AIR CLEANING TECHNOLOGIES

PlasTEP training course and Summer school 2011
Warsaw / Szczecin

Saulius Vasarevicius, VGTU

plasma for environment protection

Baltic Sea Region Programme 2007-2013

Part-financed by the European Union (European Regional Development Fund

Two Types of Air Pollutants

Particulate (Visible)

Gaseous

Example Sources Of Particulate Pollution

- Wood Processing
- Rock Quarries
- Coal Power Plants

Particulate Control (Mechanical)

- Electrostatic precipitator
- Bag house fabric filter
- Wet scrubber
- High efficiency cyclones

Particulate Control Technologies

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Remember this order:

- Settling chambers
- Cyclones
- ESPs (electrostatic precipitators)
- Spray towers
- Venturi scrubbers
- Baghouses (fabric filtration)

All physical processes

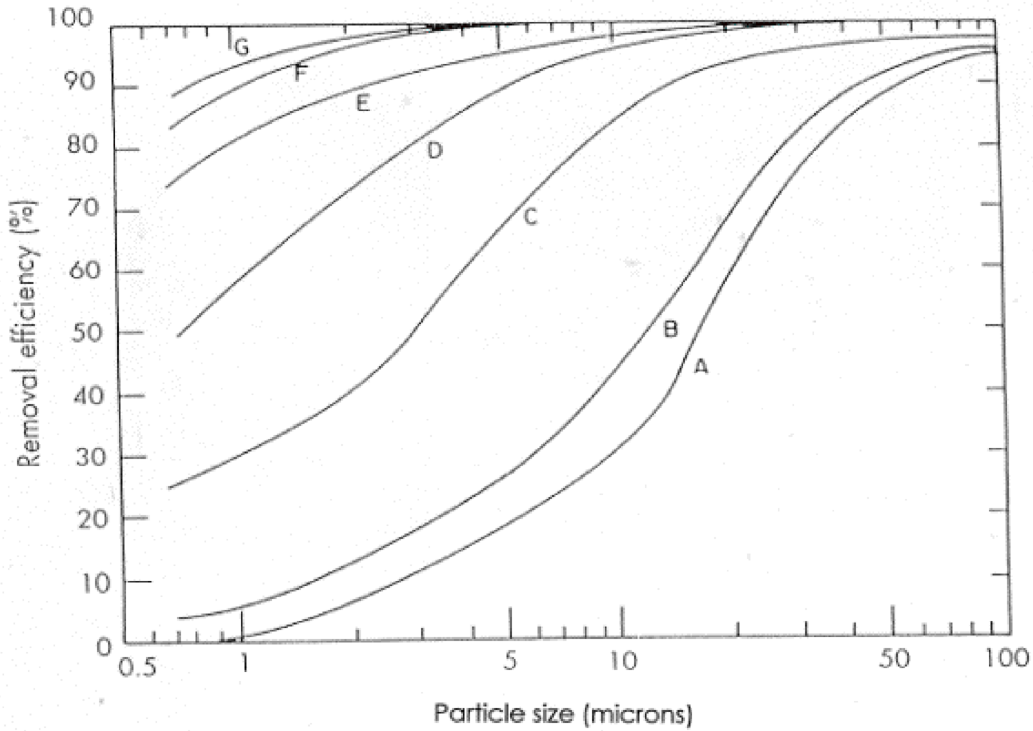

FIGURE 21-8. Comparison of removal efficiencies: (A) baffled settling chamber, (B) cyclone "off the shelf," (C) carefully designed cyclone, (D) electrostatic precipitator, (E) spray tower, (F) venturi scrubber, (G) bag filter

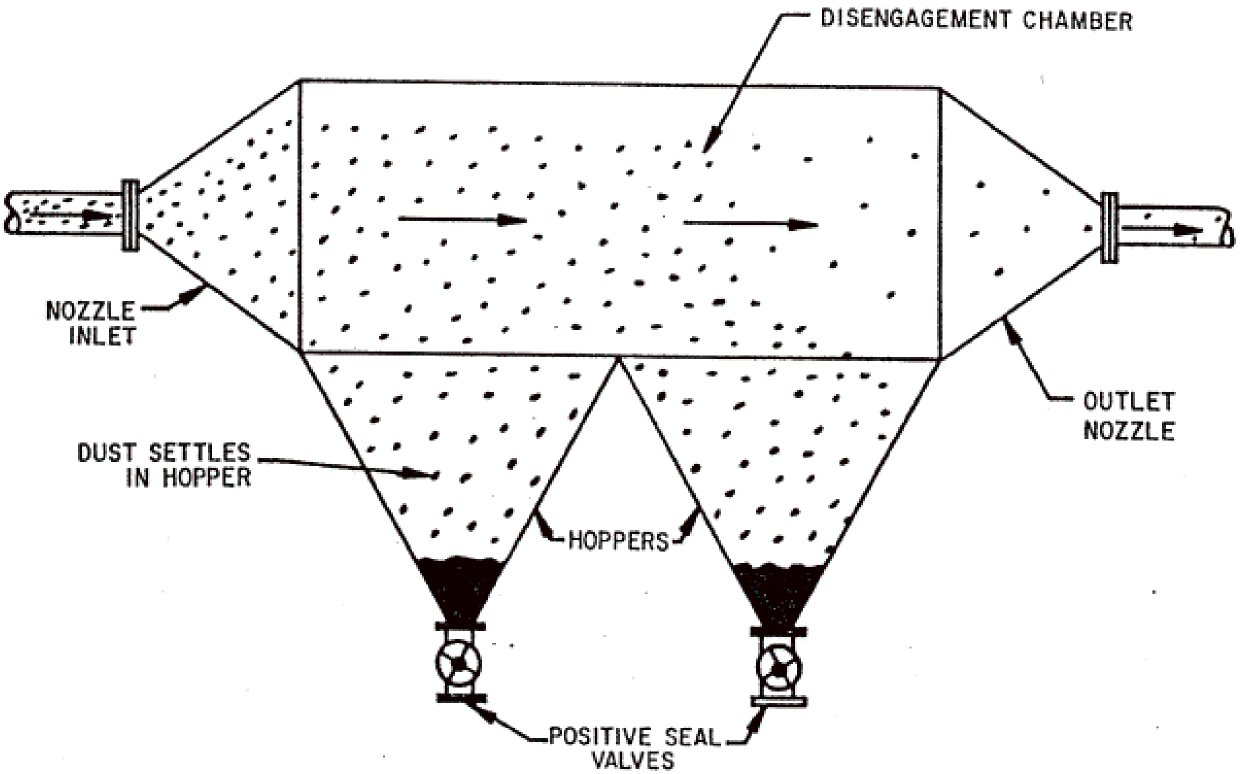

Fig. 6.1. Simple gravity settling chamber.

Flue Gas Cleaning – The state of the art

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Selection criteria

	ESP	Bag house	Scrubber	Cyclones (normal)	Spraycone Cyclones
Emission mg/Nm^3	100	30	200	250	< 100
Reliability	++	+	++	++++	++++
Cost	++++	++++	+++	+	+

Cyclone

- Most Common
- Cheapest
- Most Adaptable

CYCLONES

- **Principle**
  - The particles are removed by the application of a centrifugal force. The polluted gas stream is forced into a vortex. the motion of the gas exerts a centrifugal force on the particles, and they get deposited on the inner surface of the cyclones

Overall collection η

$$\eta(\%) = \frac{C_i - C_o}{C_i}$$

C_i ⟵ inlet concentration

C_o ⟵ outlet concentration

CYCLONES (CONTD.)

Construction and Operation

The gas enters through the inlet, and is forced into a spiral.

- At the bottom, the gas reverses direction and flows upwards.
- To prevent particles in the incoming stream from contaminating the clean gas, a vortex finder is provided to separate them. the cleaned gas flows out through the vortex finder.

CYCLONES (CONTD.)

Advantages of Cyclones

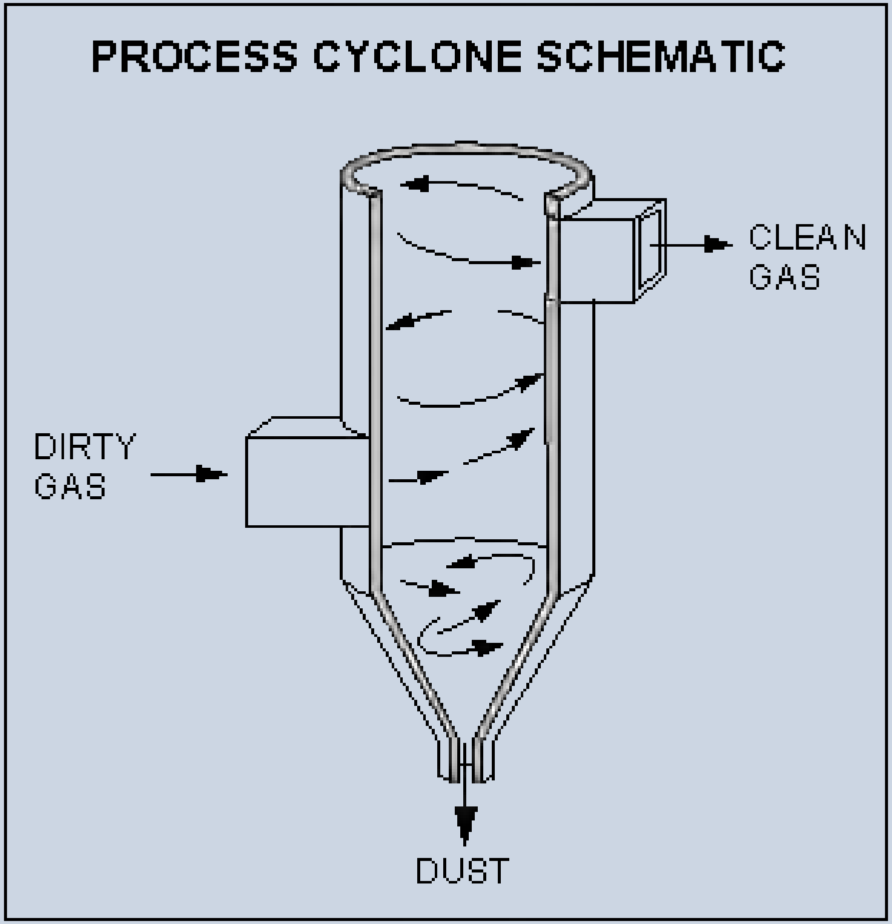
- Cyclones have a lost capital cost
- Reasonable high efficiency for specially designed cyclones.
- They can be used under almost any operating condition.
- Cyclones can be constructed of a wide variety of materials.
- There are no moving parts, so there are no maintenance requirements.

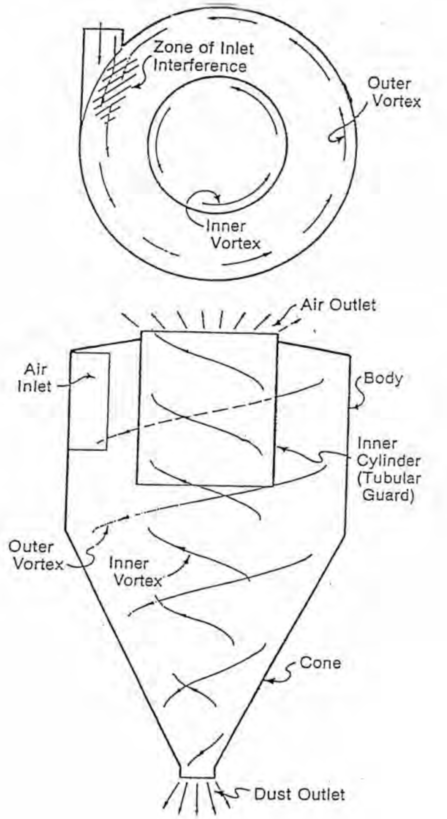
Mechanical Collectors – Cyclones

Advantages: Good for larger PM

Disadvantages: Poor efficiency for finer PM

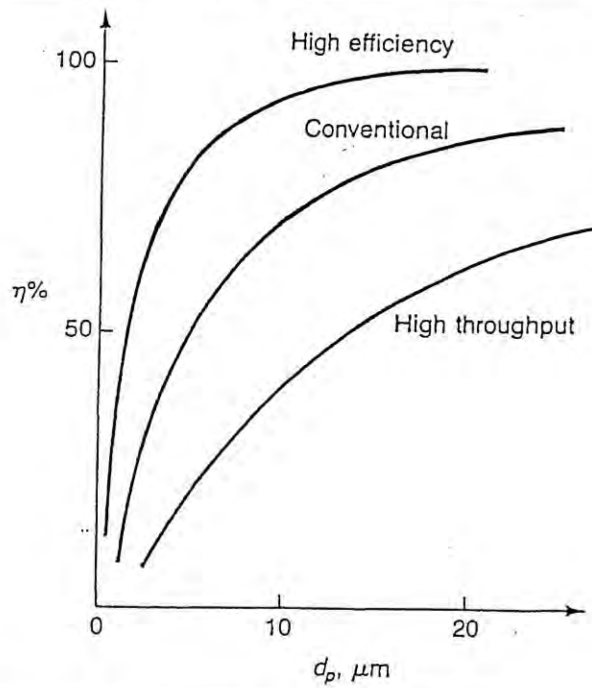
Difficult removing sticky or wet PM


PROCESS CYCLONE SCHEMATIC
CLEAN GAS
DIRTY GAS
DUST



Common cyclone showing turbulent entry zone. (From Alden, 1939.)

Figure 4.3 General relationship of collection efficiency versus particle size for cyclones.



NOTE: Efficiency versus size curves represent broad generalizations, not exact relationships.

Cyclone Operating Principle

"Dirty" Air Enters The Side.

The Air Swirls Around The

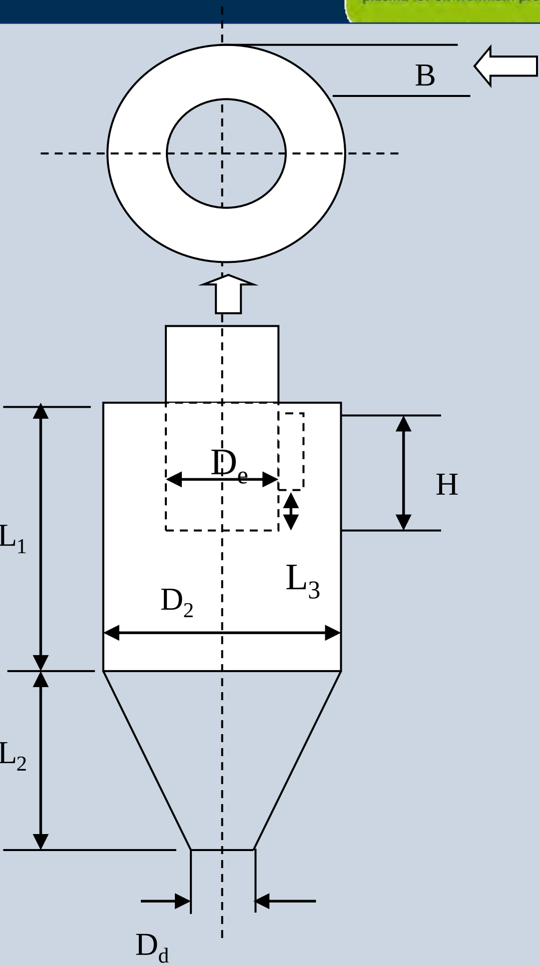
Cylinder And Velocity Is Reduced.

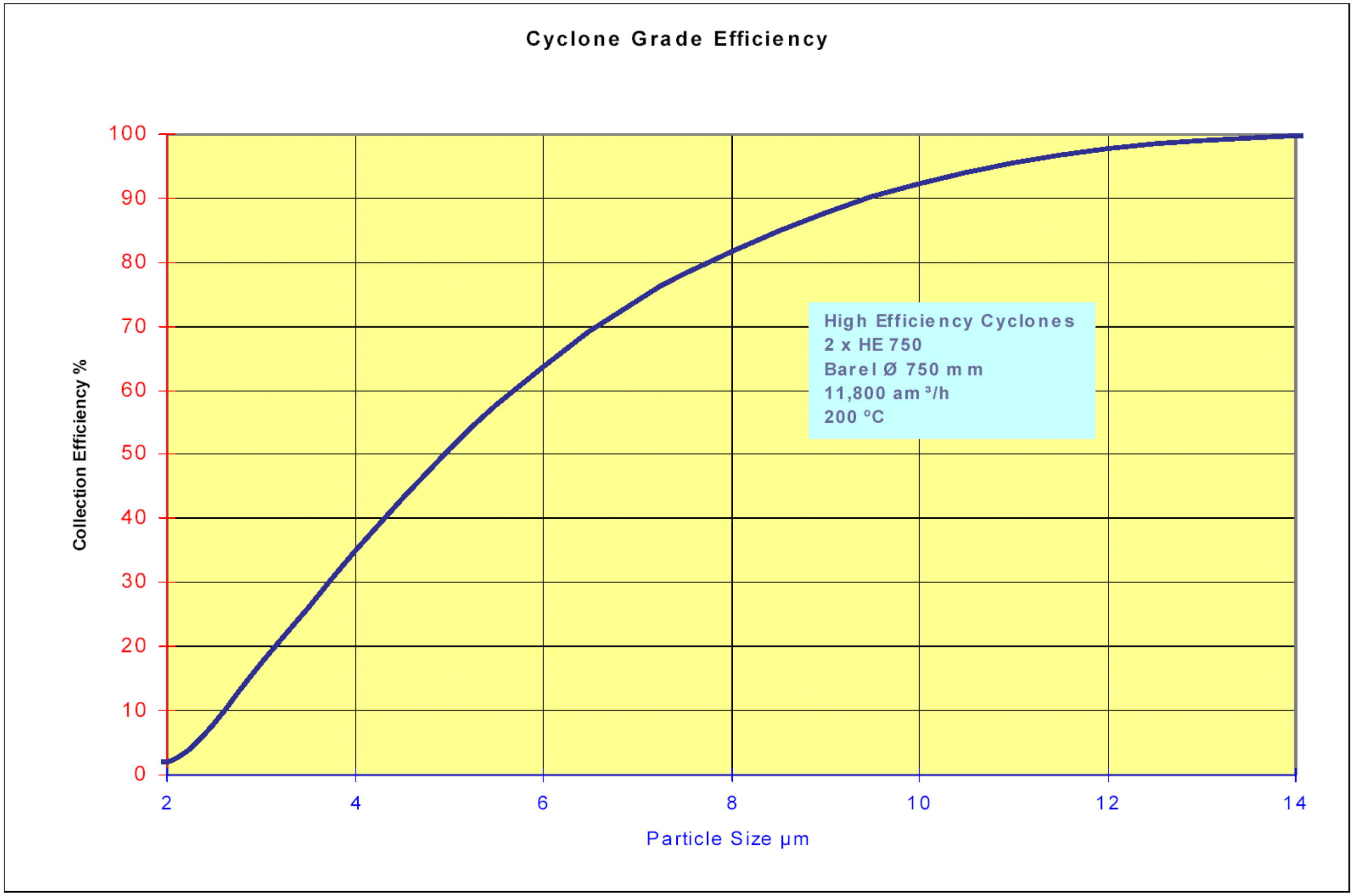
Particulate Falls Out Of The Air To The Bottom Cone And Out.

$$d_{0.5} = \left[\frac{9 \mu B^2 H}{\rho_p Q_g \, \theta} \right]^{1/2}$$

$$\theta = \frac{\pi}{H} \left(2L_1 + L_2 \right)$$

$d_{0.5}$ = cut diameter at 50% removal
m = dynamic viscosity of gas, Pa-s
B = width, m
H = height, m
r_p = particle density, kg/m3
Q_g = gas flow rate, m3/s
q = effective number of turns




Cyclone Grade Efficiency
100
90
80
70
60
50
40
30
20
10
0
Collection Efficiency %
2
4
6
8
10
12
14
Particle Size µm
High Efficiency Cyclones
2 x HE 750
Barel Ø 750 mm
11,800 am³/h
200 °C

Ex. 6-9

Given:

D_2 = 0.5 m

Q_g = 4 m^3/s

T = 25 °C

r_p = 800 kg/m^3

Q = What is the removal efficiency for particles with ave diameter of 10 mm?

For standard Cyclone:

B = 0.25 D_2 = 0.13 m

H = 0.5 D_2 = 0.25 m

L_1 = L_2 = 2 D_2 = 1 m

$$\theta = \frac{\pi}{0.25}\left(2(1)+1\right) = 37.7$$

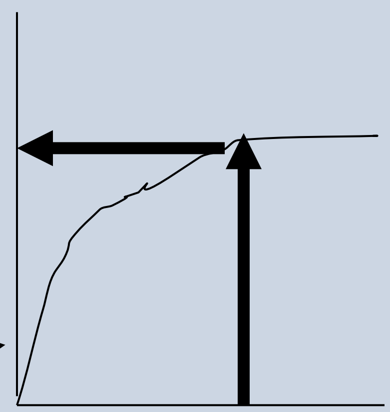
h = 0.95

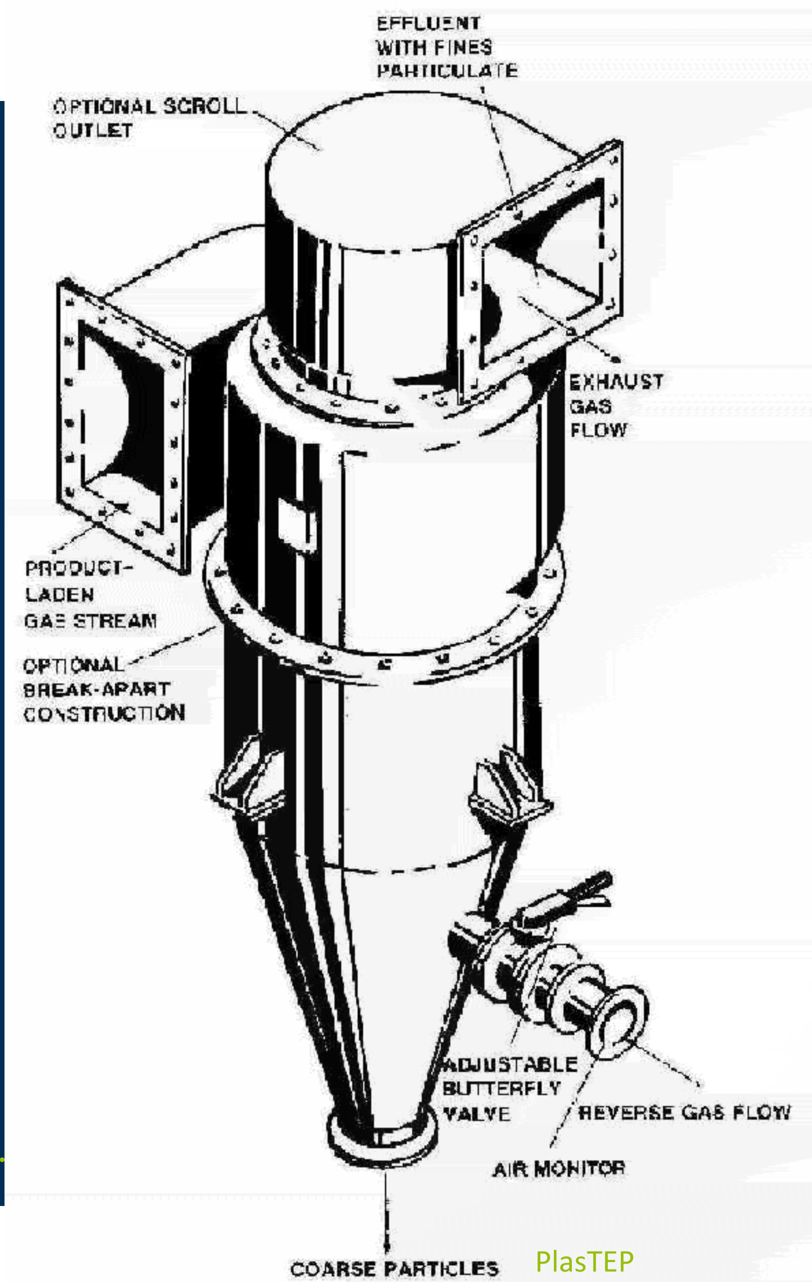
$$d_{0.5} = \left[\frac{9(18.5x10^{-6})(0.13)^2(0.25)}{(800)(4)(37.7)}\right]^{0.5} = 2.41x10^{-6}$$

$$= 2.41(\mu m)$$

@ d =10 mm

$$\frac{d}{d_{0.5}} = \frac{10}{2.41} = 4.15$$




EFFLUENT
WITH FINES
PARTICULATE
OPTIONAL SCROLL
OUTLET
EXHAUST
GAS
FLOW
PRODUCT-
LADEN
GAS STREAM
OPTIONAL
BREAK-APART
CONSTRUCTION
ADJUSTABLE
BUTTERFLY
VALVE
REVERSE GAS FLOW
AIR MONITOR
COARSE PARTICLES

Flue Gas Cleaning – The state of the art

History:

1975 - 1980 work with Prof. Stairmond (UK)
Cyclones for coal fired gas turbine 80 MW PFBC

1993 – 1998
basic research in
cyclone technology

CyDesign **- Cape Town**
development center

Flue Gas Cleaning – The state of the art

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On site technology studies & testing:

JTA boiler training center

Glass melting furnace

Flue Gas Cleaning – The state of the art

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Commercial applications of high efficiency cyclones:

BurnerMax
Fluidized bed furnace
High efficiency cyclones
operating at 400 C

Flue Gas Cleaning – The state of the art

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High efficiency cyclone plant
with fully evaporative
fine agglomeration sprays
(Installation 1997)

Efficiency > 99 %

Emission < 20 mg / Nm^3

Flue Gas Cleaning – The state of the art

What is the agglomeration spray?

- Water spray with very fine droplets
- Fully evaporative (dry system)
- Droplets capture small particles
- and agglomerate them
- Larger particles are easily collected

Typical water consumption
30 liter / t steam generation

Flue Gas Cleaning – The state of the art

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Case study:

Wet scrubber installed at a 130 t/h JTA water-tube boiler

Inlet conditions:

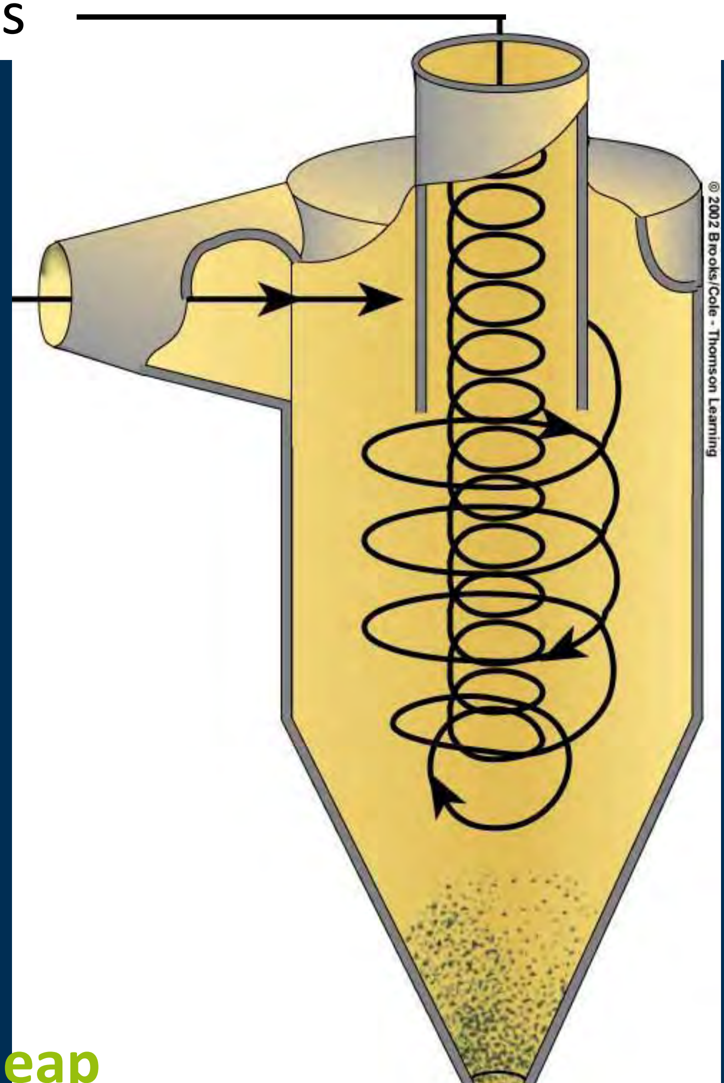
- 5000 mg / Nm^3
- 5 % (250 mg / $Nm^{3)}$ < 5 micron
- Emission > 300 mg / Nm^3

- Required 120 mg / Nm^3

Cyclone Separator - **Cheap**

Cleaned gas

Dirty gas



Dust discharge

Does NOT produce hazardous materials like other

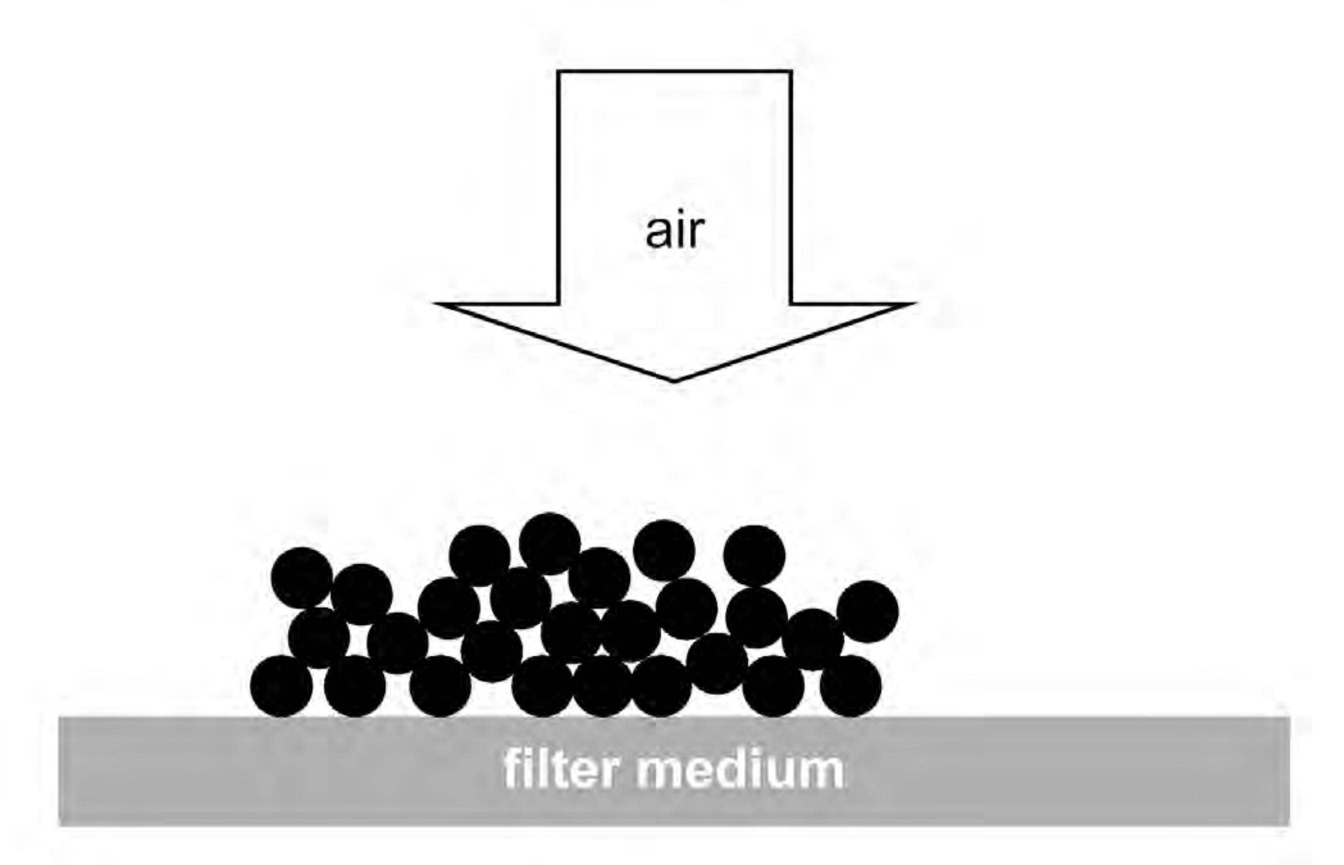
Multiple Cyclones (Multi clone)

Smaller Particles Need Lower

Air Flow Rate To Separate.

Multiple Cyclones Allow Lower Air Flow Rate, Capture Particles to 2 microns

Air Filtration

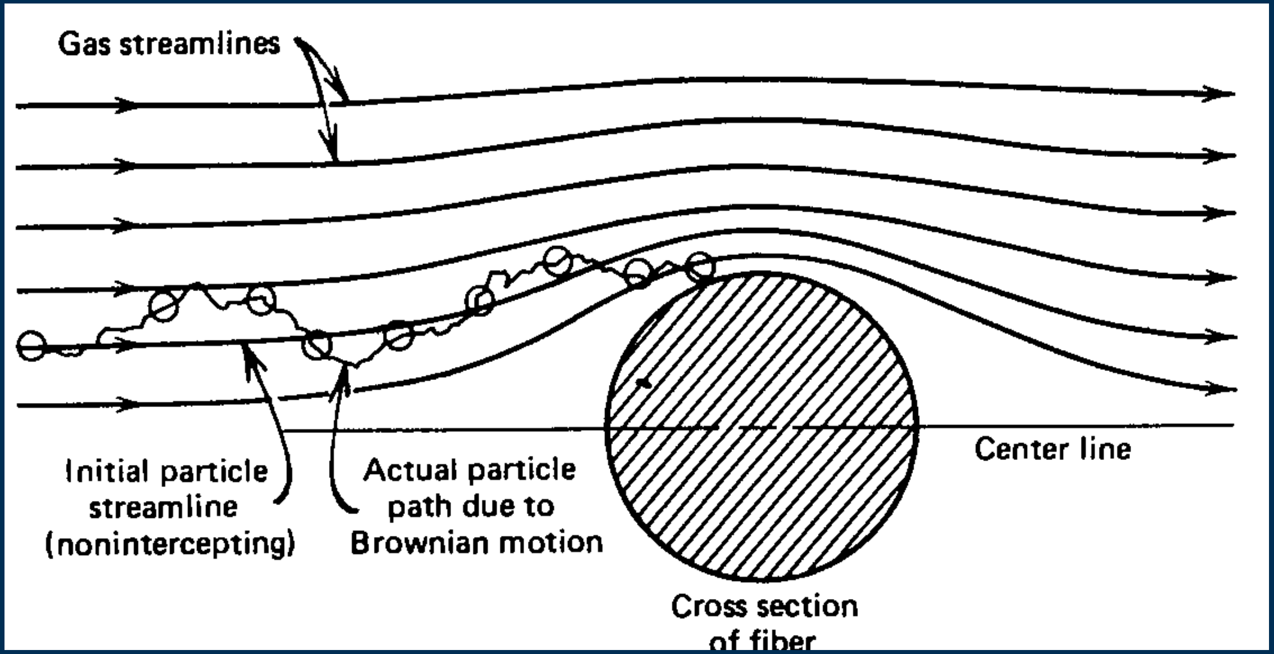


Diffusion

Q: How does efficiency change with respect to d_p?

a. Efficiency goes up as d_p decreases

b. Efficiency goes down as d_p decreases

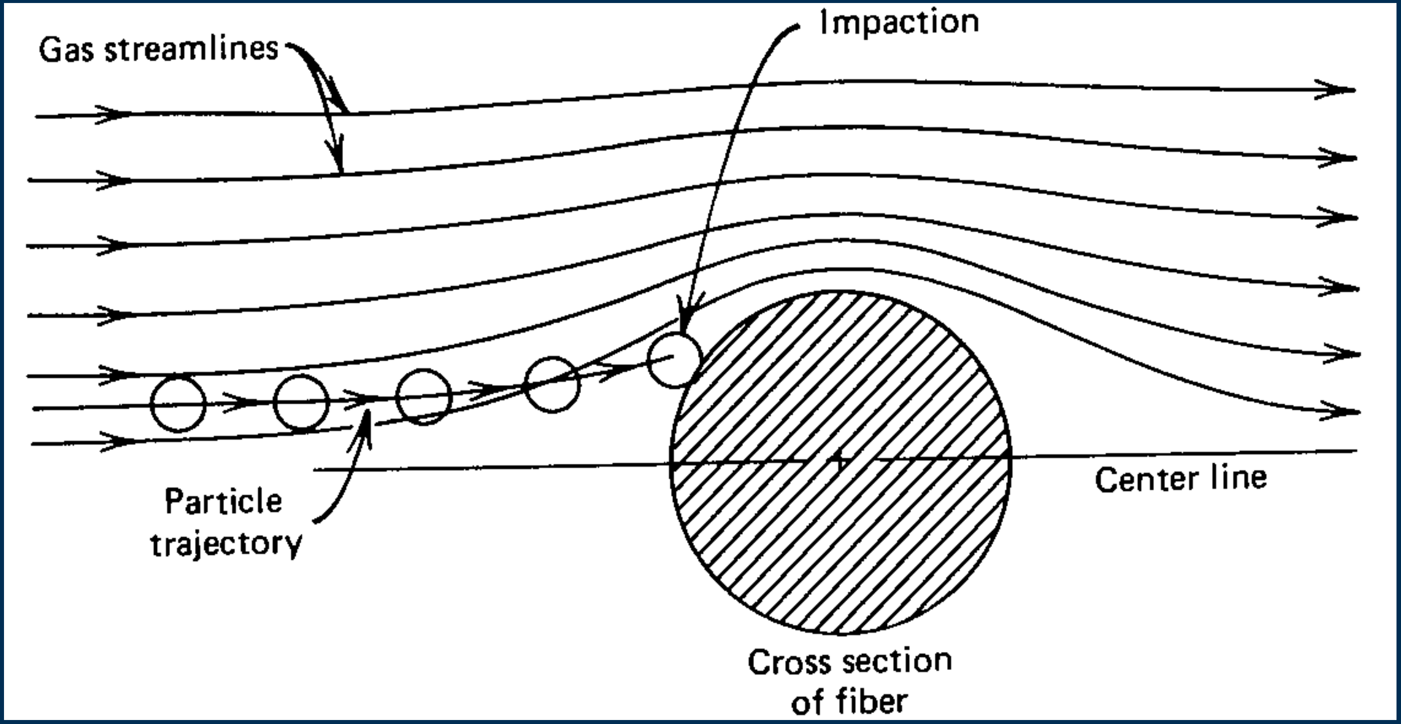


Impaction

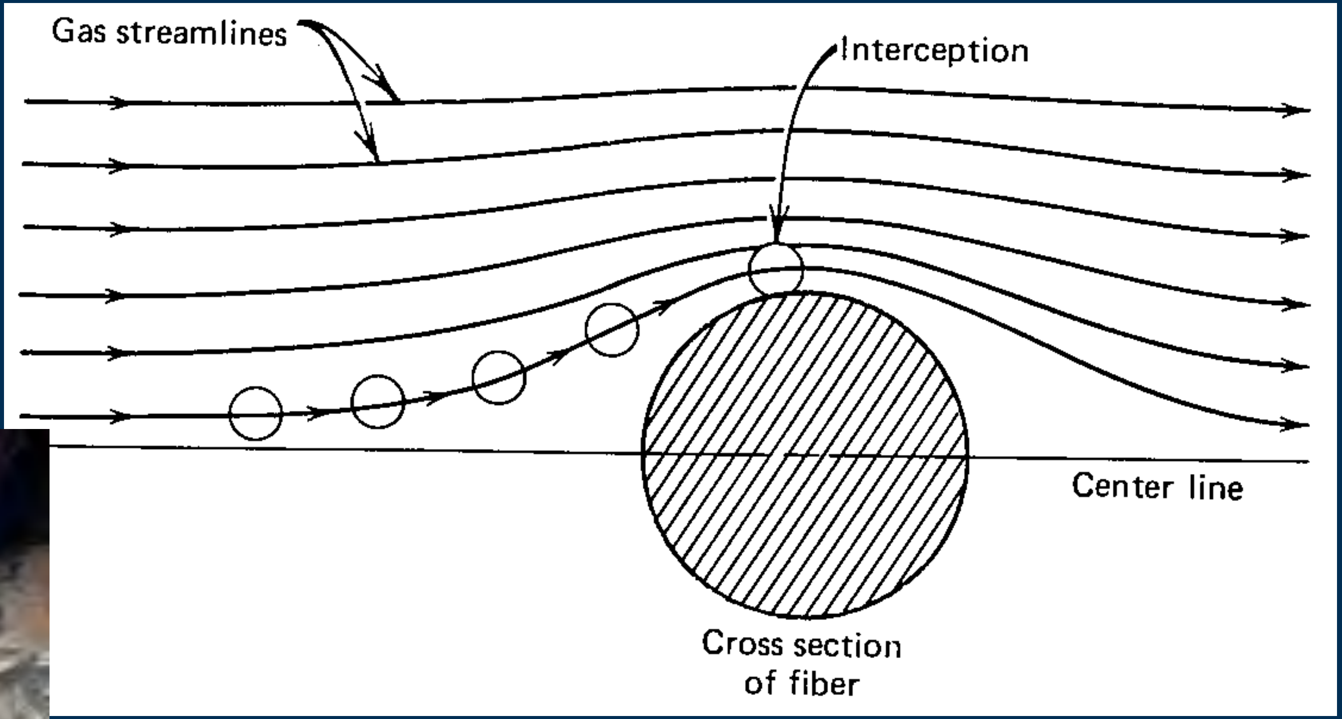
Q: How does efficiency change with respect to d_p?

a. Efficiency goes up as d_p decreases

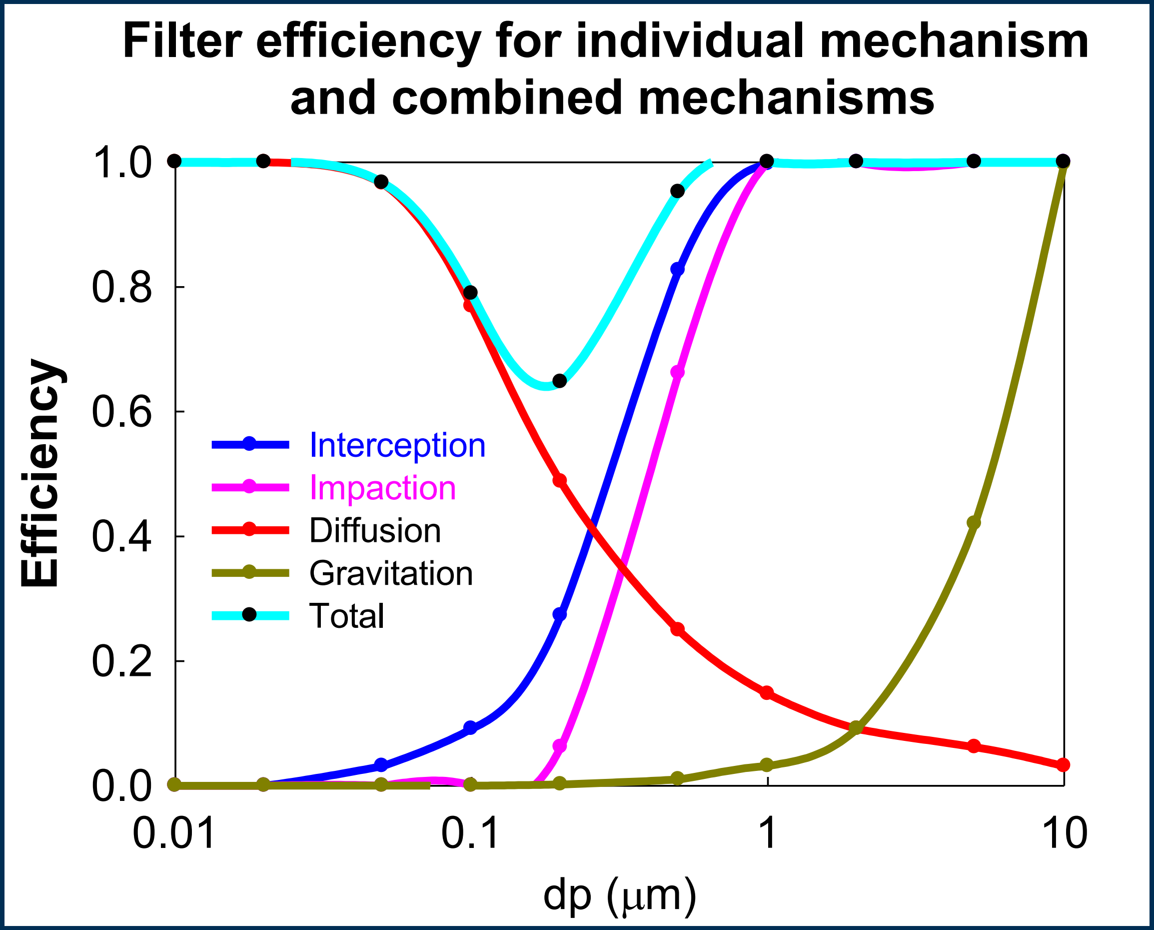
b. Efficiency goes down as d_p decreases



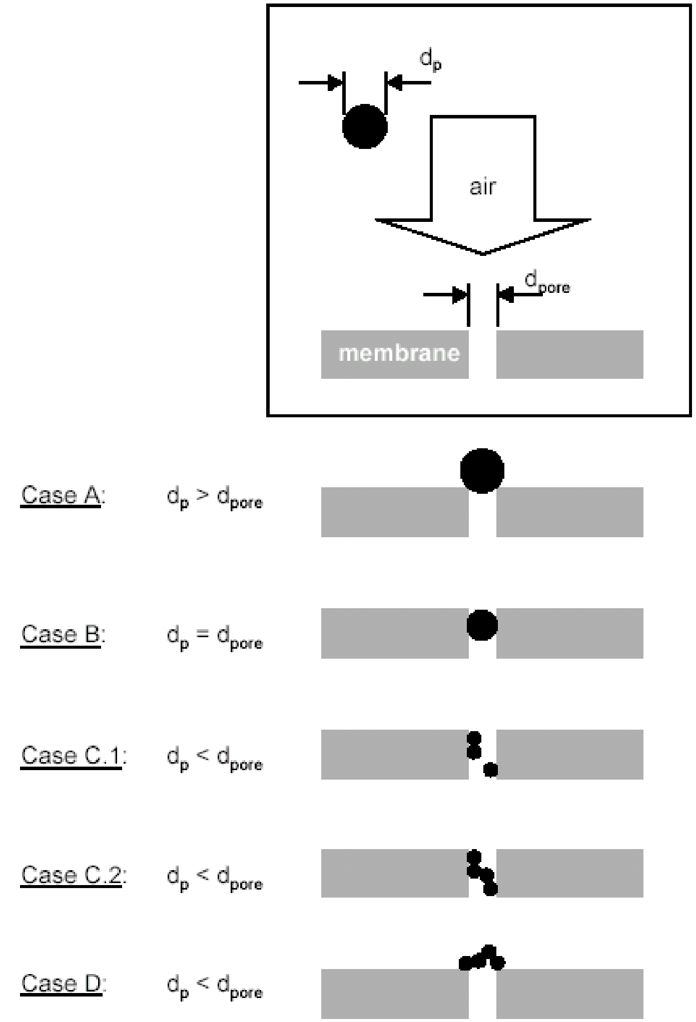
Interception



Fat Man's Misery,
Mammoth Cave NP


Filter efficiency for individual mechanism and combined mechanisms
Efficiency
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.1
1
10
dp (μm)
Interception
Impaction
Diffusion
Gravitation
Total

Case A: Pore blocking
Case B: Pore plugging
Case C1: Pore narrowing
Case C2: Pore narrowing w/lost pore
Case D: Pore bridging

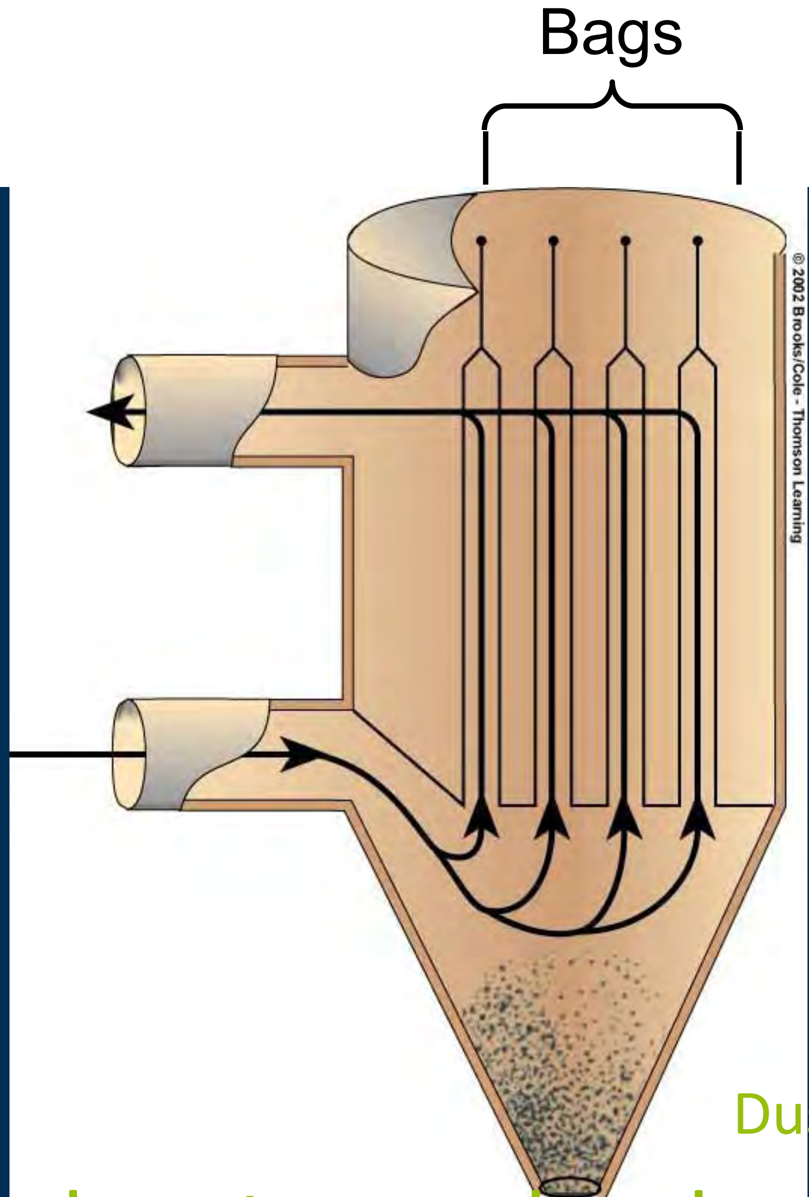


Air Filtration

- Impaction
- Diffusion
- Straining (Interception)
- Electrostatics

Air Filter

- High removal efficiency for < 5 µm particles



Baghouse Filter – **only one to remove hazardous fine particles**

Advantages/Disadvantages

- Very high collection efficiencies
- Pressure drop reasonably low (at beginning of operation, must be cleaned periodically to reduce)
- Can’t handle high T flows or moist environments

Fabric Filters / Baghouses

Advantages: Good efficiency for various sizes of particles

Disadvantages: Not to be used around corrosive substances, explosive gases, or sticky and wet particles

ADVANTAGES OF FABRIC FILTERS

- Very high collection efficiency
- They can operate over a wide range of volumetric flow rates
- The pressure drops are reasonably low.
- Fabric Filter houses are modular in design, and can be pre-assembled at the factory

FABRIC FILTERS (CONTD.)

Disadvantages of Fabric Filters

- Fabric Filters require a large floor area.
- The fabric is damaged at high temperature.
- Ordinary fabrics cannot handle corrosive gases.
- Fabric Filters cannot handle moist gas streams
- A fabric filtration unit is a potential fire hazard

DESIGN OF FABRIC FILTERS

- The equation for fabric filters is based on Darcy's law for flow through porous media.
- Fabric filtration can be represented by the following equation:

  $S = K_e + K_s w$

  Where,

  S = filter drag, N-min/m^3

  K_e = extrapolated clean filter drag, N-min/m^3

  K_s = slope constant. Varies with the dust, gas and fabric, N-min/kg-m

  W= Areal dust density = LVt, where

  L = dust loading (g/m3), V = velocity (m/s)
- Both K_e and K_s are determined empirically from pilot tests.

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Fabric Filters

$$\Delta P = \Delta P_f + \Delta P_p + \Delta P_s$$

ΔP ⟶ Total pressure drop

ΔP_f ⟶ Pressure drop due to the fabric

ΔP_p ⟶ Pressure drop due to the particulate layer

ΔP_s ⟶ Pressure drop due to the bag house structure

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Darcy's equation

$$\Delta P_f = \frac{D_f \mu V}{60\ K_f} \qquad \Delta P_p = \frac{D_p \mu V}{60\ K_p}$$

ΔP_f	Pressure drop N/m^2
ΔP_p	Pressure drop N/m2
D_f	Depth of filter in the direction of flow (m)
D_p	Depth of particulate layer in the direction of flow (m)
μ	Gas viscosity kg/m-s
V	superficial filtering velocity m/min
K_f, K_p	Permeability (filter & particulate layer m^2)
60	Conversion factor δ/min
	V = Q/A
Q	volumetric gas flow rate m^3/min
A	cloth area m^2

Dust Layer

$$D_p = \frac{LVt}{\rho_L}$$

L	Dust loading kg/m³
t	time of operation min
ρ_L	Bulk density of the particulate layer kg/m³

$\Delta P = \Delta P_f + \Delta Pp$

$$\Delta P = \left(\frac{D_f \mu}{60K_f}\right) V + \left(\frac{\mu}{60K_p \rho_l}\right) LVt\, V$$

$$\frac{\Delta P}{V} = k_1 + k_2\,(LVt)$$

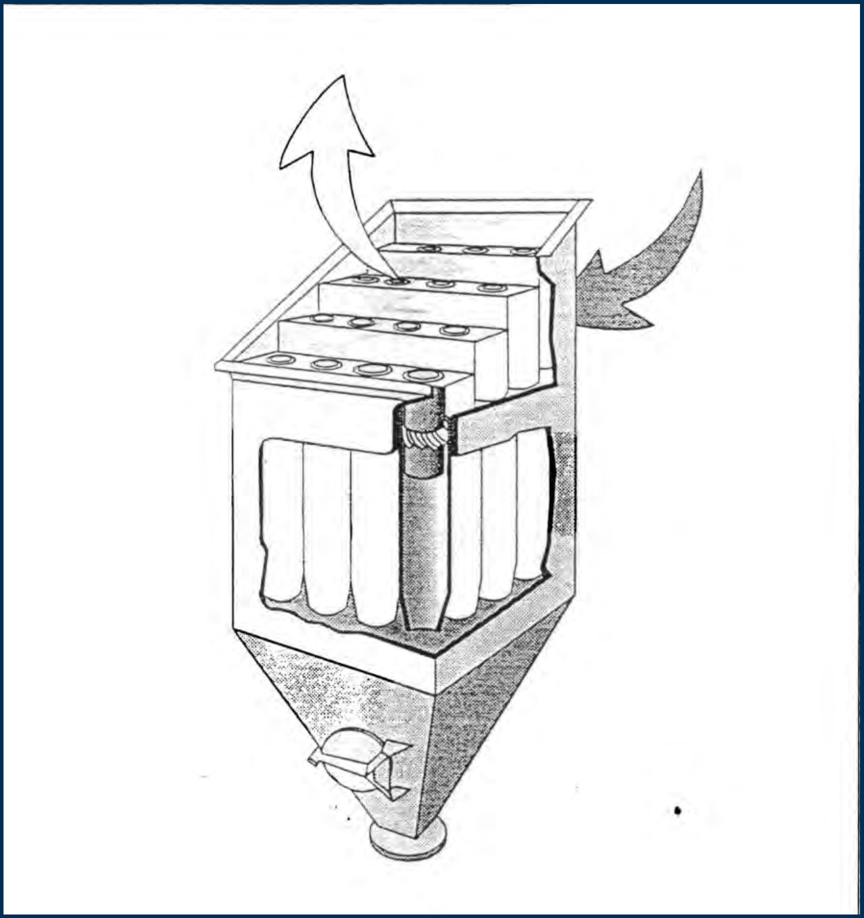
Filter Drag S = $\Delta P/V$

Areal dust density W = LVt

$S = k_1 + k_2 W$

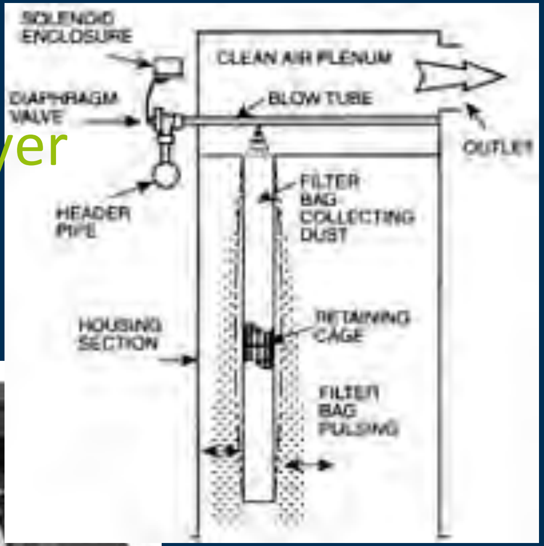
Wet Particle Scrubbers

- Particulate control by impaction, interception with water droplets
- Can clean both gas and particle phases
- High operating costs, high corrosion potential



Baghouse Filters

- Particulate control by impaction, interception, diffusion on fabric & dust layer



Baghouses

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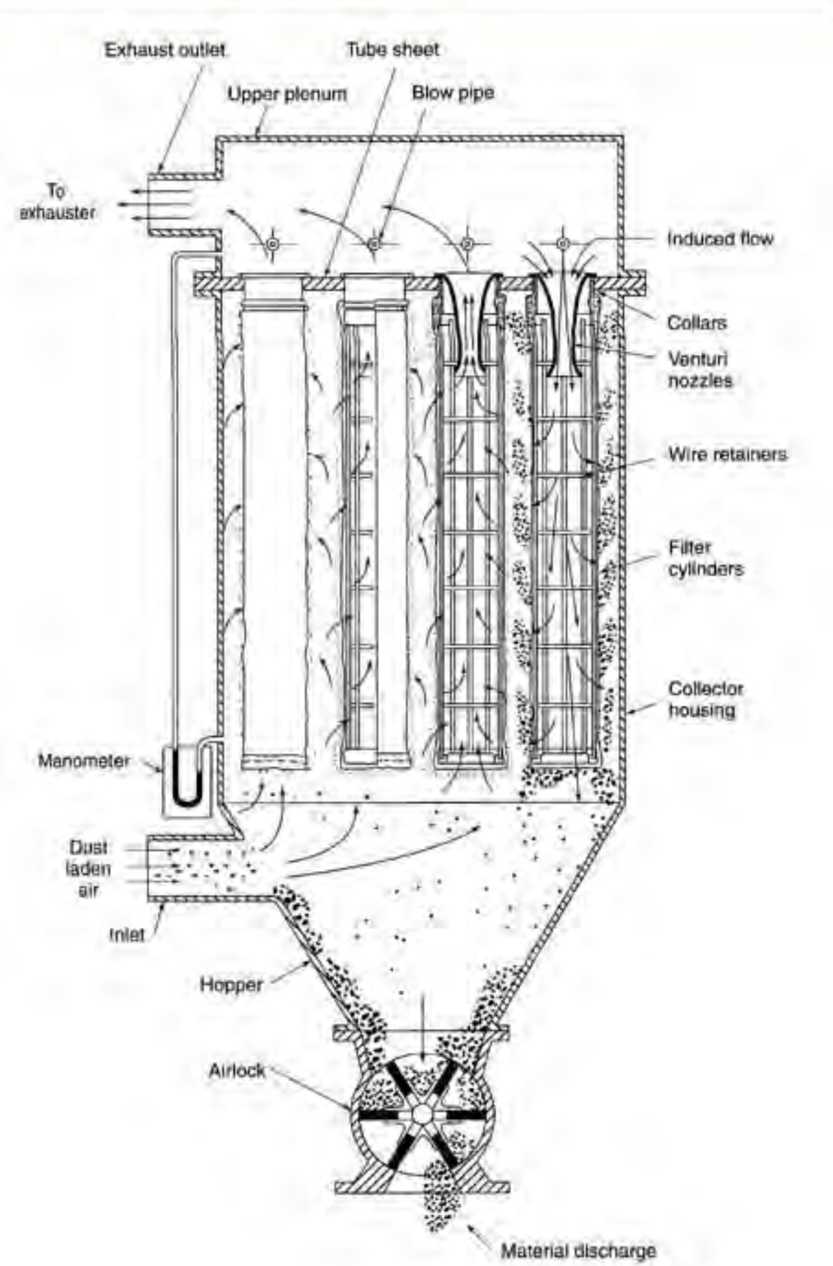
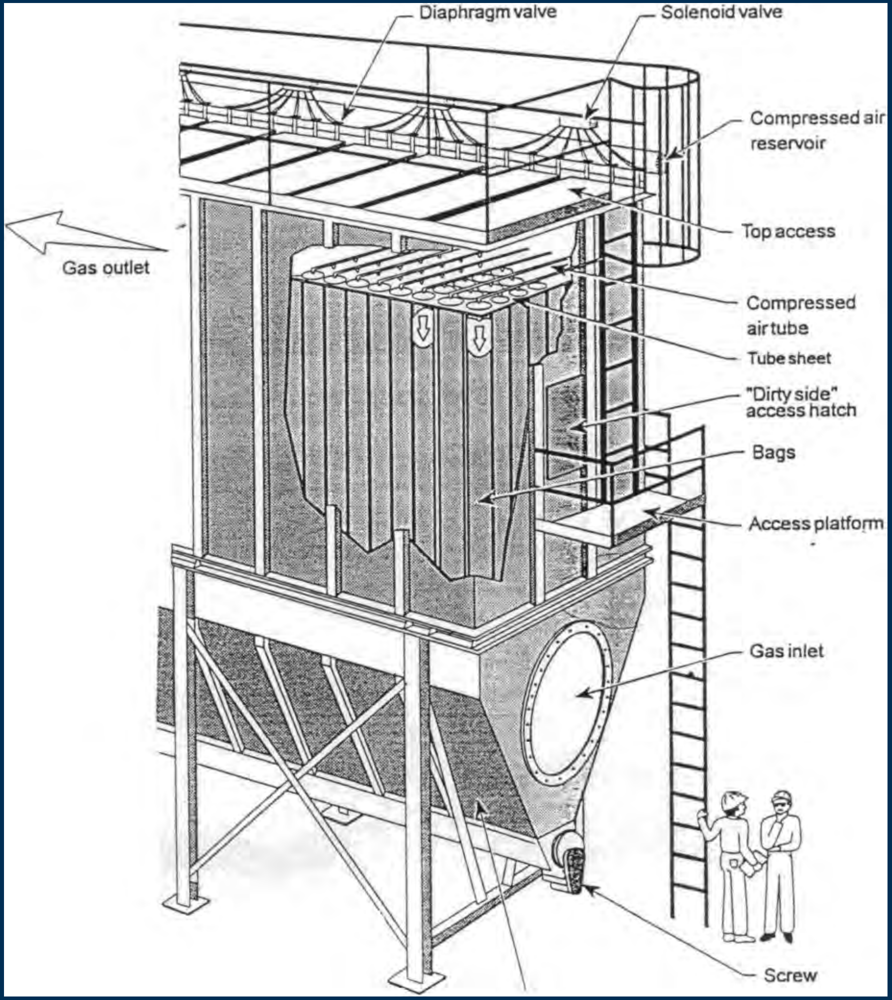
- Fabric filtration – vacuum cleaner
- High removal efficiency for small particles
- Not good for wet or high temperature streams
- Uses fabric bags to filter out PM
- Inexpensive to operate (process based)
- Bags cleaned by periodic shaking or air pulse
- Creates solid-waste stream

Pulse-Air-Jet Type Baghouse




Diaphragm valve
Solenoid valve
Compressed air reservoir
Top access
Gas outlet
Compressed air tube
Tube sheet
"Dirty side" access hatch
Bags
Access platform
Gas inlet
Screw

About Baghouses

Efficiency Up To 97+%

(Cyclone Efficiency 70-90%)

Can Capture Smaller Particles Than A Cyclone

More Complex, Cost More To Maintain Than Cyclones plasma for environment protection

Types of Baghouses

- The three common types of baghouses based on cleaning methods
  a. Reverse-air
  b. Shaker
  c. Pulse-jet

ELECTROSTATIC PRECIPITATOR (CONTD.)

- **Advantages of Electrostatic Precipitators**

- Electrostatic precipitators are capable very high efficiency, generally of the order of 99.5-99.9%.
- Since the electrostatic precipitators act on the particles and not on the air, they can handle higher loads with lower pressure drops.
- They can operate at higher temperatures.
- The operating costs are generally low.

- **Disadvantages of Electrostatic Precipitators**

- The initial capital costs are high.
- Although they can be designed for a variety of operating conditions, they are not very flexible to changes in the operating conditions, once installed.
- Particulate with high resistivity may go uncollected.

Electrostatic Precipitator (ESP)

- High Efficiency
- Able to Handle Large Air Flow Rates
- Or Can Be Very Small (Smoke Eaters In Bars and Restaurants)

Type 4: Electrostatic Precipitators

Types include:

- Dry, negatively charged
- Wet-walled, negatively charged
- Two-stage, positively charged

Electrostatic Precipitators

Advantages: Good efficiency

Disadvantages: Dependent upon resistivity of PM, cannot be used around explosive gases plasma for environment protection

DESIGN OF ELECTROSTATIC PRECIPITATORS

- The efficiency of removal of particles by an Electrostatic Precipitator is given by

$$\eta = 1 - e^{\left(-\frac{wA}{Q}\right)}$$

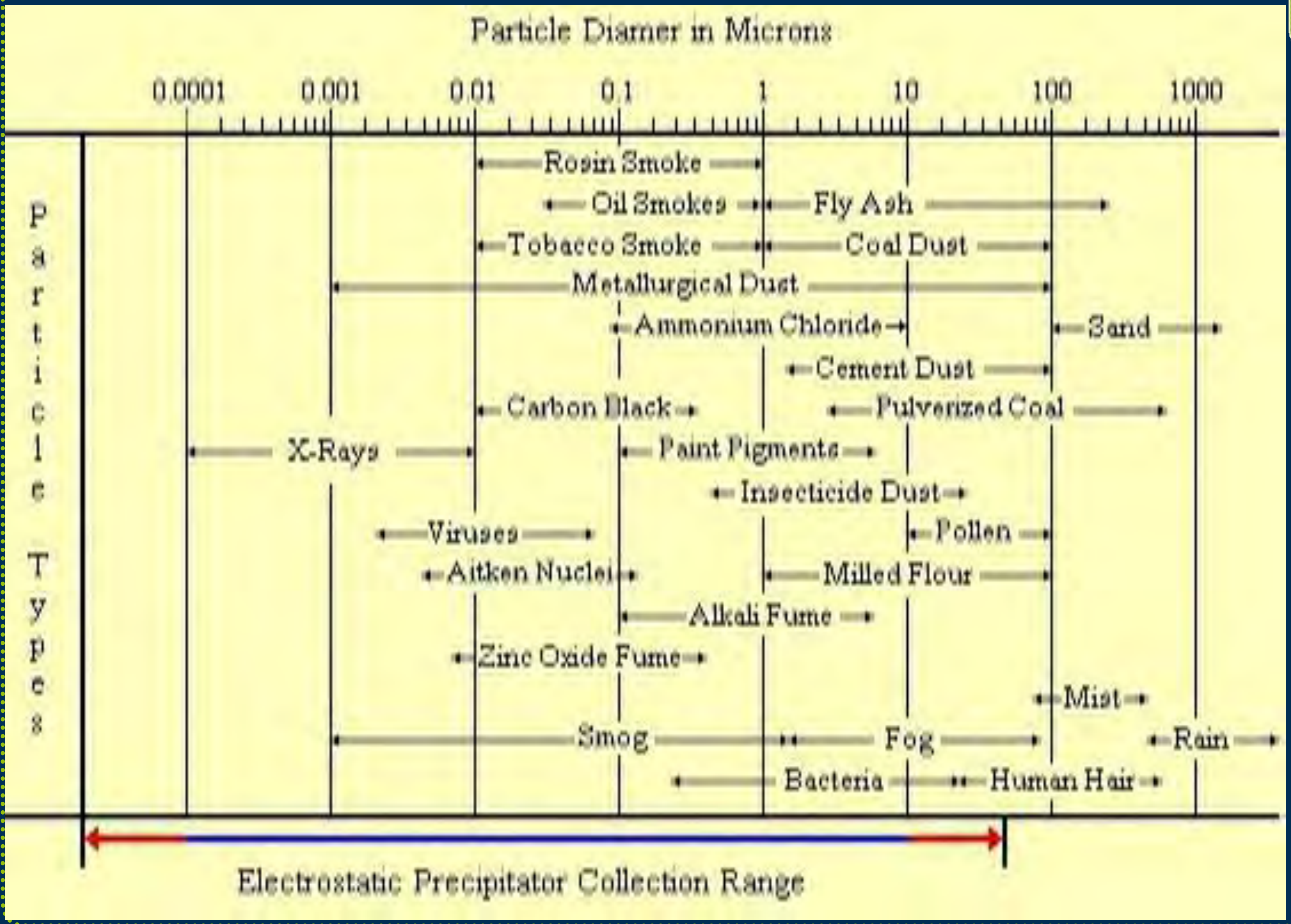
η = fractional collection efficiency

w = drift velocity, m/min.

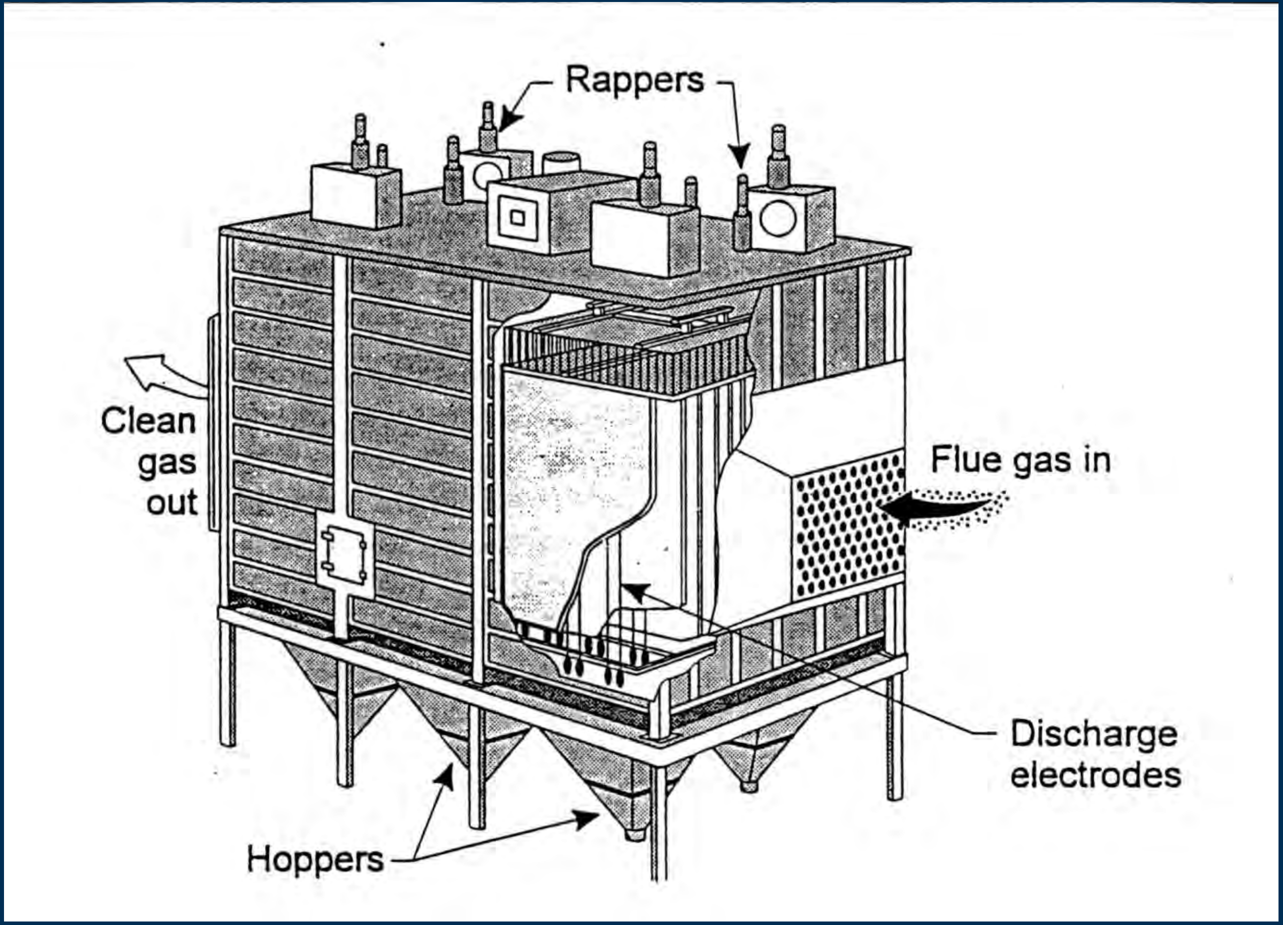
A = available collection area, m^2

Q = volumetric flow rate m^3/min

http://www.ppcbio.com/ppcdespwhatis.htm



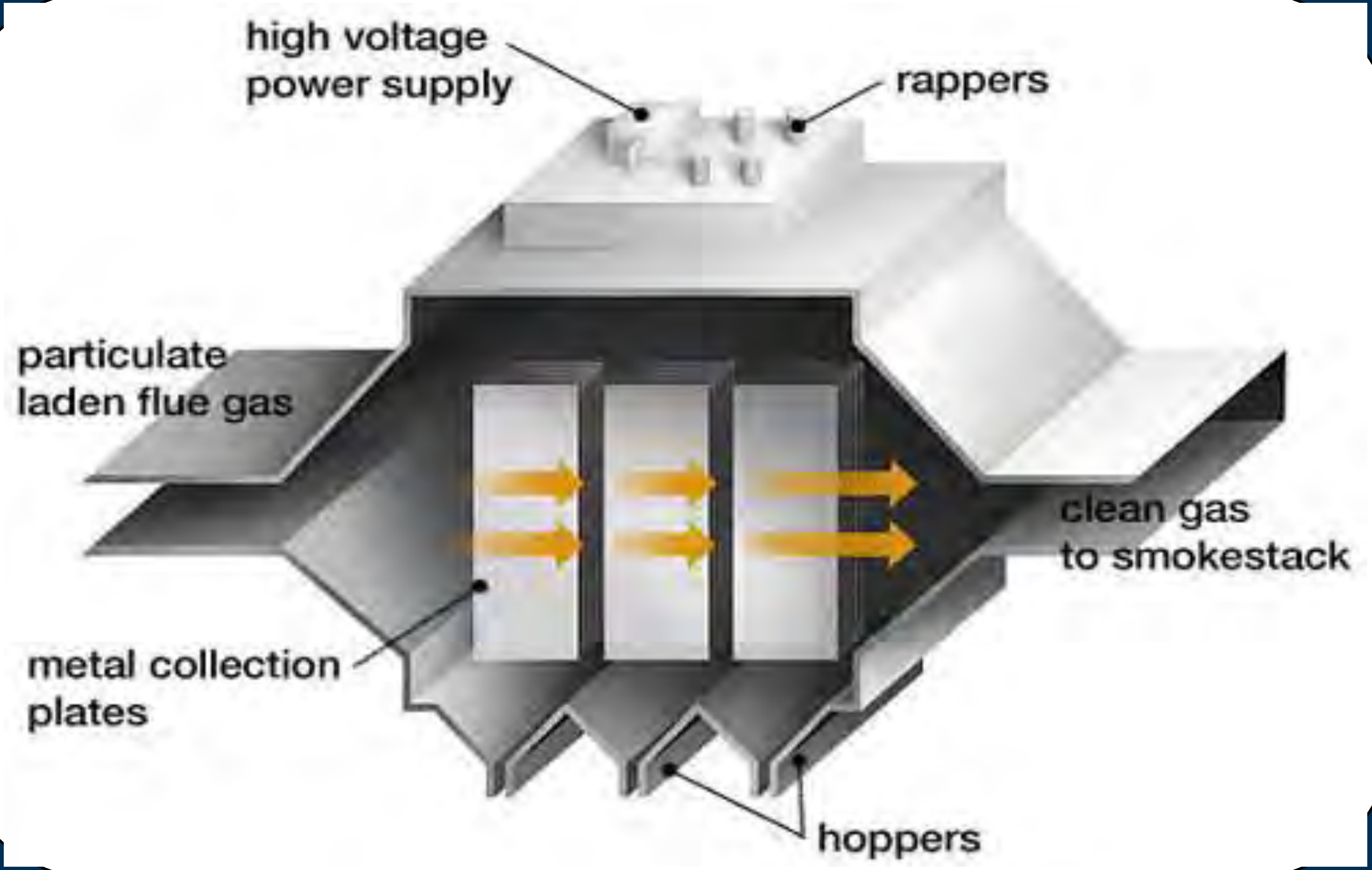
Electrostatic Precipitator Drawing



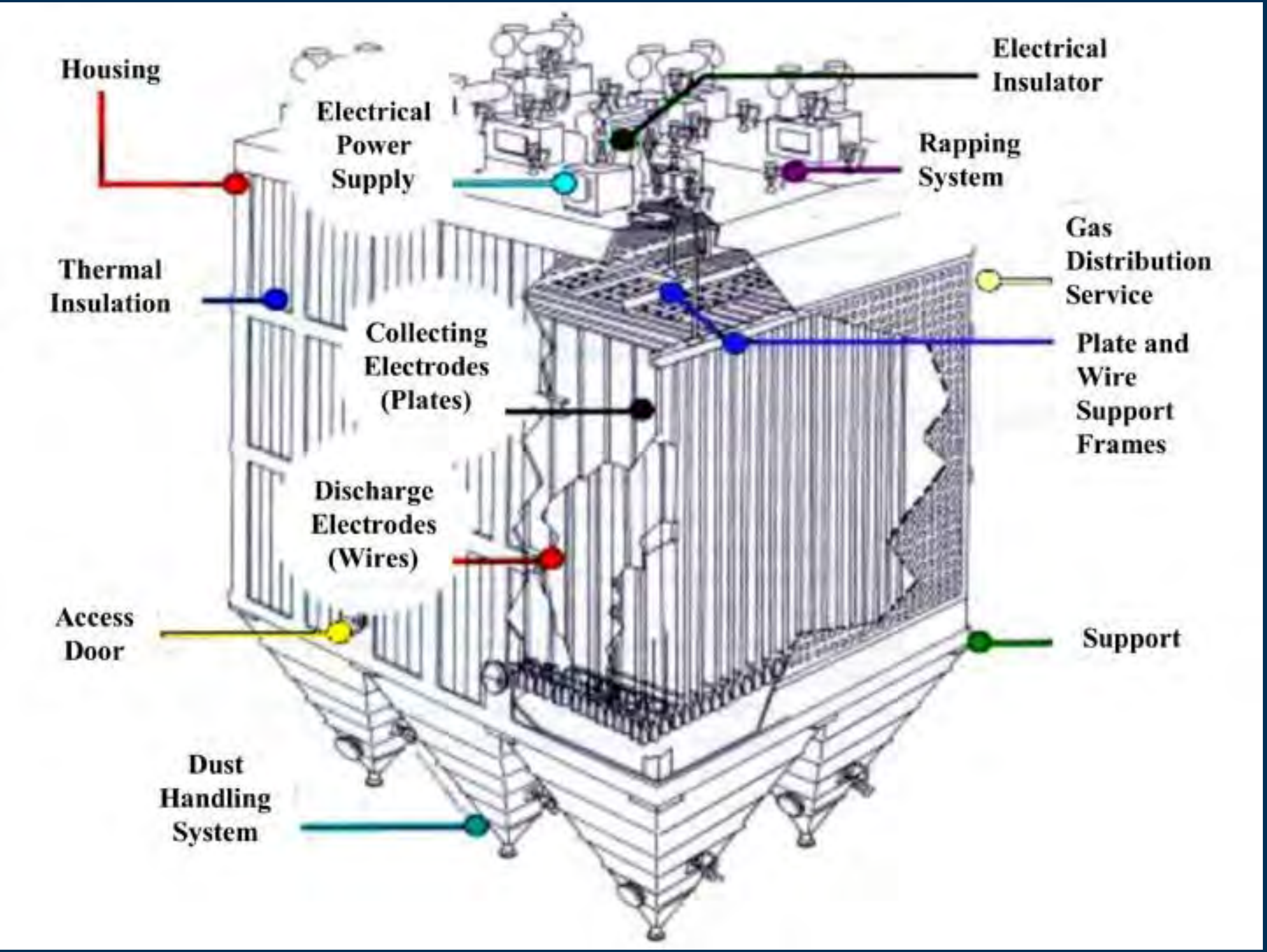
ESPs

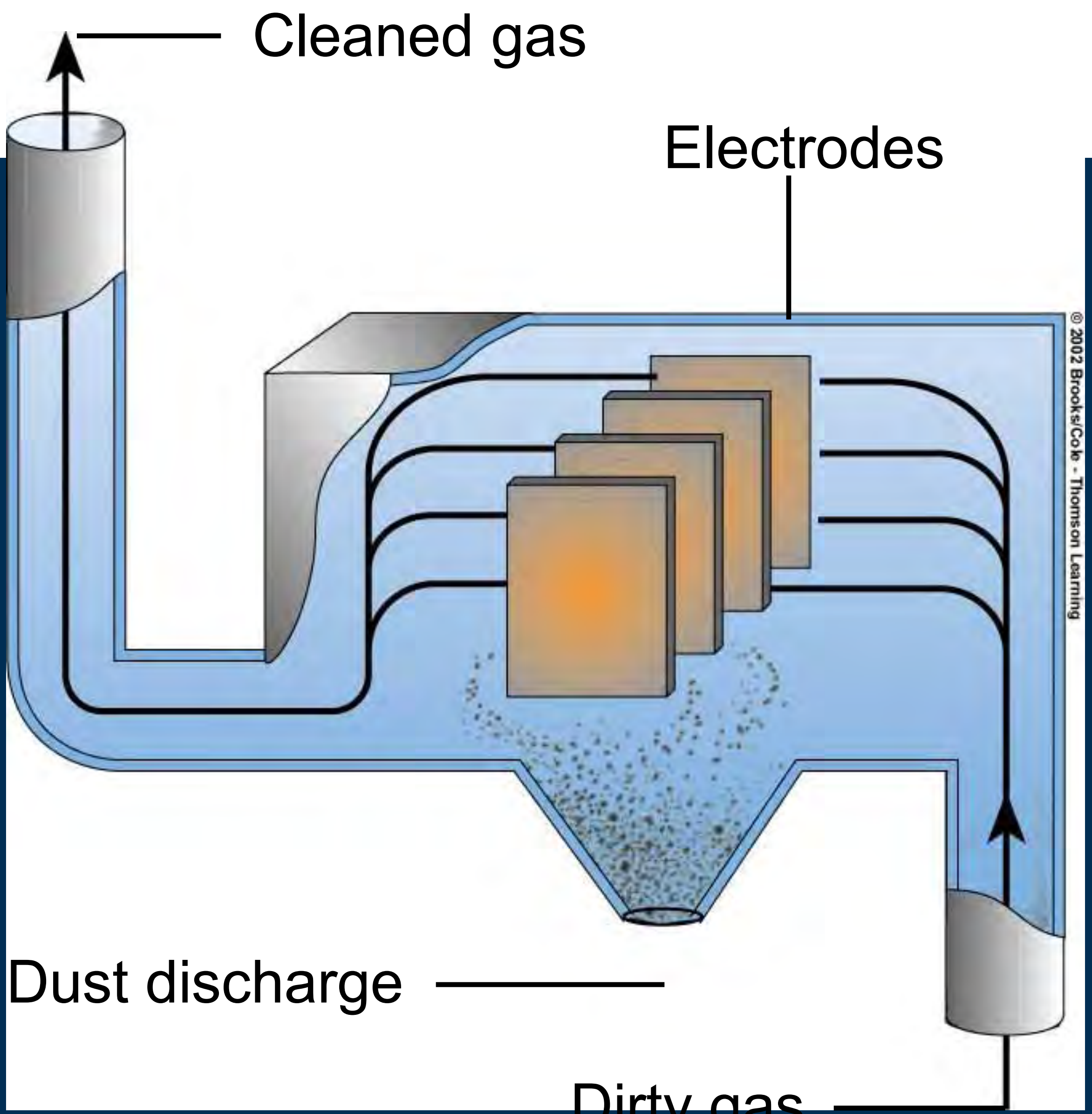
- Electrostatic precipitator
- More expensive to install,
- Electricity is major operating cost
- Higher particulate efficiency than cyclones
- Can be dry or wet
- Plates cleaned by rapping
- Creates solid-waste stream
- Picture on next slide

Electrostatic Precipitator Concept



Electrostatic Precipitator





Electrostatic Precipitator – **static plates collect particles**

Principle

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High-Voltage Charges Wires

Gases Are Ionized

Particles Become Charged

Collection Plates (Opposite Charge) Attract Particles

Rapper Knocks Plates So That The Collected Dust Layer Falls Into Hoppers

Wet Type

- Venturi
- Static packed
- Moving bed
- Tray tower
- Spray towers

Scrubbers

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- Gas Contacts A Liquid Stream
- Particles Are Entrained In The Liquid
- May Also Be A Chemical Reaction
- Example: Limestone Slurry With Coal Power Plant Flue Gas

Scrubbers

Advantages: Good efficiency, can collect (potentially explosive) gaseous pollutants as well as PM, small size

Disadvantages: Requires a lot of water, generates waste stream

SCRUBBER

- **Efficiency**

$$\eta = 1 - Exp\ (-KR\sqrt{\psi})$$

where,

k = Scrubber coefficient (m^3 of gas/ m^3 of liquid)

R = Liquid-to-gas flow rate (Q_L/Q_G)

ψ = internal impaction parameter

- Internal impaction parameter

$$\psi = \frac{c\ \rho_p V_g (d_p)^2}{18\ d_d \mu}$$

where,

c = cunningham correction factor

ρ_p = particle density (kg/m^3)

Vg = speed of gas at throat (m/sec)

d_p = diameter of particle (m)

d_d = diameter of droplet (m)

μ = dynamic viscosity of gas, (Pa-S)

WET SCRUBBERS (CONTD.)

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Advantages of Wet Scrubbers

Wet Scrubbers can handle incoming streams at high temperature, thus removing the need for temperature control equipment.

- Wet scrubbers can handle high particle loading.
- Loading fluctuations do not affect the removal efficiency.
- They can handle explosive gases with little risk.
- Gas adsorption and dust collection are handled in one unit.
- Corrosive gases and dusts are neutralized.

Disadvantages of Wet Scrubbers

- High potential for corrosive problems
- Effluent scrubbing liquid poses a water pollution problem.

Venturi Scrubber

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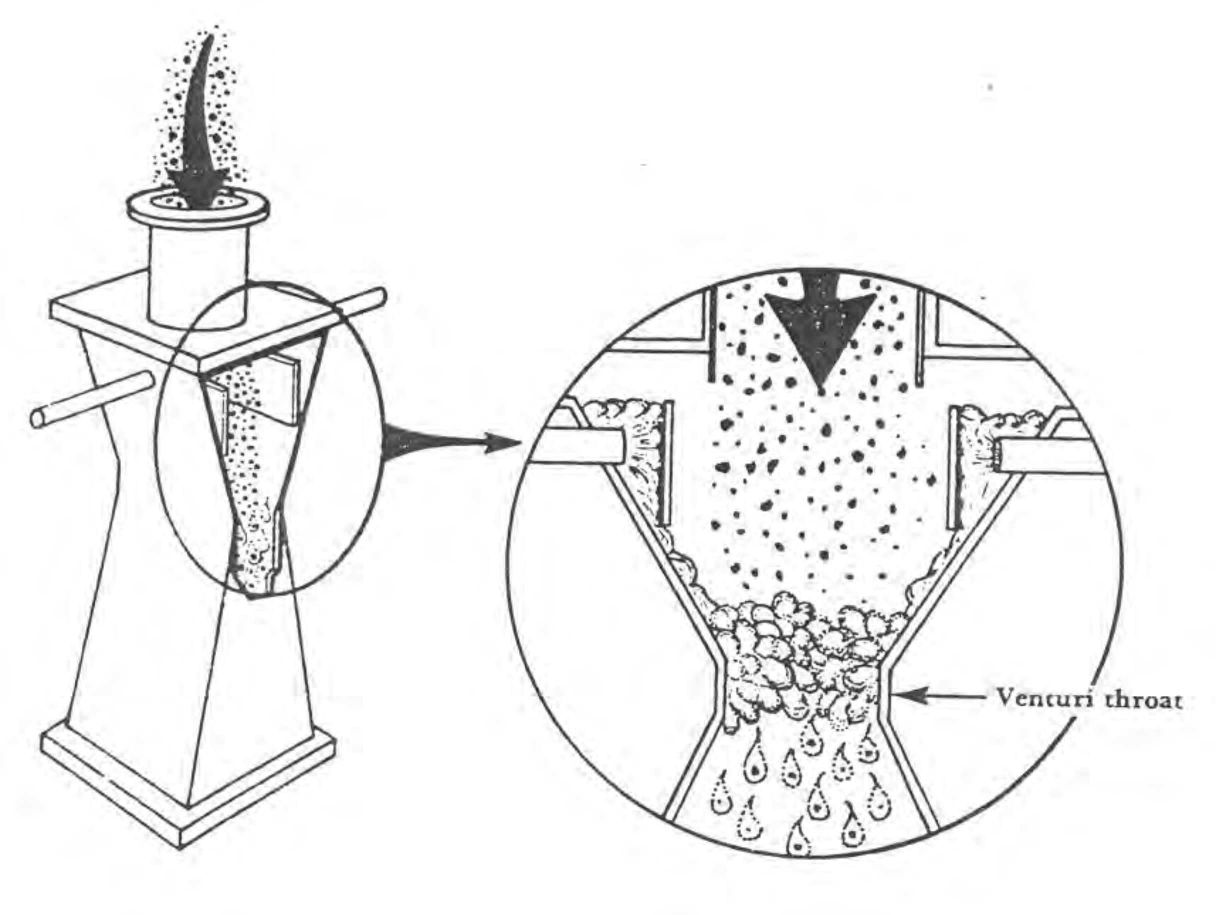
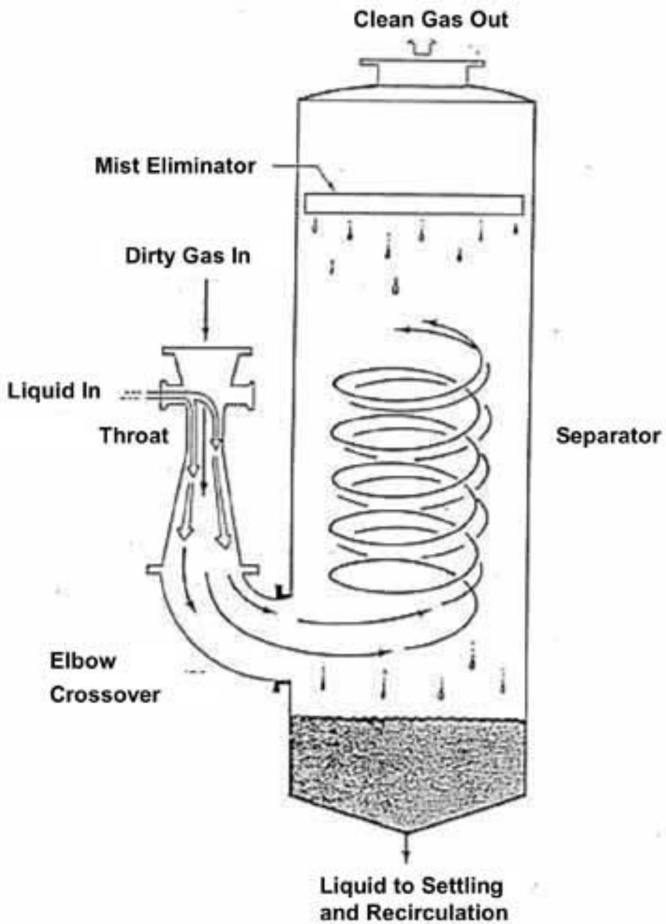
- High intensity contact between water and gas => high pressure drop
- Venturi action modified spray tower
- High removal efficiency for small particles
- Creates water pollution stream
- Can also absorb some gaseous pollutants (SO_2)

Venturi Scrubber



Detail illustrates cloud atomization from highvelocity gas stream shearing liquid at throat

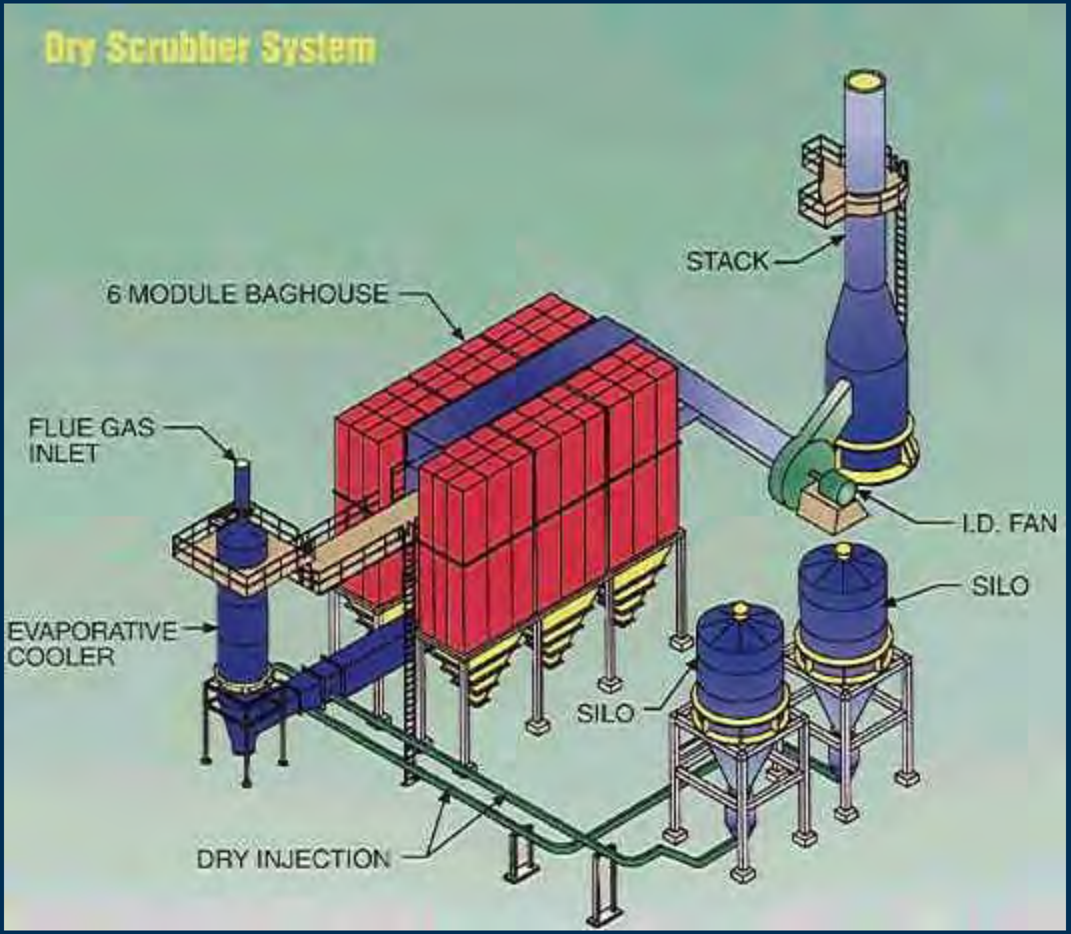


Typical Venturi Scrubber with a cyclone separation configuration

Vertical Venturi Scrubber

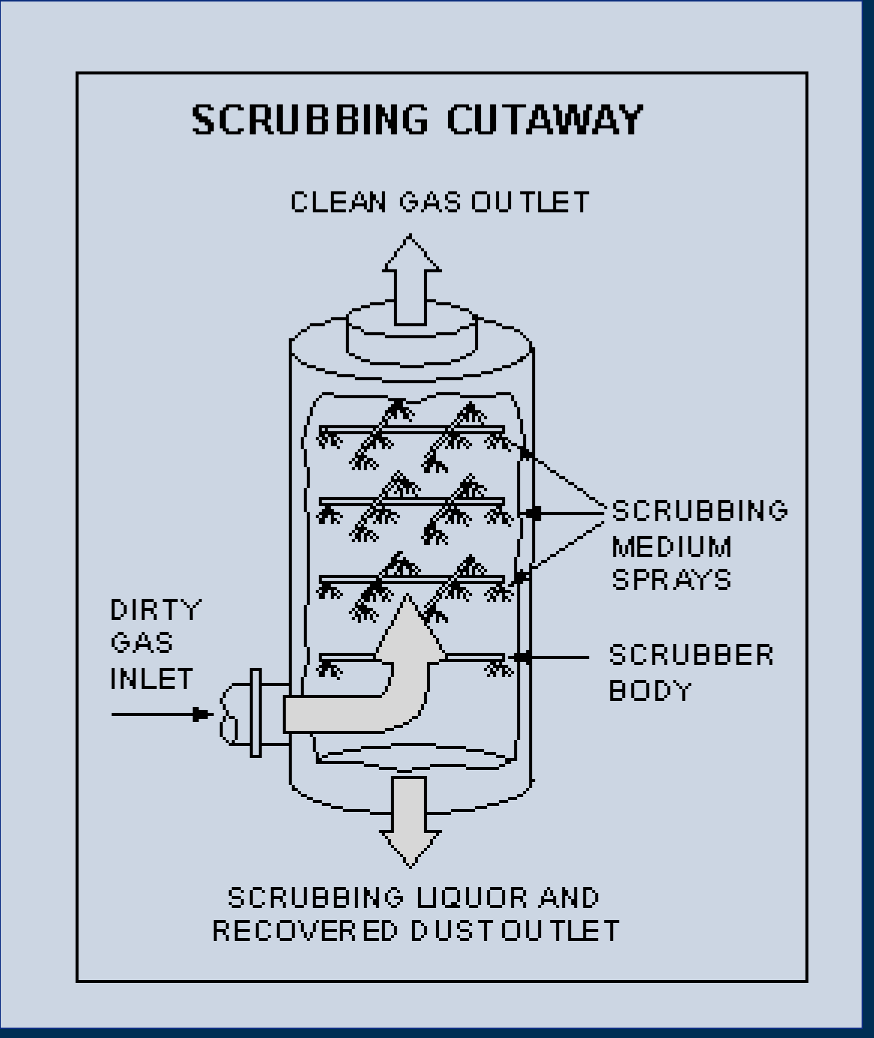
Packed Bed Scrubber

Dry Scrubber System



http://www.fkinc.com/dirctspraydry.htm#topca

Tower Scrubber



Spray Tower

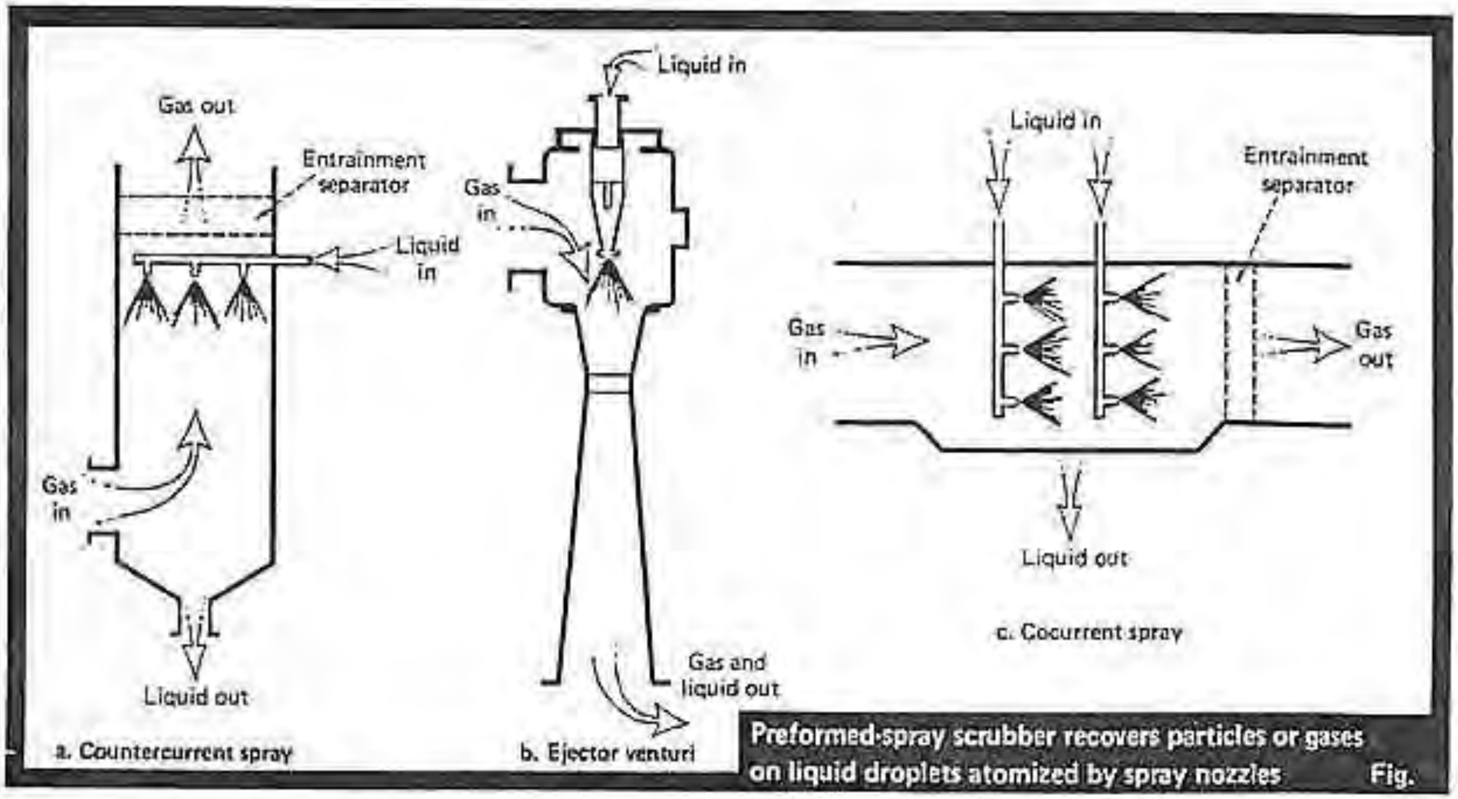


Figure 4b Adapted from Calvert (1977).