• Inertial motion and deposition of particles

If fluid flow is imposed on the particle motion, the governing equation for particle motion becomes $m\frac{d\vec{u}}{dt} = -f(\vec{u} - \vec{u}_f)$ for a given $\vec{u}_f$

For small particles and small mass loading (or small volume fraction), particle motion can not change "the given fluid flow motion."

One way coupling → Only flow field affects particle motion.

→ Stokesian Particles

Non-dimensionalize

$$\theta = \frac{tU}{L} \qquad \vec{u}_1 = \frac{\vec{u}}{U}$$

$$Stk\frac{d\vec{u}}{d\theta} = -(\vec{u}_1 - \vec{u}_{f_1})$$ where $$Stk = \frac{\tau}{\tau_{flow}} = \frac{m/f}{L/U}$$

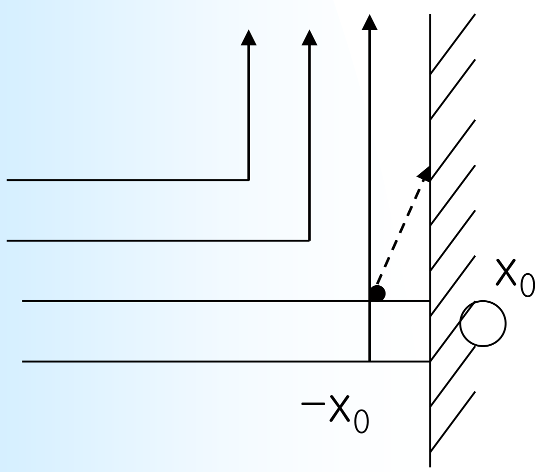
Small *Stk* no. cases, $\vec{u}_1 = \vec{u}_{f_1}$

Particle should follow the fluid motion.

If you add external force such as gravity, $m\frac{d\vec{u}}{dt} = -f(\vec{u} - \vec{u}_f) + m\vec{g}$

Examples: Stagnation flow toward a flat plate

· Idealized flow



$$m\frac{d\vec{u}}{dt} = -f(\vec{u} - \vec{u}_f)$$

$$\tau\frac{du_x}{dt} + u_x = u_{fx} = 0$$

$$\tau\frac{du_y}{dt} + u_y = u_{fy} = U$$

$$x(0) = -x_0 \qquad y(0) = x_0$$

$$\frac{dx}{dt}(t=0) = U \qquad \left.\frac{dy}{dt}\right)_{t=0} = 0$$

Sol.) $x(t) = -x_0 + U\tau(1-\exp(-t/\tau))$

$$y(t) = x_0 - u\tau(1-\exp(-t/\tau)) + Ut$$

particle trajectory

$$y = -x - U\tau \ln\left[1 - U\tau(x + x_0)\right]$$

$t \to \infty \qquad x(t) = -x_0 + U\tau$

$$y(t) = x_0 - U\tau + Ut$$

∴ For the particles following the streamlines at $x_0 = U\tau$

$$x(\infty) = 0$$

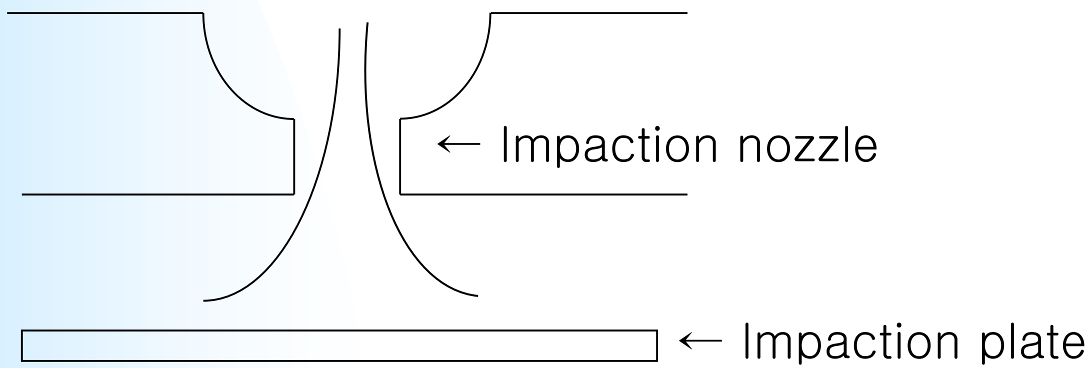
Therefore, particles within the region $0 < x_0 < U\tau$

will be collected

• Impactor

Impactor is the one of most widely used equipment for collecting aerosol particles or measuring aerosol particles. Of course, impactors utilize "inertial effect of aerosol particles" and all inertial impactors operate on the same principle.

Impactor has "a nozzle" and "a plate" called "impaction plate".

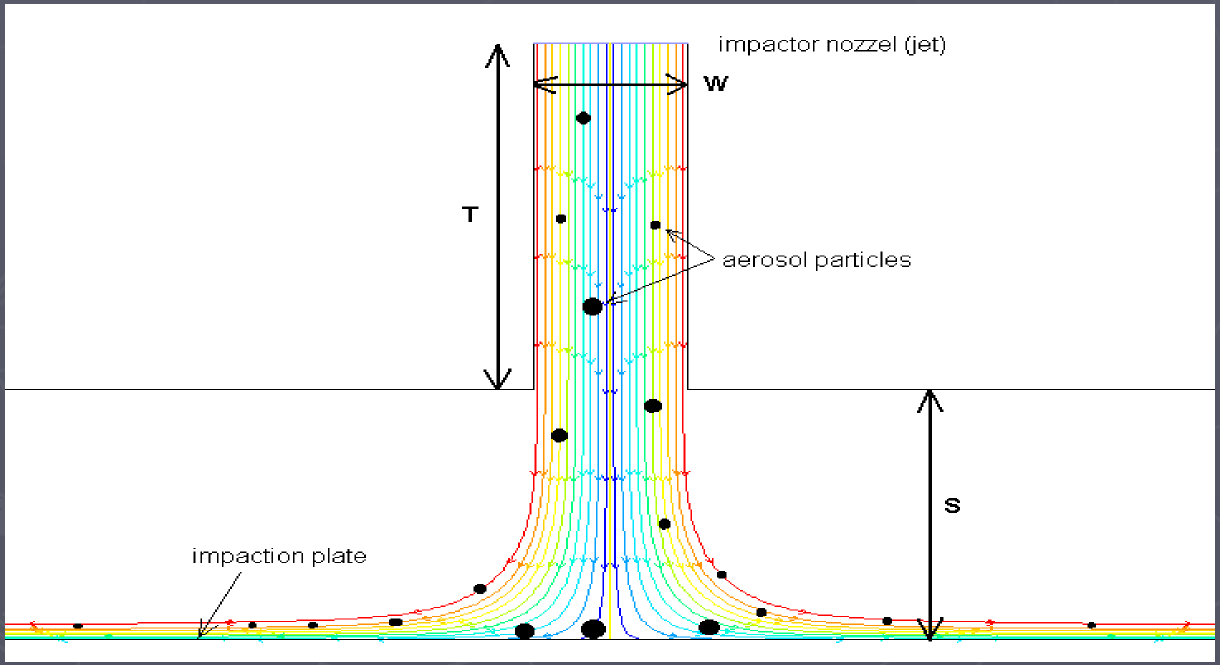


"The existence of an impactor plate" right ahead of impaction nozzle deflects the flow forming a bend in the streamlines. Particles whose inertia exceed a certain value are unable to follow the streamlines and finally

collide on the impaction plate. Smaller particles can still follow the flow without collision, therefore, remain airborne.
Thus the impactor separates aerosol particles into two size ranges; Particles larger than a certain size that should be removed, smaller particles that can escape “this impaction plate” without contact.
Then, we need to know “this critical size” that divides two particle sizes. We call this “cut off size” for the impactor.

What is Impactor?

- Impaction: when aerosol suddenly changes direction, particles tend to continue along their original paths due to their inertia and will strike the object.-> device called “**impactor**”

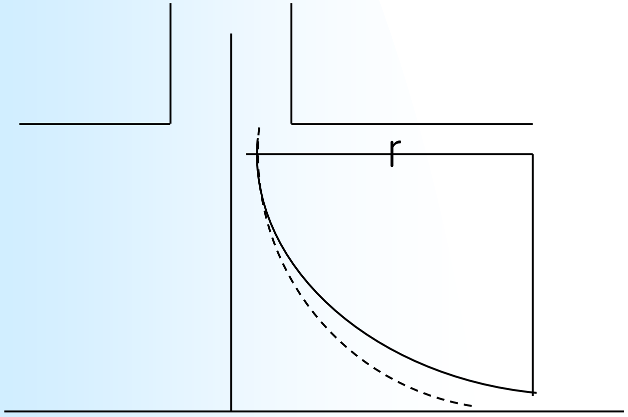


- Application: removal of particles by the lungs, air cleaning, aerosol sampling, particle deposition (patterning), etc.

- Typical components of an impactor

1. Aerosol Inlet
2. Acceleration Nozzle
3. Collision Plate or Collection Plate
4. Impactor Wall
5. After Filter
6. Vacuum Pump

- Rough and simplified Analysis on impactor



Let's suppose that a streamline form one quarter circle having a radius of **r** and assume the flow velocity is uniform U.

Then particles following streamline will experience centrifugal force causing it to deviate from the streamline and to move toward the impaction plate.

$$m_p a_r = f v_r \qquad \therefore v_r = \frac{m_p}{f} a_r = \tau a_r$$

particle deviation velocity
in the direction of **r**

$$= \tau \frac{U^2}{r}$$

The time needed for particle starting from the nozzle to reach the plate is

$$t = \frac{2\pi r}{4} \frac{1}{U}$$

Therefore, total deviation distance during this time is

$$v_r t = \tau \frac{U^2}{r} \cdot \frac{\pi r}{2} \frac{1}{U} = \frac{\pi}{2} \tau U = \Delta$$

This means that particles located more than a distance △ from the centerline could escape the impaction plate without collision.

However, particles that exist within △ will be colliding on the plate. If we assume "no bounce", the collection efficiency $\eta = \dfrac{\Delta}{D_j/2}$

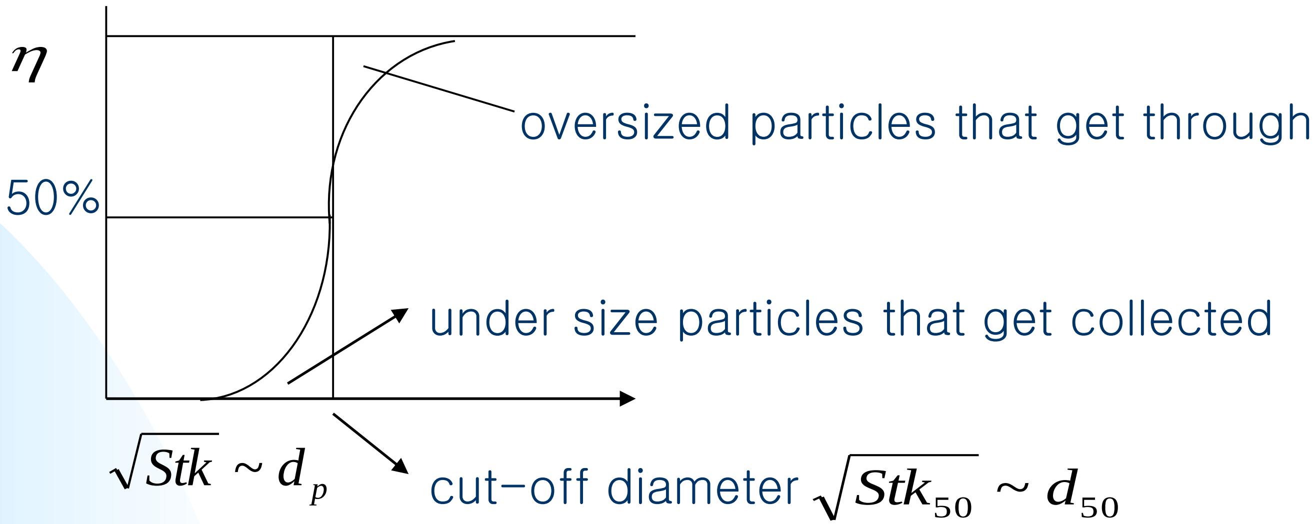
$$= \frac{\pi \tau U}{D_j} = \frac{\pi}{2}\frac{\tau U}{D_j/2} = \frac{\pi}{2}\frac{\tau}{D_j/2U} = \frac{\pi}{2}\frac{\tau}{\tau_{flow}}$$

$$= \frac{\pi}{2}(Stk) = f(Stk)$$

→ <u>function of *Stk* number</u>

For higher S*tk* number, higher efficiency

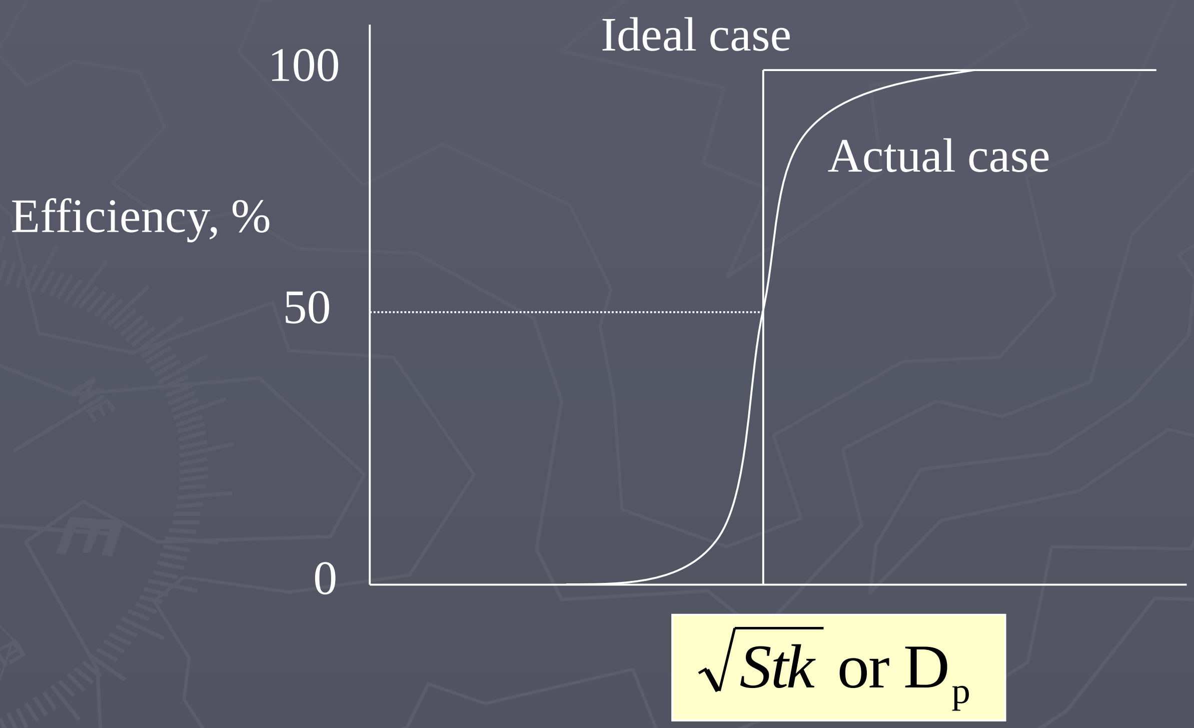
Further detailed analysis can be easily done using CFD and solving the equation of motion of particles.



$$Stk = \frac{\rho_p d_p^2 C_c U}{9 \mu D_j}$$

$$d_{p_{50}} \sqrt{C_C} = \sqrt{\frac{Stk_{50} \cdot 9 \mu D_j}{\rho_p U}}$$

- Efficiency of Impactor(%)
  = Number of collected particles/Number of incoming particles



- 50% efficiency point -> cutoff diameter!

- Small cut-off diameter requires smaller D_j or higher **U**
- Low pressure → Higher C_c → Smaller cut-off → low pressure impactor

-Cascade Impactor

One impactor + filter: one cut-off diameter

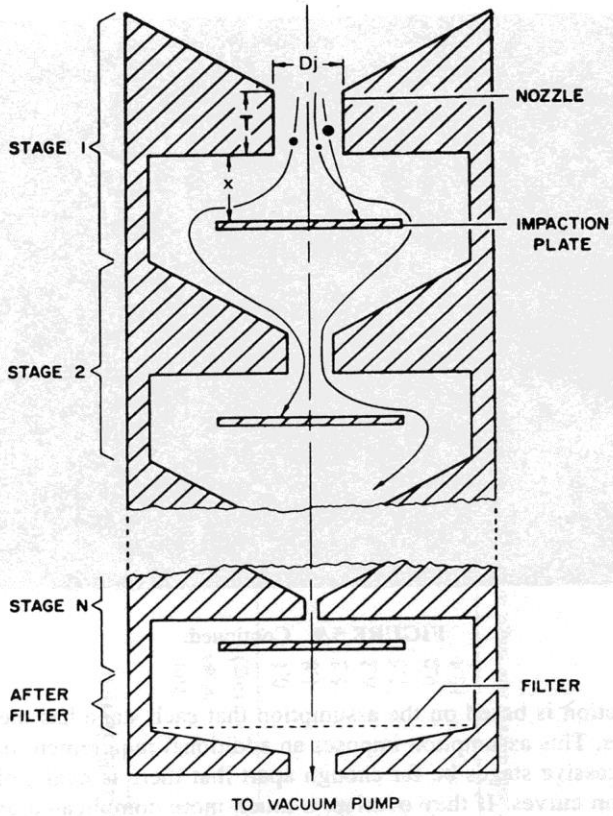
→ provide one-point on the cumulative distribution curve

→ If you change the flow velocity, this also gives possibility changing cut-off diameter.

But, there are practical limitations on the range of flow velocity that can be used (especially bounce problem)

Solution is "the use of several impactors at the same time"

→ Serial method is common → Cascade impactor having several impactor stages → The particles captured on the impaction plate of a given stage represent all particles smaller than the cut-off size of the previous stage and larger than the cut-off size of the given stage



(*a*)

IGURE 5.9 Cascade impactor (*a*) Schematic diagram. Reprinted with permission from *erosol Measurement,* by Dale Lundgren et al. Copyright 1979 by the Board of Regents of ie State of Florida. (*b*) Eight stage Anderson ambient cascade impactor with nozzle plate nd impaction plate shown at left.

The sequential separation divides the entire distribution of particles into a series f contiguous groups according to their aerodynamic diameters. From the gravimet-

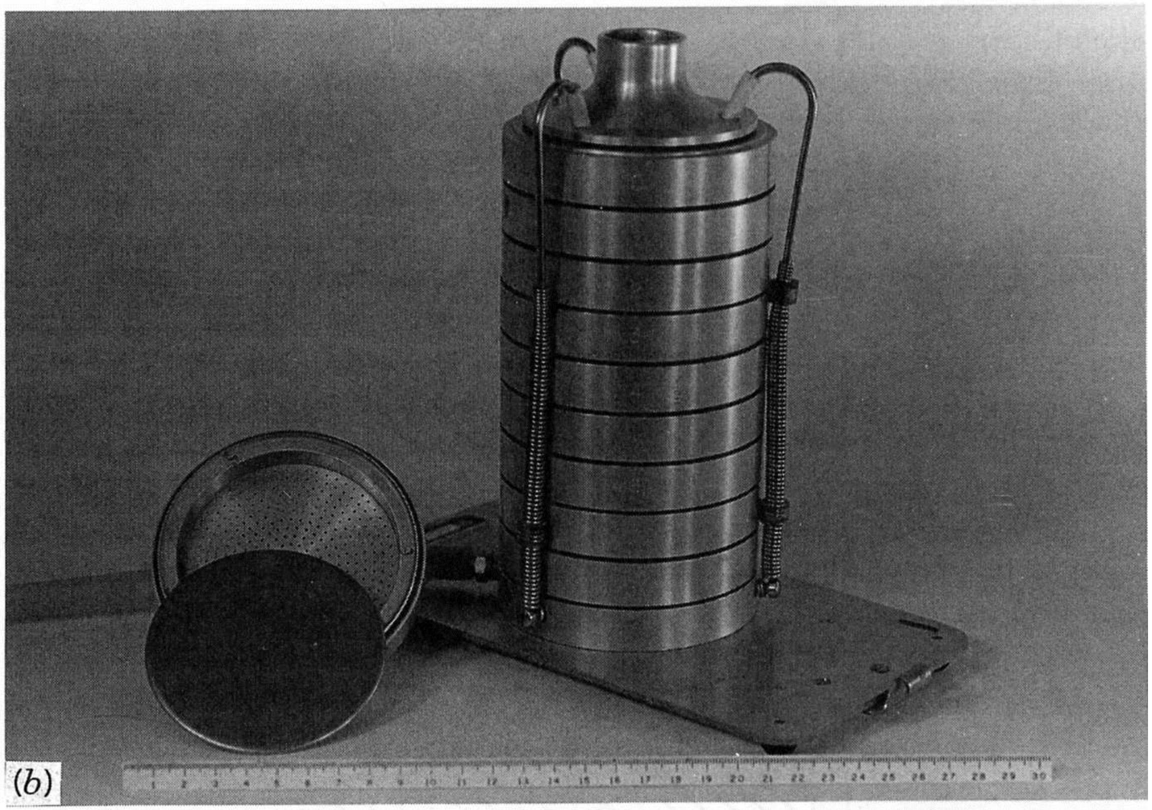
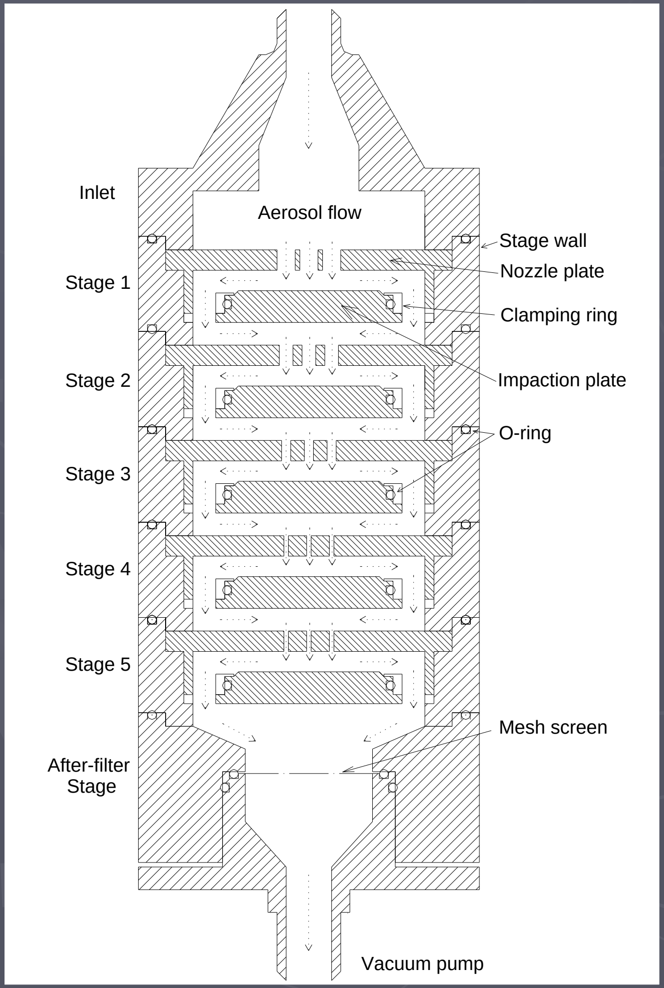


FIGURE 5.9 Continued.

- Cascade impactor (Kwon *et al.*, 2003)



Cutoff diameter

- Definition of cutoff diameter: aerodynamic diameter where 50% collection efficiency acquired
- Example of efficiency curves for Cascade impactor

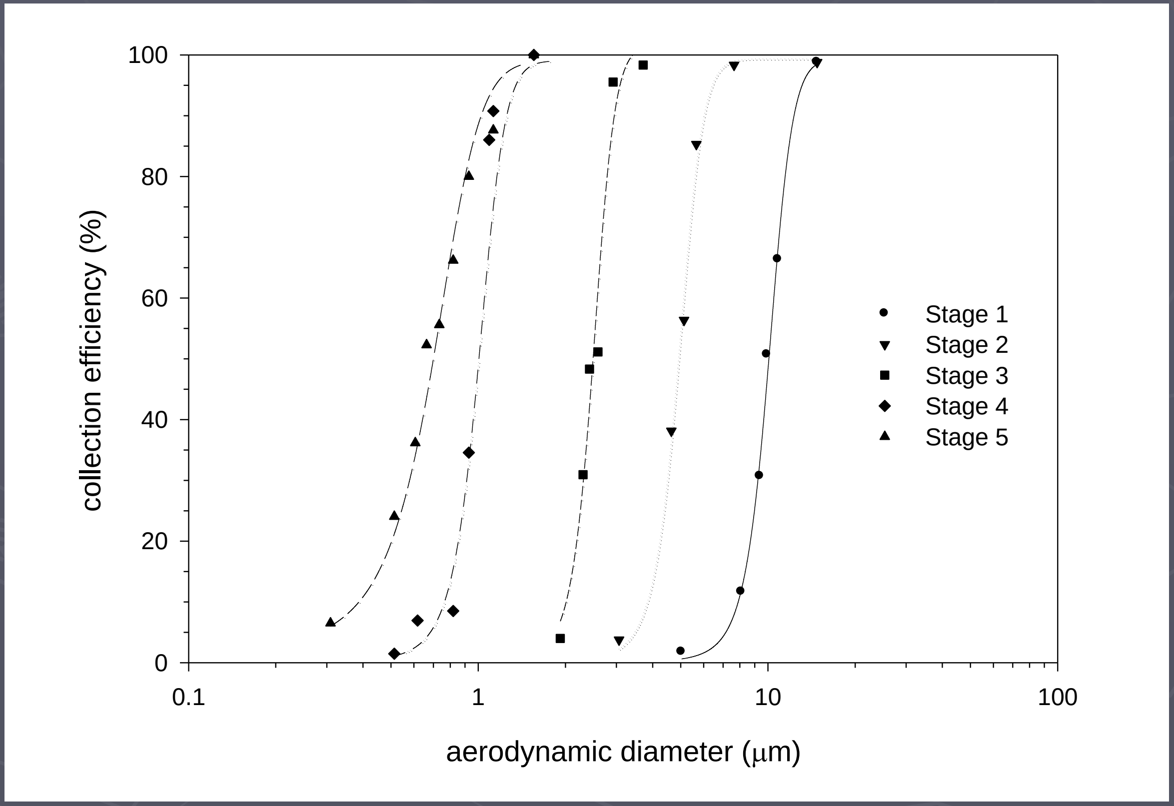


TABLE 5.5 Example of Cascade Impactor Data Reduction

Stage Number	Initial Mass (mg)	Final Mass (mg)	Net Mass (mg)	Mass Fraction (%)	d_{50} (μm)	Size Range of Collected Particles (μm)	Cumulative Mass Fraction[a] (%)
1	850.5	850.6	0.1	0.6	9.0	>9.0	100.0
2	842.3	844.1	1.8	11.0	4.0	4.0–9.0	99.4
3	855.8	861.0	5.2	31.7	2.2	2.2–4.0	88.4
4	847.4	853.6	6.2	37.8	1.2	1.2–2.2	56.7
5	852.6	855.1	2.5	15.2	0.70	0.70–1.2	18.9
Downstream filter	78.7	79.3	0.6	3.7	0	0–0.70	3.7
			16.4	100.0			

[a]Cumulative mass fraction is plotted against the upper limit of each size range, to construct a cumulative mass distribution curve.

TABLE 5.6 Characteristics of Selected Commercial Cascade Impactors

Type	Make and Model	Flow Rate (L/min)	Number of Stages	Jets/ Stage	Range[a] of d_{50} (μm)
Ambient	Mercer (02–130)[b]	1	7	1	0.3–4.5
Ambient	Multijet CI (02–200)[b]	10	7	1–12	0.5–8
Ambient	One ACFM Ambient[c]	28	8	400	0.4–10
Ambient (HiVol)	Series 230[c]	1420	5	9 slots	0.5–7.2
Personal	Marple Model 298[c]	2	8	4 slots	0.5–20
Source Test	In-Stack Mark 3[c]	21	8	20 slots	0.3–12
Low Pressure	Low Pressure[c]	3	12	1	0.08–35
Micro-Orifice	MOUDI[d]	30	9	≤2000	0.06–16.7
Viable	Viable[c]	28	6	400	0.65–7

[a]Range of d_{50} is for the flow rate given in column 3.
[b]In-Tox Products, Albuquerque, NM.
[c]Graseby Andersen, Inc., Smyrna, GA.
[d]MSP Corporation, Minneapolis, MN.

Commercialized CI

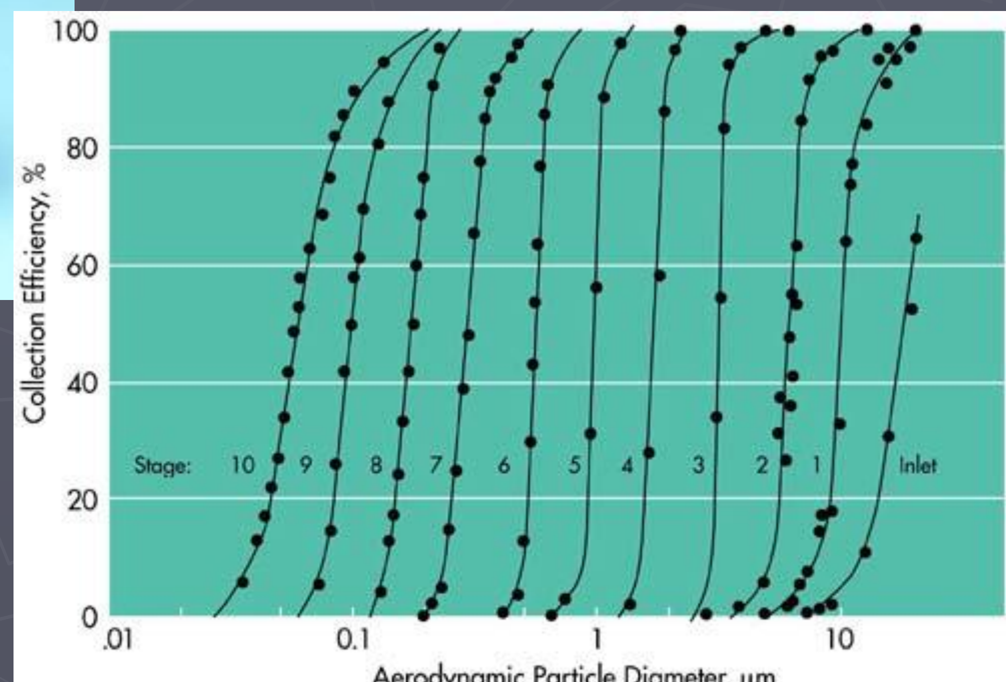
- **Andersen** CI (Thermo Electron Corp.): The Eight Stage Cascade Impactor utilizes eight jet stages enabling classification of aerosols from 9 micrometers and above to 0.4 micrometers (at 28.3 lpm) and allows airborne particulate to impact upon stainless steel impaction surfaces or a variety of filtration media substrates.

http://www.andersoninstruments.com/cascade_impactors.htm

Commercialized CI

- **MOUDI**(MSP): Micro orifice uniform deposit impactor

http://www.mspcorp.com



Commercialized CI

- **ELPI**(Dekati): Electrical low pressure impactor
- **Operation principle**:

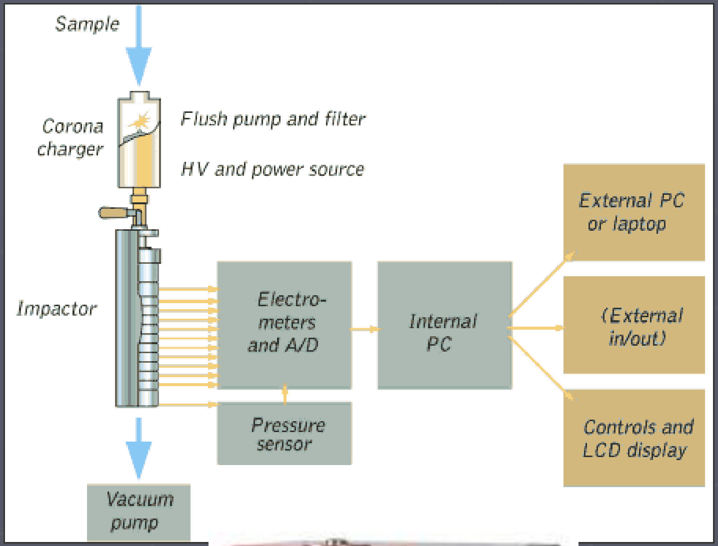
  1)The gas sample containing the particles is first sampled through a unipolar corona charger.

  2) The charged particles then pass into a low pressure impactor with electrically isolated collection stages.

  3) The electric current carried by charged particles into each impactor stage is measured in real time by a sensitive multichannel electrometer.

  4) The particle collection into each impactor stage is dependent on the aerodynamic size of the particles.

  5) Measured current signals are converted to (aerodynamic) size distribution using particle size dependent relations describing the properties of the charger and the impactor stages.



http://www.dekati.fi

The impaction plate is removable for subsequent measurement of mass.

–"Bounce" depends on particle material, velocity and the type of impaction surface.

Coating the impaction plate with a thin film of oil or grease reduces bounce. Silicone oil, grease

– Particles can be deposited in the passage ways between stages of a cascade impactor → inter stage loss → It is important to minimize sharp turns. d_{50} for cascade impactors is "aerodynamic diameter".

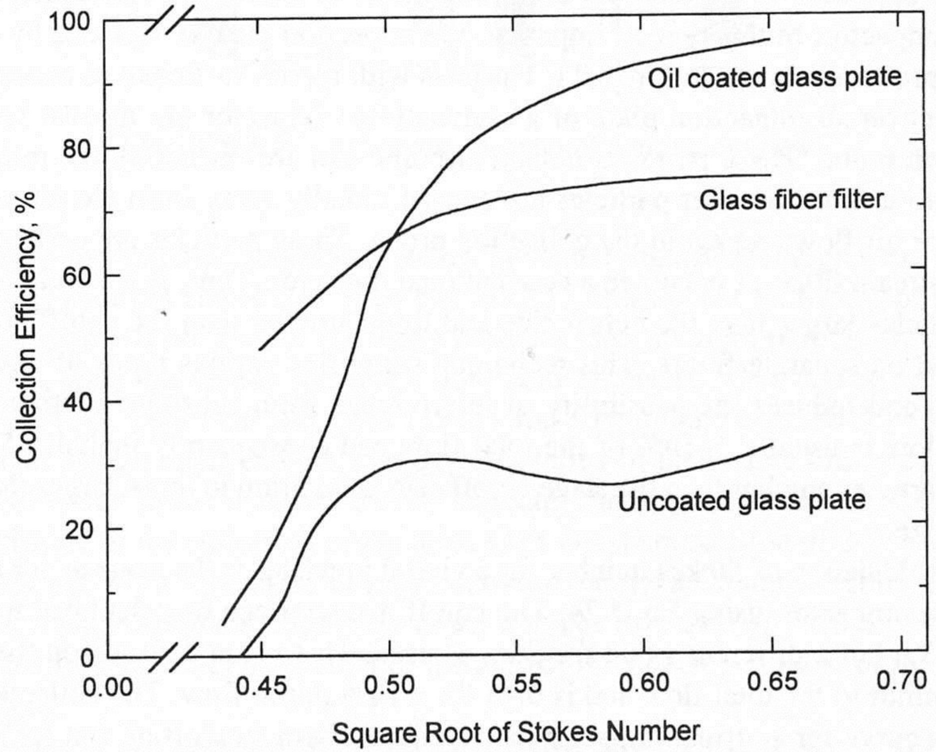


FIGURE 5.10 Effect of collection surface on impactor cutoff curve. After Rao and Whitby (1978).

d50 for cascade impactors is "aerodynamic diameter"

"Diameter of the unit density sphere that has the same settling velocity as the particles

$$V_{TS} = \frac{C_c \rho_p g d_p^2}{18\mu} = \frac{C_c g d_a^2}{18\mu}$$

$$\boxed{C_c(d_p)\rho_p d_p^2 = d_a^2 C_c(d_a)}$$

d_a: aerodynamics diameter

Same V_{TS} means same *stk* no.

$$\frac{\rho_p d_p^2 U C_c}{9\mu D_j} = \frac{d_a^2 U C_c(d_a)}{9\mu D_j}$$

$$\boxed{\therefore C_c(d_p)\rho_p d_p^2 = C_c(d_a) d_a^2}$$