CEV4512 INDUSTRIAL AIR POLLUTION CONTROL

YTU
Environmental Engineering Department

COURSE OUTLINE

1	Introduction
2	Process Design – Overview of APC Units - Gas Control units
3	Process Design – Overview of APC Units -Gas Control units
4	Process Design – Process Flowsheets
5	Process Design – Material and Energy Balance
6	Economic Aspects and Feasibility Studies of APC
7	Design of Waste Gas Collection Systems
8	Design of Waste Gas Collection Systems
9	MIDTERM
10	Design of Waste Gas Collection Systems
11	Industral applications
12	Industral applications
13	Industral applications
14	FINAL

CHAPTER 1
Air Pollution Control Equipment Overview

OUTLINE

- Control of primary particulates (1)
  - Gravity Settler (17)
  - Cyclones (18)
  - Electrostatic precipitators
  - Fabric filters
  - Particulate scrubbers
  - HEPA filters
- Control of primary gases
  - Adsorbers
  - Absorbers
  - Incinerators
  - DeNOx systems
  - Biofilters

CONTROL OF PRIMARY PARTICULATES (1/50)

Precleaners | Primary control units

Gravity settlers
Mechanical collectors
Cyclone separators

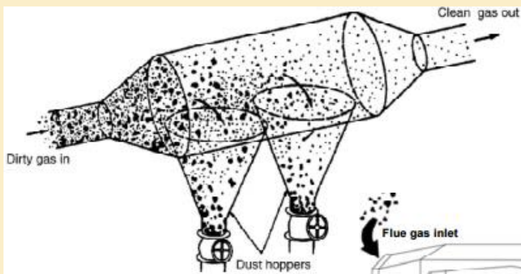
Electrostatic precipitators
Particulate scrubbers
Fabric filters
HEPA filters

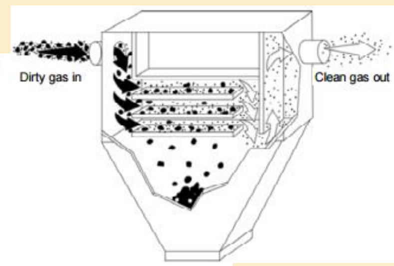
CONTROL OF PRIMARY PARTICULATES (2/50)

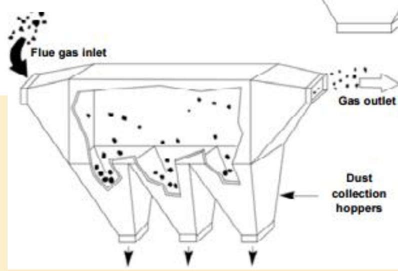
- Settling Chambers (1/17)
  - Removal of PM at reduced gas velocities by gravitational settling
  - Two main types
    - Gravity settlers
      - Horizontal flow
    - Elutriators
      - Vertical flow
      - Usually designed to remove PM greater than a specified size
  - Gravity settlers (1/10)
    - Applicable to particles of aerodynamic diameter (d_p) > 10μ
    - Usually applied to d_p > 50μ

CONTROL OF PRIMARY PARTICULATES (3/50)

- Settling Chambers (2/17)
  - Gravity settlers (2/10)







CONTROL OF PRIMARY PARTICULATES (4/50)

- Settling Chambers (3/17)
  - Gravity settlers (3/10)
    - Achievable emission limits (1/1)
      - Collection efficiency varies with
        - Particle size
        - Gravity settler's design
      - Most effective for large and dense particles
      - Settling velocities > 13 cm/s, which is the case if
        - d_p > 50μ for low density particles
        - d_p > 10μ for high density particles
        - Smaller particles require excessive horizontal distances & excessive settler volumes
      - Collection efficiency for PM_{10} < 10% (usually)
      - Multiple-tray types increase collection efficiencies
        - Reasonably acceptable efficiencies for d_p > 15μ

    Applicable to point sources

CONTROL OF PRIMARY PARTICULATES (5/50)

- Settling Chambers (4/17)
  - Gravity settlers (4/10)
    - Theory of operation (1/2)
      - Simplest and oldest particle collector
      - Usually built in the form of long, horizontal, rectangular chambers with
        - An inlet on one end and an exit at the side or top of opposite end
      - Flow within must be horizontal and uniform without macroscopic mixing
        - Usually ensured by flow straighteners at the inlet
      - Settled particles are withdrawn from hoppers
        - Via drag scrapers and screw conveyers
      - Dust removal system must be sealed to prevent air leak into chamber which
        - Causes increased turbulence within chamber
        - Causes dust re-entrainment
        - Prevents dust from being properly discharged from the device

CONTROL OF PRIMARY PARTICULATES (6/50)

- Settling Chambers (5/17)
  - Gravity settlers (5/10)
    - Theory of operation (2/2)
      - Two main types
        - Expansion chambers
          - Gas velocity is reduced in a large chamber
        - Multiple-tray chambers
          - Settling distance is reduced by building multiple trays for particles to settle out
          - Requires lower volumes than expansion chambers to obtain same collection efficiency for a given particle size
      - Efficiency of gravity settlers increases with residence time
        - Gas velocity is an important design parameter
          - Too high, then particles re-entrain
          - Too low, then unreasonably large chambers are required
        - Size of gravity settler are usually determined by gas velocity
          - Restrict gas velocity to less than 3 m/s (preferably less than 0.3 m/s)

CONTROL OF PRIMARY PARTICULATES (7/50)

- Settling Chambers (6/17)
  - Gravity settlers (6/10)
    - Gas stream characteristics (1/1)
      - Air flow
        - Size is restricted to 4.25 m for shipping restrictions
        - This size usually corresponds up to 45 Nm^3/s
        - Typical gas loads range between 0.23 and 0.45 Nm^3/s per m^3 of chamber volume
      - Temperature
        - Limited by the materials of construction
        - Usually allows up to 540 °C
      - Pollutant loading
        - Usually 22 to 4900 g/Nm^3 for expansion chambers
        - Less than 2.5 g/Nm^3 for multiple-tray chambers
      - Other considerations
        - Leakage of cold air results in quenching & condensation.
          - Condensation cause corrosion, dust buildup, plugging of hopper
          - Use thermal insulation to keep temperature above dew point to prevent it.

CONTROL OF PRIMARY PARTICULATES (8/50)

- Settling Chambers (7/17)
  - Gravity settlers (7/10)
    - Pretreatment requirement: None
    - Advantages
      - Low capital cost
      - Very low energy cost
      - No moving parts. Requires few maintenance and causes low operating costs
      - Excellent reliability
      - Low pressure drop
      - Not subject to abrasion due to low gas velocities
      - Provide incidental cooling of gas stream
      - Dry collection and disposal
      - Temperature & pressure limitations depend only on the materials of construction

CONTROL OF PRIMARY PARTICULATES (9/50)

- Settling Chambers (8/17)
  - Gravity settlers (8/10)
    - Disadvantages
      - Relatively low PM collection efficiencies
        - Particularly for d_p > 15μ
      - Unable to handle sticky materials
      - Large physical size
      - Trays in multiple tray chamber may warp at high temperatures
    - Other considerations
      - Most common failure is plugging
        - In expansion chambers → results in hopper discharge seal failure
        - In multiple-tray chambers → results in plugging individual gas passages
        - Prevented by using hopper level indicators or continous monitoring
      - Scheduled internal inspection for air leakage and condensation
      - Instrumentation: A differential static pressure sensor to monitor level of plugging

CONTROL OF PRIMARY PARTICULATES (10/50)

- Settling Chambers (9/17)
  - Gravity settlers (9/10)
    - Typical industrial applications (1/1)
      - Have been used extensively in the past.
      - Metal refining plants
        - To collect large particles such as arsenic trioxide from smelting
      - Power and heating plants
        - To collect large, unburned carbon particles for re-injection into the boiler
      - Good for cooling the gas stream prior to fabric filter
        - Especially if sparks exist, gravity settlers are used as spark traps to prevent fabric filters from catching fire
      - Usually applied to prevent abrasion or excessive dust loadings in primary devices
      - Upstream use has declined due to more efficient devices, and increasing space restrictions
      - Multiple-tray chambers have never been used widely because of difficulty in removing settled dust from horizontal trays

CONTROL OF PRIMARY PARTICULATES (11/50)

- Settling Chambers (10/17)
  - Gravity settlers (10/10)
    - Costs (2015 dollars)
      - Materials and manufacturing sector depends on imports of materials
        - Costs are given in dollars
      - In terms of 2015 dollars
      - Beware of inflation effects and exchange rates
      - For
        - Gas loadings of 0.22 to 0.45 Nm^3/s per m3 of chamber volume,
        - Particulate concentrations of 22 to 4900 g/Nm^3
        - Collection efficiency of 50%
      - Capital cost: \$570 – \$18,850 per Nm^3/s
      - Annual O&M cost: \$22 – \$810 per Nm^3/s
      - Cost effectiveness: \$0.02 – \$6.70 per metric ton of pollutant controlled

CONTROL OF PRIMARY PARTICULATES (12/50)

- Settling Chambers (11/17)
  - Elutriators (1/7)
    - Used to collect particles geater than a specified size
    - Applicable to d_p > 10µ
    - Achievable emission limits (1/1)
      - Collection efficiency varies with
        - Particle size
        - Elutriator design
        - Increases with particle size, decreases with gas velocity & number of vertical tubes
      - Settling velocities > 13 cm/s, which is the case if
        - d_p > 50µ for low density particles
        - d_p > 10µ for high density particles
        - Smaller particles require excessive vertical distances & excessive elutriator volumes
      - Collection efficiency for PM_{10} < 10% (usually)

    Applicable to point sources

CONTROL OF PRIMARY PARTICULATES (13/50)

- Settling Chambers (12/17)
  - Elutriators (2/7)
    - Theory of operation (1/1)
      - Essentially a vertical settling chamber
      - Consists of one or more tubes in series
      - Large particles with terminal settling velocities greater than gas velocity settles
      - Allows selection of particles size to be collected by changing gas velocity
      - Size classification is possible by using a series of tubes with increasing diameter
      - Settled particles are collected by hoppers
      - Dust removal system must be sealed to prevent air leakage that
        - Causes turbulence within the tubes
        - Causes particle re-entrainment
        - Prevents proper dust discharge

CONTROL OF PRIMARY PARTICULATES (14/50)

- Settling Chambers (13/17)
  - Elutriators (3/7)
    - Gas stream characteristics (1/1)
      - Air flow
        - Typical flowrates are 0.23 – 3.7 Nm^3/s
      - Temperature
        - Limited by the materials of construction
        - Usually allows up to 540°C
      - Pollutant loading
        - Usually 22 to 4900 g/Nm^3 for expansion chambers
      - Other considerations
        - Leakage of cold air results in quenching & condensation.
          - Condensation cause corrosion, dust buildup, plugging of hopper
          - Use thermal insulation to keep temperature above dew point to prevent it.

CONTROL OF PRIMARY PARTICULATES (15/50)

- Settling Chambers (14/17)
  - Elutriators (4/7)
    - Pretreatment requirement: None
    - Advantages
      - Low capital cost
      - Low energy cost
      - No moving parts: Requires few maintenance and low operating costs
      - Excellent reliablity
      - Low pressure drop
      - Not subject to abrasions due to low gas velocities
      - Provide incidental cooling of gas stream
      - Temperature and pressure limitations depend only on materials of construction
      - Dry collection and disposal

CONTROL OF PRIMARY PARTICULATES (16/50)

- Settling Chambers (15/17)
  - Elutriators (5/7)
    - Disadvantages
      - Relatively low collection efficiency
      - Unsuitable for sticky materials
      - Large physical size
    - Other considerations
      - Most common failure is plugging
        - In expansion chambers → results in hopper discharge seal failure
        - In multiple-tray chambers → results in plugging individual gas passages
        - Prevented by using hopper level indicators or continous monitoring
      - Scheduled internal inspection for air leakage and condensation
      - Instrumentation: A differential static pressure sensor to monitor level of plugging

CONTROL OF PRIMARY PARTICULATES (17/50)

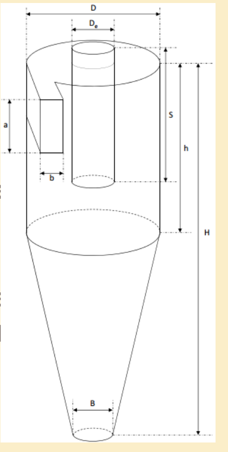
- Settling Chambers (16/17)
  - Elutriators (6/7)
    - Typical industrial applications (1/1)
      - Usually designed for specific applictions
      - Not suitable to meet stringent air pollution regulations
      - Usually applied for size classification of particles for
        - Disposal
        - Re-introduction into the process
      - Often followed by another collector (e.g., cyclones)
      - Treats the lowest volumes of flue gases
        - Thus, considered as a process control device rather than air pollution control equipment
      - Typically used in
        - Granulated plastics processes,
        - Secondary metal operations,
        - Food and agricultural processes,
        - Petrochemical industries

CONTROL OF PRIMARY PARTICULATES (18/50)

- Settling Chambers (17/17)
  - Elutriators (7/7)
    - Costs (2015 dollars) (1/1)
      - For
        - Gas loadings of 0.23 to 3.7 Nm^3/s
        - Particulate concentrations of 22 to 4900 g/Nm^3
        - Collection efficiency of 50%
      - Capital cost: \$16,600 – \$28,200 per Nm^3/s
      - Annual O&M cost: \$2,700 – \$5,400 per Nm^3/s
      - Cost effectiveness: \$0.19 – \$22.20 per metric ton of pollutant controlled

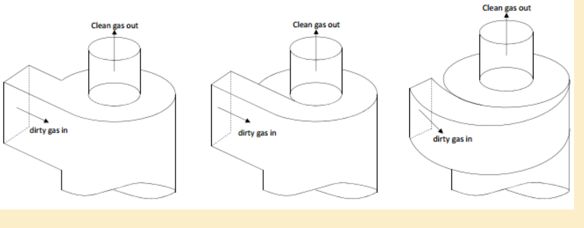
CONTROL OF PRIMARY PARTICULATES (19/50)

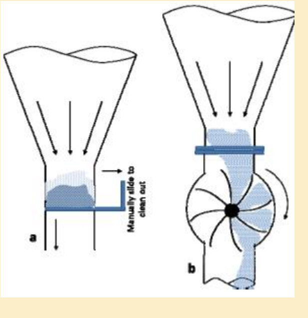
- Cyclones (1/19)
  - Watch videos provided
    - Video 1 through Video 6 for a basic understandi
      - Involve CFD-based simulations of cyclones
    - Video 7 for a sludge dewatering application
    - Video 8 and Video 9 for installing a cyclone syste
      - Clear Vue CV1800 installation
      - Nordfab ductwork installation
    - Video 10 for a review of various cyclone branche
      - DustRIGT Vortex, Clear Vue Mini CV06, and Oned
    - Video 11 through Video 17
      - For various aspects of cyclones separators
      - Focus on building cyclones



CONTROL OF PRIMARY PARTICULATES (20/50)

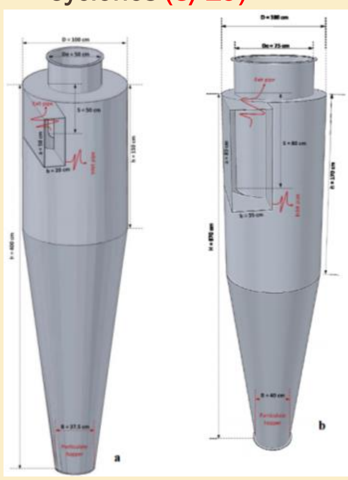
- Cyclones (2/19)

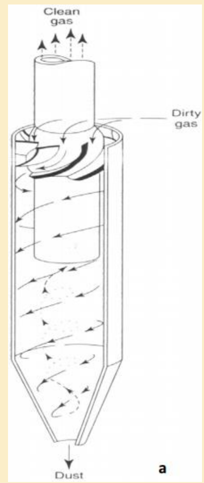


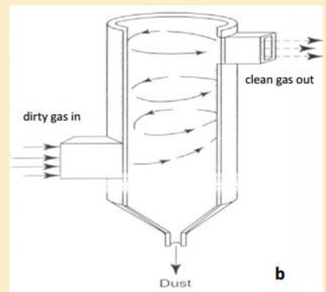


CONTROL OF PRIMARY PARTICULATES (21/50)

- Cyclones (3/19)







CONTROL OF PRIMARY PARTICULATES (22/50)

- Cyclones (4/19)
  - Used to collect particles greater than 10µ
  - Most high efficiency cyclones are designed to collect PM_{10} with reasonably high collection efficiencies
  - Achievable emission limits (1/4)
    - Collection efficiency increases with increasing
      - particle size or density
      - inlet velocity
      - cyclone body length
      - number of turns in cyclone
      - ratio of body diameter to outlet diameter
      - dust loading
      - smoothness of cyclone inner wall

CONTROL OF PRIMARY PARTICULATES (23/50)

- Cyclones (5/19)
  - Achievable emission limits (2/4)
    - Collection efficiency decreases with increasing
      - gas viscosity
      - body diameter
      - outlet diameter
      - cross sectional area of inlet duct
      - gas density
    - Air leakage into the dust outlet decreases control efficiency
    - Three main types of single cyclones
      - High-efficiency cyclones
      - Conventional cyclones
      - High-throughput cyclones

CONTROL OF PRIMARY PARTICULATES (24/50)

- Cyclones (6/19)
  - Achievable emission limits (3/4)
    - High-efficiency cyclones
      - Efficiencies range between
        - 80% and 99% for PM
        - 60% and 95% for PM_{10}
        - 20% and 70% for $PM_{2.5}$
      - High pressure drops (up to 30 cm H_2O)
    - Conventional cyclones
      - Efficiencies range between
        - 70% and 90% for PM
        - 30% and 90% for PM_{10}
        - 0% and 40% for $PM_{2.5}$
      - Moderate pressure drops (up to 15 cm H_2O)

CONTROL OF PRIMARY PARTICULATES (25/50)

- Cyclones (7/19)
  - Achievable emission limits (4/4)
    - High-throughput cyclones
      - Efficiencies range between
        - 80% and 99% for PM
        - 10% and 40% for PM_{10}
        - 0% and 10% for $PM_{2.5}$
      - High pressure drops (up to 30 cm H_2O)
    - Multicyclones
      - Efficiencies range between 80% and 95% for 5μ

CONTROL OF PRIMARY PARTICULATES (26/50)

- Cyclones (8/19)
  - Theory of operation (1/4)
    - Use centrifugal force to remova particles from the gas stream
    - Creates double vortex
      - Outer vortex. Incoming gas is forced into circular motion down the body near the inner surface
      - Inner vortex. At the bottom, gas turns and spirals up through the center tube
    - Particles are forced towards to cyclone wall by centrifugal force
      - Fluid drag force resists
        - For small particles, centrifugal force is weak. Particles leave the cyclone uncollected
        - For large particles, centrifugal force overcomes drag force. Particles are collected
    - Collected particles move downward under the effect of gravity into the hopper
    - Particles accumulated in the hopper are removed continuously/periodically

CONTROL OF PRIMARY PARTICULATES (27/50)

- Cyclones (9/19)
  - Theory of operation (2/4)
    - Classified into four types (various types also listed in various sources)
      - Depending on how the gas stream introduced
      - Depending on how the collected dust is discharged
    - Types
      - Tangential inlet, axial discharge
      - Axial inlet, axial discharge
      - Tangential inlet, peripheral discharge
      - Axial inlet, peripheral discharge
    - The most common types use tangential inlet
    - Two important parameters of performance
      - Pressure drop
      - Collection efficiency

CONTROL OF PRIMARY PARTICULATES (28/50)

- Cyclones (10/19)
  - Theory of operation (3/4)
    - Pressure drop and collection efficiency are intimately related
    - Pressure drop is very important
      - It determines operating costs
      - It determines control efficiency
    - For a given cyclone
      - Higher pressure drop means higher collection efficiency
      - Up to 25 cm H_2O (this limit should not be taken as a certain limit. Collection efficiency gradually drops as the pressure drop is increasing after some point due to re-entrainment of particles because of increased turbulence)
    - Pressure drop vs. collection efficiency
      - 500 – 1,000 Pa for low-efficiency cyclones
      - 1,000 – 1,500 Pa for medium-efficiency cyclones
      - 2,000 – 2,500 pa for high-efficiency cyclones

CONTROL OF PRIMARY PARTICULATES (29/50)

- Cyclones (11/19)
  - Theory of operation (4/4)
    - Multicyclones
      - A number of small cyclones in parallel
      - Axial inlet cyclones
      - Used when high-efficiency and large throughput is required
      - A great number of cyclones are placed in a single housing
      - Cyclones have a common inlet and outlet
    - Wet cyclonic separator
      - To enhance control efficiency, it uses a combination of
        - Centrifugal force
        - Water spray

CONTROL OF PRIMARY PARTICULATES (30/50)

- Cyclones (12/19)
  - Gas stream characteristics (1/2)
    - Air flow
      - Typical flowrates are 0.45 – 11 Nm^3/s for single cyclones
      - At the high and of above range and higher flowrates, use multiple cyclones
      - Special applications of cyclones
        - Works at flowrates up to 27.5 Nm^3/s
        - Works at flowrates as low as 0.0005 Nm^3/s (particulate sampling applications)
    - Temperature
      - Limited by the materials of construction
      - Usually allows up to 540°C

CONTROL OF PRIMARY PARTICULATES (31/50)

- Cyclones (13/19)
  - Gas stream characteristics (2/2)
    - Pollutant loading
      - Usually 2.5 to 250 g/Nm^3
      - For special applications,
        - Loadings can be as high as 17,500 g/Nm^3
        - Loadings can be as low as 1 g/Nm^3
    - Other considerations
      - More efficient with higher pollutant loadings if the device not choked
      - Higher loadings usually mean higher flow designs

CONTROL OF PRIMARY PARTICULATES (32/50)

- Cyclones (14/19)
  - Pretreatment requirement: None
  - Advantages
    - Low capital cost
    - No moving parts: Few maintenance and low operating costs
    - Relatively low pressure drop, compared to amount of PM removed
    - Temperature and pressure limitations depend on materials of construction
    - Dry collection and disposal
    - Relatively small space requirements
  - Disadvantages
    - Relatively low PM collection efficiencies, particulary for d_p < 10 μ
    - Unable to handle sticky materials
    - High efficiency units may experience high pressure drops

CONTROL OF PRIMARY PARTICULATES (33/50)

- Cyclones (15/19)
  - Other considerations
    - Using multiple cyclones (in parallel or in series)
      - Capable of treating large volumes of gas
      - Capable of achieving higher control efficiencies
      - Pressure drop increases, however
    - Several designs should be considered to achieve optimum combination of pressure drop and control efficiency

CONTROL OF PRIMARY PARTICULATES (34/50)

- Cyclones (16/19)
  - Typical industrial applications (1/2)
    - Designed for many applications
    - Incapable of meeting stringent emission limits
      - Usually serve as precleaners for more expensive devices such as
        - Fabric filters
        - Electrostatic precipitators
    - Used for recovering & recycling of food products in processes
    - Used in size classification of process materials such as catalysts
    - Used after spray dryers in food and chemical industries
    - Used after crushing, grinding, and calcinin operations in mineral industries
      - To collect salable or useful materials

CONTROL OF PRIMARY PARTICULATES (35/50)

- Cyclones (17/19)
  - Typical industrial applications (2/2)
    - Used as precleaners in ferrous and nonferrous metallurgical industries
      - To control emissions from sintering, roasters, kilns, and furnaces
    - Used for removing PM from fluid-crackin process
      - To facilitate catalyst recycling
    - Used as precleaners in fossil-fuel and wood-waste fired, industrial and commercial combustion units
      - Multiple cyclones
      - Upstream of a particulate scrubber, an electrostatic precipitator, or a fabric filter
      - To facilitate collection of $PM_{2.5}$ (greater efficiency than a single cyclone)
      - To re-inject collected fly ash into combustion unit to improve control efficiency

CONTROL OF PRIMARY PARTICULATES (36/50)

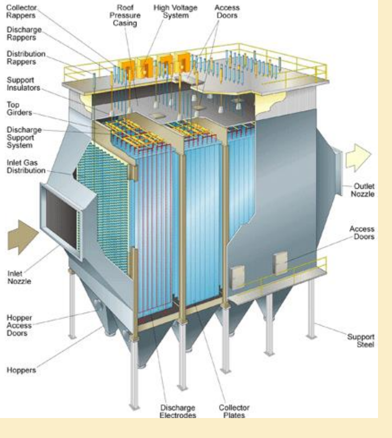
- Cyclones (18/19)
  - Costs (2015 dollars) (1/2)
    - For
      - Typical operating conditions
      - Single cyclone
      - Gas flowrates of 0.45 to 45 Nm^3/s
      - Particle loadings of 2.5 to 250 g/m^3
      - Collection efficiency of 90%
    - Costs do not involve costs for disposal or transport of collected material
    - For flowrates higher than 9–10 Nm^3/s, up to 45 Nm^3/s,
      - Use multiple cyclones
      - Same costs apply
    - Capital costs can be higher for applications which require expensive materials

CONTROL OF PRIMARY PARTICULATES (37/50)

- Cyclones (19/19)
  - Costs (2015 dollars) (2/2)
    - Capital cost: \$6,100 – \$9,850 per Nm^3/s
    - Annual O&M cost: \$2,000 – \$24,000 per Nm^3/s
    - Cost effectiveness: \$0.63 – \$585 per metric ton of collected material

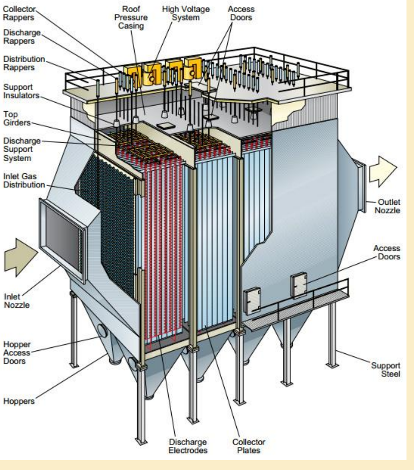
CONTROL OF PRIMARY PARTICULATES (38/50)

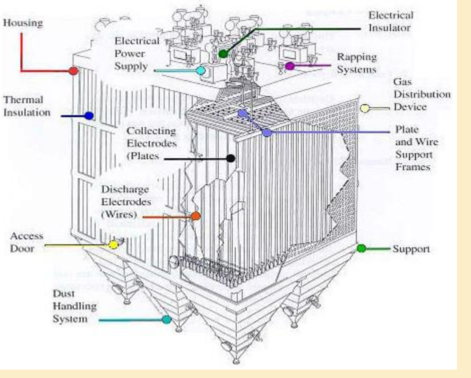
- Electrostatic Precipitators (ESPs) (1/18)
  - Watch Videos provided
    - Video 1 & Video 2
      - for operating principles of ESP
    - Video 3 for CFD simulation
    - Video 4 for Klean ESP
    - Video 7 for portable ESP
    - Video 5 for clean ESPs
    - Others
      - For miscellaneous ESP issues



CONTROL OF PRIMARY PARTICULATES (39/50)

- Electrostatic Precipitators (ESPs) (2/18)





CONTROL OF PRIMARY PARTICULATES (40/50)

- Electrostatic Precipitators (ESPs) (3/18)

CONTROL OF PRIMARY PARTICULATES (40/50)

- Electrostatic Precipitators (ESPs) (1/18)
  - Removal of particulates, including
    - PM_{10}
    - $PM_{2.5}$
    - Hazardous air pollutants (HAPs) in patriculate form
      - Mercury is in elemental vapor form
      - Excludes mercury
  - Two main types
    - Dry electrostatic precipitators
      - Wire-plate type
      - Wire-pipe type
    - Wet electrostatic precipitators
      - Wire-plate type
      - Wire-pipe type

CONTROL OF PRIMARY PARTICULATES (41/50)

- Electrostatic Precipitators (ESPs) (1/18)
  - Removal of particulates, including
    - PM_{10}
    - $PM_{2.5}$
    - Hazardous air pollutants (HAPs) in patriculate form
      - Mercury is in elemental vapor form
      - Excludes mercury
  - Two main types
    - Dry electrostatic precipitators
      - Wire-plate type
      - Wire-pipe type
    - Wet electrostatic precipitators
      - Wire-plate type
      - Wire-pipe type

CONTROL OF PRIMARY PARTICULATES (37/50)

- Electrostatic Precipitators (ESPs) (2/18)
  - Dry ESPs (1/1)
    - Achievable emission limits (1/2)
      - Collection efficiency varies with
        - Size of the ESP
        - Voltage applied
        - Distance between positively and negatively charged points
        - Dust resistivity,
        - Size distribution and chemical composition of dust
        - Gas temperature and chemical composition
      - Size is the most important factor
        - Determines treatment time
        - The longer a particle spends in ESP, the greater its chance of being collected
      - Control efficiency increases with increasing strength of electric field

CONTROL OF PRIMARY PARTICULATES (38/50)

- Electrostatic Precipitators (ESPs) (3/18)
  - Dry ESPs (2/1)
    - Achievable emission limits (2/2)
      - Older ESPs → 90% to 99.9%
      - New ones → 99% to 99.9%

Application	PM efficiency (%)	PM_{10} efficiency (%)	$PM_{2.5}$ efficiency (%)
Coal-fired boilers			
Dry bottom (bituminous)	99.2	97.7	96.0
Spreader stoker (bituminous)	99.2	99.4	97.7
Primary copper production			
Multiple hearth roaster	99.0	99.0	99.1
Reverbatory smelter	99.0	97.1	97.4
Iron and steel production			
Open hearth furnace	99.2	99.2	99.2

CONTROL OF PRIMARY PARTICULATES (39/50)

- Electrostatic Precipitators (ESPs) (4/18)
  - Dry ESPs (3/1)
    - Applicable to point sources
    - Theory of operation (1/7)
      - Uses electrical forces to move particles onto collection surfaces
      - Particles are given an electrical charge when they pass through corona
      - Electrodes are maintained at high voltage and generate the electrical field
      - Collected materials are cleaned from surfaces by
        - Rapping. In both wire-plate and wire-pipe types
        - Sonic horn. Only in wire-pipe types
      - Collected materials slide downward into the hopper
      - Hopper is evacuated periodically
        - Dust is removed through valves into dust handling system like a pneumatic conveyor

CONTROL OF PRIMARY PARTICULATES (40/50)

- Electrostatic Precipitators (ESPs) (5/18)
  - Dry ESPs (4/1)
    - Applicable to point sources
    - Theory of operation (2/7)
      - Wire-plate type
        - Gas flows horizontally and parallel to vertical plates of sheet metal
        - Plate spacing is typically between 19 to 38 cm
        - Electrodes are
          - Long wires hang between plates
          - Recently hollow pipes (25 to 40 mm in diameter)
        - The flow areas between plates are called ducts, with typically 6 to 14 m heights
        - Power supply
          - Input: Industrial AC (220 to 480 volts)
          - Output: Pulsating DC (20 kV to 100 kV)
        - Voltage applied to electrodes causes gas to break down electrically
          - An action known as corona
          - Ions generated in corona follow electric field lines from wires to plates

CONTROL OF PRIMARY PARTICULATES (41/50)

- Electrostatic Precipitators (ESPs) (6/18)
  - Dry ESPs (5/1)
    - Applicable to point sources
    - Theory of operation (3/7)
      - Wire-plate type
        - Larger particles absorb more ions than small particles
          - Electrical forces are much stronger on larger particles
        - Rapping
          - dislodges accumulated layer
          - projects some of particles back into gas stream (up to 12% for coal fly ash)
          - Re-entrained particles are collected in later sections
          - Particles re-entrained in las section have no chance to be recaptured
            - Efficiency drops
        - Non electrified clearances are necessary for internal components at the top
          - Part of gas flow around charging zones
            - Efficiency drops
            - Called sneakage. Prevented by anti-sneakage baffles

CONTROL OF PRIMARY PARTICULATES (42/50)

- Electrostatic Precipitators (ESPs) (7/18)
  - Dry ESPs (6/1)
    - Applicable to point sources
    - Theory of operation (4/7)
      - Wire-pipe type
        - Also called tubular ESP
        - Gas flows vertically through conductive tubes in parallel
        - Tubes are square or hexagonal for better geometrical placement and saving space
        - Pipes are 7 to 30 cm in diameter and 1 to 4 m in length
        - High voltage electrodes are wires o rigid masts through each tube
          - Sharp points are added to electrodes to provide additional ionization sites
        - Power supply
          - Input: Industrial AC (200 to 480 volts)
          - Output: Pulsating DC (20 kV to 100 kV)
        - Voltage applied to electrodes causes gas to break down electrically
          - An action known as corona
          - Ions generated in corona follow electric field lines from wires to plates

CONTROL OF PRIMARY PARTICULATES (43/50)

- Electrostatic Precipitators (ESPs) (8/18)
  - Dry ESPs (7/1)
    - Applicable to point sources
    - Theory of operation (5/7)
      - Wire-pipe type
        - Larger particles absorb more ions than small particles
          - Electrical forces are much stronger on larger particles
        - Sonic horn or rapping
          - dislodges accumulated layer
          - projects some of particles back into gas stream
          - Re-entrained particles are collected in later sections
          - Particles re-entrained in las section have no chance to be recaptured
            - Efficiency drops
        - No sneakage zones
        - However nonuniformities may allow some particles to avoid charging

CONTROL OF PRIMARY PARTICULATES (44/50)

- Electrostatic Precipitators (ESPs) (9/18)
  - Dry ESPs (8/1)
    - Applicable to point sources
    - Theory of operation (6/7)
      - Resistivity of collected material
        - A major concern for performance
        - Particles form a continuous layer on ESP plates/pipes
        - All the ion current must pass through layer to reach the ground
        - Current creates an electric field strong enough to cause local electrical breakdown of the cake
        - As a result, ne wions of wrong polarity between wire-pipe gap reduce charge and may cause sparking. Called BACK CORONA.
        - Back corona is prevalent when resistivity is high (usually above $2*10^{11}$ ohm.cm)
        - Too high resistivity reduces control efficiency
        - At very low resistivities (below 10^{8} ohm.cm), cake is very loose
          - Re-entrainment occurs, efficiency drops $2*10^{11}$ ohm.cm

CONTROL OF PRIMARY PARTICULATES (45/50)

- Electrostatic Precipitators (ESPs) (10/18)
  - Dry ESPs (9/1)
    - Applicable to point sources
    - Theory of operation (7/7)
      - Resistivity of collected material
        - Continously monitor resistivity
        - Resistivity changes with
          - Temperature
          - Moisture,
          - Gas composition
          - Particle composition
          - Surface characteristics
      - Specific collection area for wire-plate types
        - Ratio of surface area of electrodes to gas flow
        - Normally in the range of 45–175 m^2 per Nm^3/s, typically 80 m^2 per Nm^3/s

CONTROL OF PRIMARY PARTICULATES (46/50)

- Electrostatic Precipitators (ESPs) (11/18)
  - Dry ESPs (10/1)
    - Gas stream characteristics (1/2)
      - Air flow
        - 90 to 450 Nm^3/s for wire-plate types
          - For flowrates between 45 to 90 Nm^3/s, use flat plates instead of wires
        - 0.5 to 45 Nm^3/s for wire-pipe types
      - Temperature
        - Up to 700°C
        - Due to limitations from resistivity of dust, carefully monitor
          - Operating temperature
          - Chemical composition of dust
      - Pollutant loading
        - 2 to 110 g/m^3 for wire-plate types
        - 1 to 10 g/m^3 for wire-pipe type

CONTROL OF PRIMARY PARTICULATES (47/50)

- Electrostatic Precipitators (ESPs) (12/18)
  - Dry ESPs (11/1)
    - Gas stream characteristics (2/2)
      - Other considerations
        - Most efficient at resistivities between $5*10^3$ and $2*10^{10}$ ohm.cm
        - Particles of aerodynamic diameters between 0.1 and 1μ are most difficult to collect
        - Particles of aerodynamic diameters between 0.2 and 0.4μ show most penetration
          - Most likely a result of transition region between field and diffusion charging
    - Pretreatment requirement