

# Impactors and Particle Size Distribution (1)

National Institute for Occupational Safety and Health  
Division of Respiratory Disease Studies  
Field Studies Branch

Ju-Hyeong Park, Sc.D., M.P.H., C.I.H.

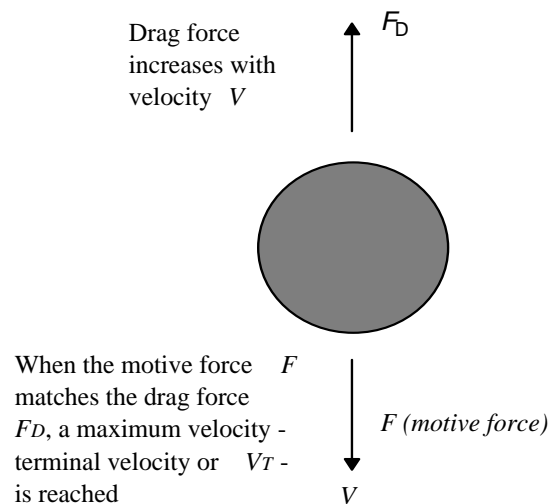


**Particle motion, particle size, and**  
**aerodynamic diameter**

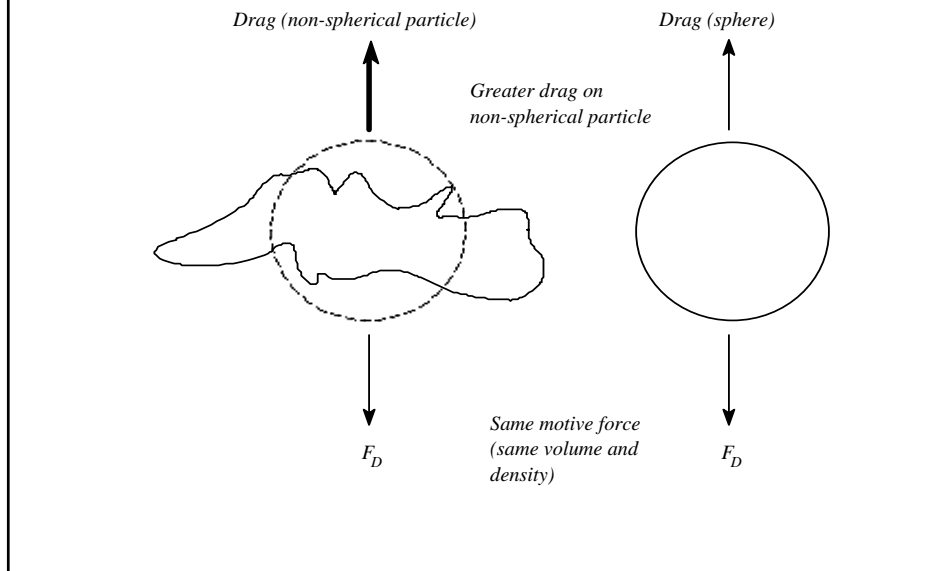
## Terminology about particle motions

- ❖ Drag force
  - ❑ Forces that opposes particle motions relative to surrounding gas
- ❖ Terminal velocity
  - ❑ A velocity reached where the applied force matches the drag force
  - ❑ The maximum velocity attainable with the applied force
- ❖ Steady-state motion
  - ❑ Particles traveling at their terminal velocity

## Particle drag and terminal velocity



## Drag force for different shape of particle



## Particle diameters

- ❖ **There are no absolutes when it comes to particle diameter**
- ❖ Diameter is defined by the method used to measure it
  - ❑ Direct method: microscope
  - ❑ Indirect methods: inertial, electrical, diffusional, and optical methods

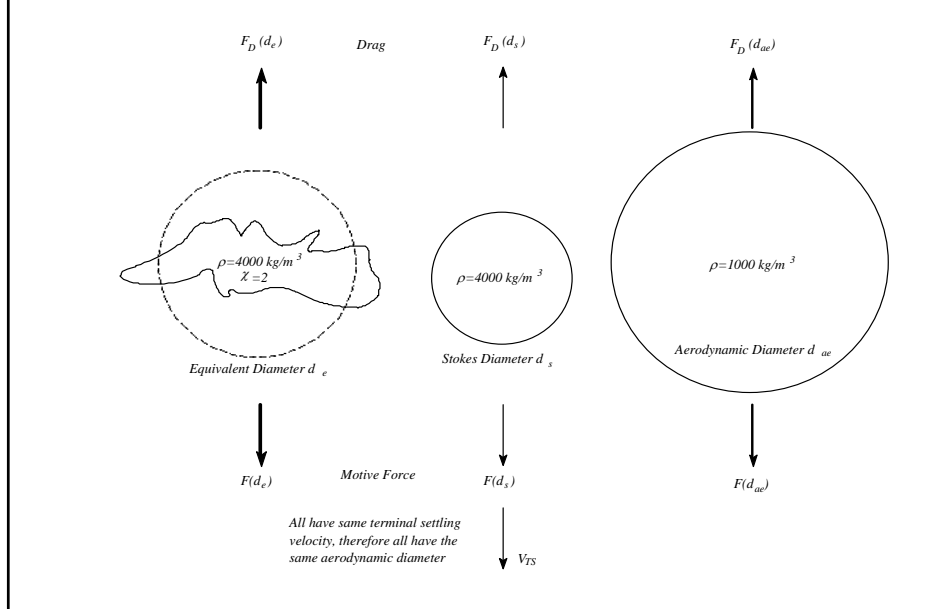
## Particle diameters

- ❖ Physical diameter (direct)
  - ❑ What you would see if you examined it under a microscope
    - Equivalent projected area diameter
    - Feret's diameter
    - Martin's diameter
- ❖ Fiber diameter (direct)
- ❖ Stokes diameter (indirect)
- ❖ Thermodynamic diameter (indirect)
- ❖ **Aerodynamic diameter** (indirect)

## Aerodynamic diameter

- ❖ The diameter of a sphere of density 1000 kg/m<sup>3</sup> **with the same settling velocity** as the particle of interest
- ❖ The aerodynamic diameter standardizes for:
  - ❑ Shape: Sphere
  - ❑ Density
    - The density of a water droplet
    - $1000 \text{ kg/m}^3 = 1 \text{ g/cm}^3 = 1 \text{ g/ml}$
- ❖ Useful aerosol concept used in many application

## Aerodynamic diameter



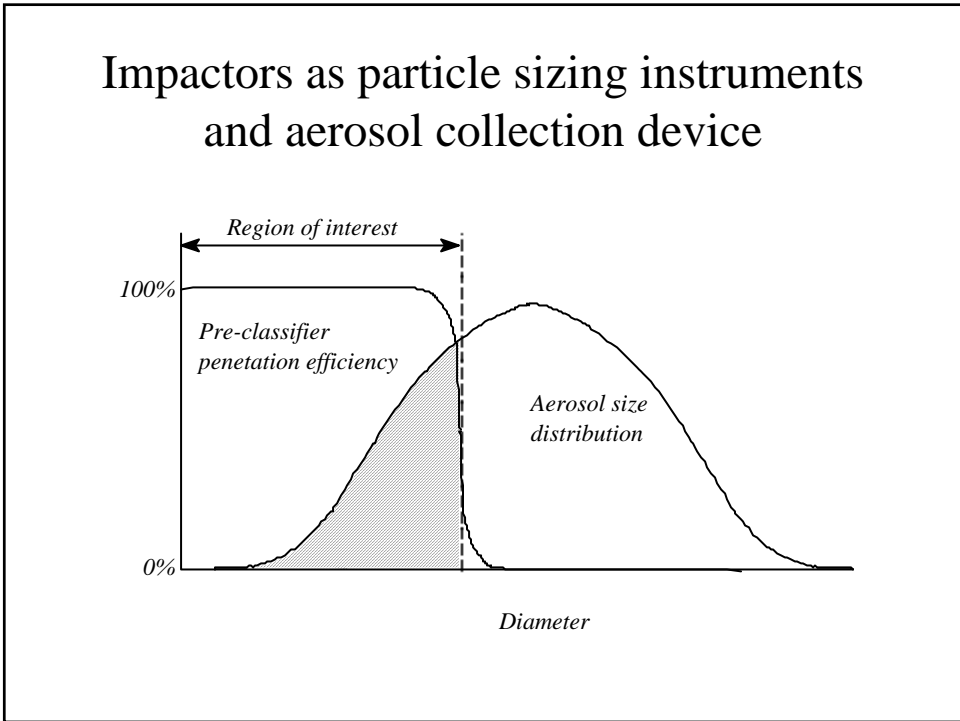
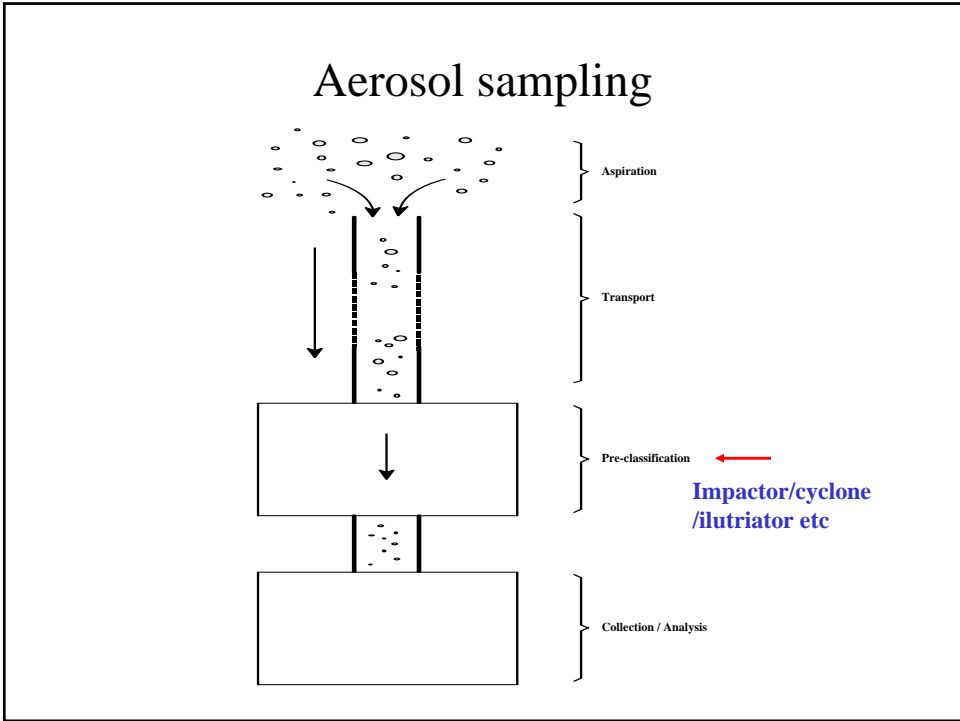
## Aerodynamic diameter

- ❖ In many situations, we don't need to know the true size, shape factor, and density
  - If we know its aerodynamic diameter
- ❖ Key particle property for characterizing filtration, respiratory deposition, and the performance of many types of air cleaners
- ❖ Cascade impactors use aerodynamic separation to measure aerodynamic particle size

## Aerodynamic diameter and impactors

### Particles Size

- ❖ Monodisperse aerosols
  - ❑ A single size of particle (a single particle diameter)
- ❖ Polydisperse aerosols
  - ❑ Different particle sizes
  - ❑ Two or more orders of magnitude
  - ❑ Most aerosols are polydisperse
- ❖ Determines physical properties of aerosols
  - ❑ Needs characterization of size distribution



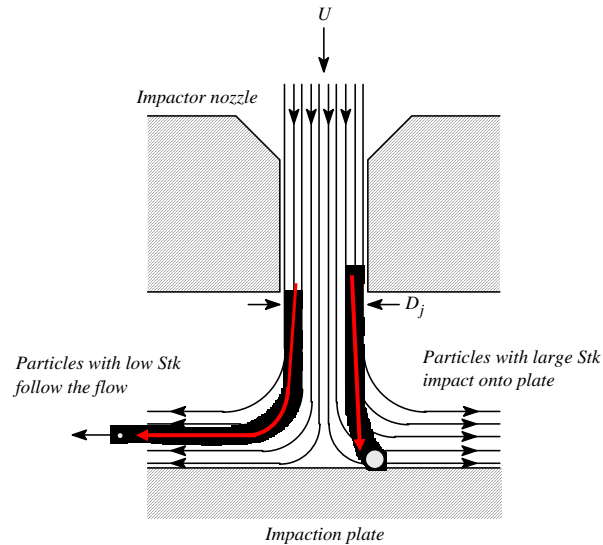
## Impaction

- ❖ One of the aerosol separation processes (or particle deposition mechanism in human respiratory system)
  - ❑ Impaction, settling, diffusion, interception, and electrostatic deposition
- ❖ Inertial impaction
  - ❑ Tendency to continue traveling in the initial direction when airstream is forced to change the direction

## Inertial impactors

- ❖ The most versatile
  - ❑ The measurement of particle size distribution by mass
- ❖ The most widely used aerosol pre-classifier
- ❖ Particles with high inertia (high Stokes number)
  - ❑ Follow the flow, and
  - ❑ Deposit or impact on the impaction plate below the nozzle
  - ❑ Particle collection (or penetration) is defined in terms of Stokes number ( $Stk$ )

## Inertial impactor

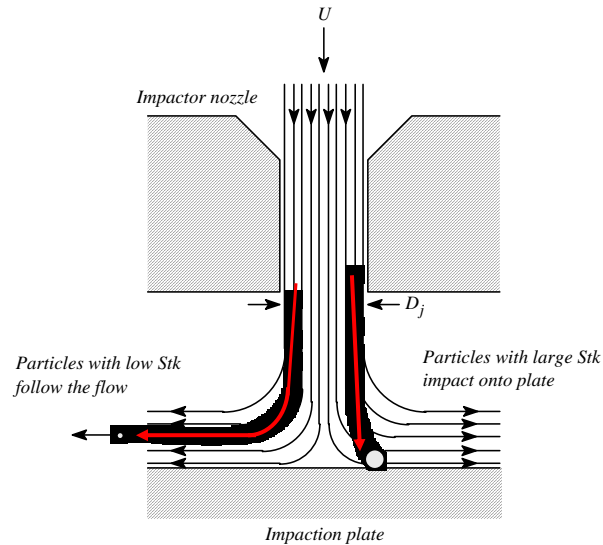


## Stokes number

$$Stk = \frac{\tau U}{D_j/2} \quad \propto d_a^2$$

- ❖  $D_j/2$ : nozzle radius
- ❖  $\tau$ : relaxation time
  - Time required for a particle to adjust or 'relax' its velocity to a new condition of forces
- ❖  $U$ : Mean aerosol velocity in the nozzle
- ❖ The nozzle to plate distance: little influence on the flow pattern within the impactor

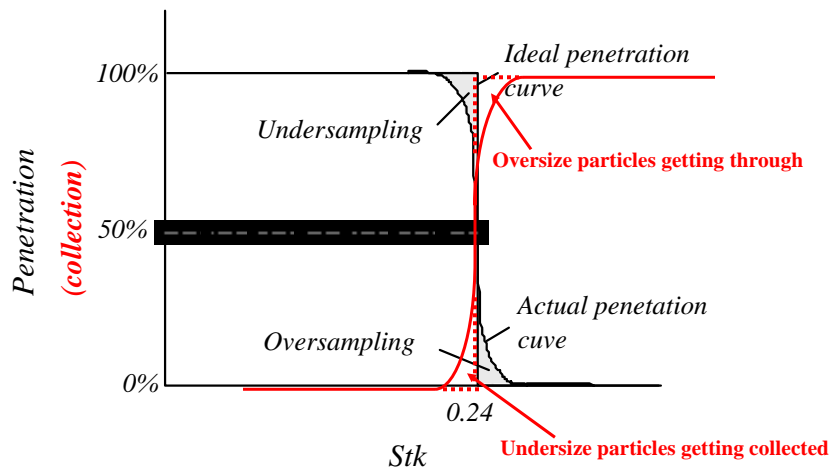
## Inertial impactor



## Impactor collection efficiency ( $E_i$ )

- ❖ Function of Stokes number:  $f(Stk)$
- ❖ No simple relationship between  $Stk$  and  $E_i$
- ❖ Generating collection efficiency curve for an impactor
  - ❑ Required repeated numerical analysis
    - Pattern of streamline for a particular impactor geometry
    - Particle trajectory determination for a given size
    - Determination of collection efficiency for that particles
    - Repeat these processes for many particle sizes

## Penetration or collection through a circular jet impactor



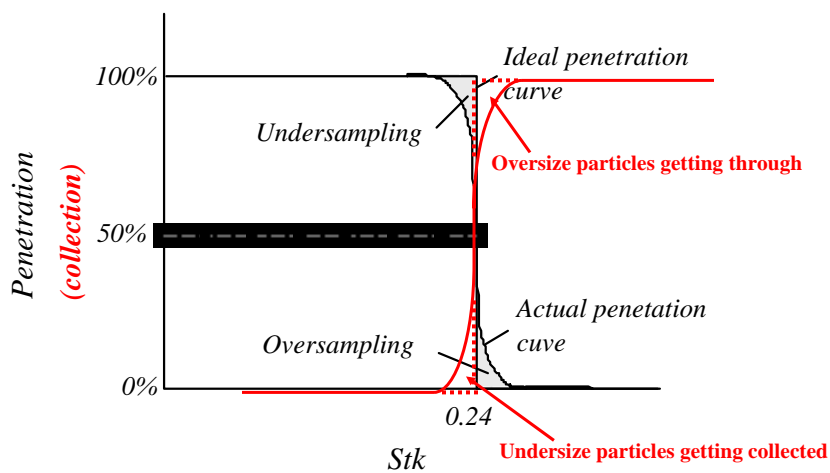
## Cutoff diameter ( $d_{50}$ )

- ❖ Complete curve of collection efficiency versus particle size- not necessary
  - ☐ Impactors with “**sharp-cutoff**” curve
  - ☐ Ideal step-function efficiency curve
    - All particles > a certain aerodynamic size: collected
    - All particles < a certain aerodynamic size: passing through

## Cutoff diameter ( $d_{50}$ )-continued

- ❖ “A certain aerodynamic size” is  $d_{50}$ 
  - ❑ Stokes number ( $Stk_{50}$ ) or particle size that gives 50% collection efficiency
    - The location of the ideal cutoff curve that best fits the actual cutoff curve
- ❖ Assumption
  - ❑ Mass of oversize particles getting through = Mass of undersized particles getting collected

## Penetration or collection through a circular jet impactor



## $d_{50}$ and Stokes number

$$Stk = \frac{\tau U}{D_j/2} \propto d_a^2$$

$$d_{50} \sqrt{Cc} = \left[ \frac{9\eta D_j (Stk_{50})}{\rho_p U} \right]^{1/2}$$

- Cc: Slip correction factor
- $\eta$ : Air viscosity
- $\rho_p$ : Density of particles

## Cutoff diameter ( $d_{50}$ )-continued

- ❖ A sub-micrometer cutoff diameter requires a small-diameter nozzle operating at a high velocity
- ❖ Practical limitation on these parameters
  - Smallest cutoff size for conventional impactor
    - 0.2-0.3  $\mu\text{m}$
- ❖ Approach to extend this limit
  - Micro-orifice impactor: 0.06  $\mu\text{m}$
  - Low-pressure impactor: 0.05  $\mu\text{m}$ 
    - By increasing slip correction factor

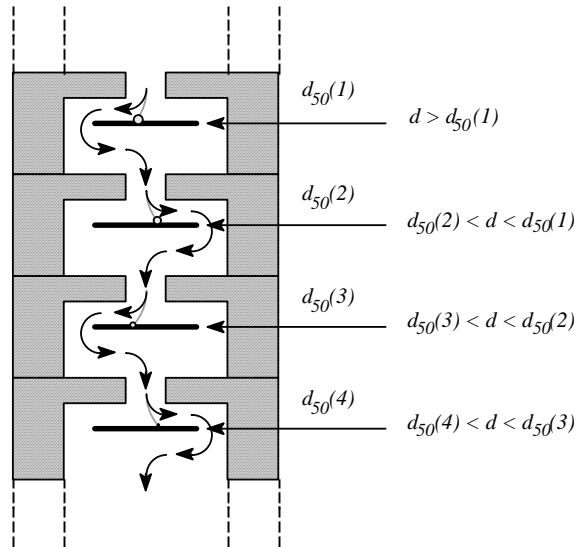
## Inertial impaction and aerodynamic diameter

- ❖ Inertial impaction
  - ❑ Is aerodynamic process
  - ❑ Governed by aerodynamic diameter

## Limitations of impactors

- ❖ Solid particle bouncing rather than deposition
- ❖ Over loading in the lower stages
- ❖ Under normal atmospheric conditions
  - ❑ Hard to collect smaller particles than 0.2  $\mu\text{m}$

## Cascade impactors



**What is wrong on this cascade impactor?**

## Cascade Impactors

- ❖ Several impactors in series
- ❖ Arranged in order of decreasing cutoff size
  - ❑ Decreasing by nozzle size → increasing average nozzle exit velocity → collecting smaller particles → reducing cutoff size ( $d_{50}$ )
- ❖ Large cutoff size comes first
- ❖ Each stage: removable impaction plate for gravimetric (or chemical) determination
- ❖ After-filter followed by the last stage
  - ❑ Captures all particles < the cutoff of the last stage

## Data collected from cascade impactor

Stage #	Size Range ( $\mu\text{m}$ )	$d_{50}$ ( $\mu\text{m}$ )	Initial Mass (mg)	Final Mass (mg)	Net Mass (mg)	Mass Fraction (%)	Cumm. Mass Fraction (%)
1	>9.0	9.0	850.5	850.6			
2	4.0-9.0	4.0	842.3	844.1			
3	2.2-4.0	2.2	855.8	861.0			
4	1.2-2.2	1.2	847.4	853.6			
5	0.7-1.2	0.70	852.6	855.1			
Back filter	0-0.7	0	78.7	79.3			
Total							

## Why do we use cascade impactor?

- ❖ To obtain information about particle size distribution

## Cascade impactor data reduction

Stage #	Size Range ( $\mu\text{m}$ )	$d_{50}$ ( $\mu\text{m}$ )	Initial Mass (mg)	Final Mass (mg)	Net Mass (mg)	Mass Fraction (%)	Cumm. Mass Fraction (%)
1	>9.0	9.0	850.5	850.6	0.1	0.6	100.0
2	4.0-9.0	4.0	842.3	844.1	1.8	11.0	99.4
3	2.2-4.0	2.2	855.8	861.0	5.2	31.7	88.4
4	1.2-2.2	1.2	847.4	853.6	6.2	37.8	56.7
5	0.7-1.2	0.70	852.6	855.1	2.5	15.2	18.9
Back filter	0-0.7	0	78.7	79.3	0.6	3.7	3.7
Total					16.4	100.0	

## Cascade impactor data reduction

- ❖ The procedure to obtain
  - ☐ Cumulative mass distribution plot, and
  - ☐ The mass median diameter from the data collected from cascade impactor