cassette and filter are weighed as a unit
    - Open-face calibration required
      - No easy way to connect a calibration device
      - “Pickle Jar” and other open-face calibration methods
  - Inhalable samplers adopted by TLV
    - Refer to Appendix D of TLV book
    - OSHA sampling should be traditional open-face
**Sedimentation-Based Techniques**

- **Sedimentation** = “settling out” by gravity
  - Particulate matter tends to remain suspended in air
    - Normal ventilation rates usually exceed settling velocity
  - **Sedimentation devices**
    - Elutriators (settling chambers)
      - Vertical elutriator
        » Cotton dust sampling
      - Horizontal elutriator

**Elutriators**

- **Horizontal elutriator (cont).**
  - BMRC sampler, intended to capture respirable size particles
    - 5 µm midpoint
    - Seldom used today
Inertial techniques: Cyclones

• Cyclones
  – Centrifugal forces cause larger sized particles to move to be removed from the air stream
  – The cyclone acts as a “pre-separator”
    • Large particles collect in the “grit pot”
    • Smaller particles pass through the cyclone and are collected on a filter
    • “Cut size” \( d_{50} \) (50% efficiency size)
      – 5 \( \mu \)m (old BMRC)
      – 4.5 \( \mu \)m (OSHA)
      – 4 \( \mu \)m (ACGIH, ISO/CEN, “Soderholm”)

Cyclones

10 mm Dorr-Oliver Cyclone (OSHA)
BGI metal cyclone
SKC aluminum cyclone
Cyclones

- Cyclone calibration
  - Often no direct way to connect calibrator
  - “Jar” method
    - Cyclone is placed into a “pickle jar”
    - Calibrator is connected to the jar inlet

- Cyclone calibration (cont)
  - Calibration adapters attach to the cyclone, providing a means to connect the calibrator
  - Calibrators can be attached directly to other cyclones, like the BGI metal cyclone

SKC calibration adapter
Cyclones

• Cyclone flow rates are critical to assure performance
  – 1.7 lpm (Dorr-Oliver) for 4.5 µm
  – 1.9 lpm (SKC) for 5 µm (old BMRC)
  – 2.5 lpm (SKC) for 4.0 µm
  – 2.2 lpm (BGI) for 4.0 µm

Cyclone Sampling

• Respirable Silica (NIOSH 7500)
  – Equipment
    • 10 mm nylon cyclone
    • Cassette w/5 µm PVC filter
    • 1.7 lpm
  – Collect a bulk sample of dust
  – Analysis
    • Filter is dissolved, and the suspension is re-filtered onto a silver membrane filter
    – Filter is analyzed by X-Ray Diffraction
  – Evaluation
    • PEL for dust mixture is based on % quartz, cristobalite, and tridymite (refer to OSHA guidance).
**OSHA Silica Sampling**

PEL for respirable silica

\[
= \frac{10 \text{ mg/m}^3}{\% \text{ quartz} + 2(\% \text{ cristobalite}) + 2(\% \text{ tridymite}) + 2}
\]

**Impaction-Based Technologies**

- Widely used to characterize aerosols
  - “Jet and Plate” impactors direct a stream of high-velocity air against a collection surface, characterized by the 50% cut size, \(d_{50}\)
    - Single-stage impactors often used as “preseparators”
    - “Cascade” impactors allow for simultaneous collection of multiple particle size fractions
      - “Anderson” sampler to characterize dust or biological sampling
      - “Marple” personal breathing zone sampler
  - “Virtual Impactor” separates particles into two streams (“dichotomous” samplers)
  - Konimeter (historic), dust impacted on glass plate, microscope counted
Impaction-Based Technologies

Inertial impactors: (a) conventional jet-to-pate impactor collecting a single size fraction (say all particles over 10 µm); (b) multistage or cascade impactor in which each stage collects a different size fraction; and (c) virtual impactor or dichotomous sampler in which size fractions are separated but not removed from the airstream.

Anderson Cascade Impactor
**SKC Button Aerosol Sampler for inhalable dust sampling**

- ACGIH/ISO collection curve
- 4 lpm flowrate
- 25 mm filter

**SKC Personal Environmental Monitor for PM10 and PM2.5**

- US-EPA collection curve
- 2, 4 or 10 lpm flowrate
- 37 mm PTFE filter