Lecture 2.21

Emission Control System: Electrostatic Precipitator (ESP)

Agenda

- Need for Particulate Emission Control
- Basic Operating Principles of ESPs
- Mechanisms of Particle Charging (Corona Discharge)
- Particle Migration and the Deutsch-Anderson Equation
- Mechanical Systems: Rapping and Hopper Evacuation
- Electrical Systems: Transformer-Rectifier (TR) Sets
- Performance Factors: Ash Resistivity and Gas Flow

Introduction to Particulate Emission Control

- Combustion of pulverized coal generates significant quantities of fly ash, typically constituting 70-80% of total ash.
- Uncontrolled fly ash emissions cause severe respiratory health issues and environmental degradation (smog, reduced visibility).
- Regulatory standards require modern power plants to achieve particulate collection efficiencies exceeding 99.9%.
- Alternative technologies include fabric filters (baghouses) and wet scrubbers, but ESPs remain dominant due to their ability to handle large gas volumes with low pressure drop.

Operating Principle of Electrostatic Precipitators

- An ESP separates suspended particles from a gas stream through the application of high-voltage electrostatic forces.
- Step 1: Ionization - Gas molecules are ionized by a high-voltage corona discharge.
- Step 2: Charging - Suspended particles collide with ions and acquire a negative electrostatic charge.
- Step 3: Migration - Negatively charged particles are drawn towards grounded, positively charged collection plates by the electric field.
- Step 4: Removal - Collected dust is periodically dislodged into bottom hoppers via mechanical rapping.

Schematic of a Dry Electrostatic Precipitator

- Discharge Electrodes: High-voltage wires or rigid masts emitting electrons.
- Collection Electrodes: Grounded parallel steel plates providing the collection surface.
- Gas Distribution Plates: Perforated baffles at the inlet ensuring uniform gas flow velocity.
- Hoppers: Pyramidal structures at the base for temporary ash storage.

Corona Generation and Ionization

- A strong electric field is established by applying a highly negative DC voltage (typically 30 kV to 100 kV) to the discharge electrodes.
- When the voltage gradient near the electrode exceeds the electrical breakdown strength of the gas (corona onset voltage), localized ionization occurs.
- This creates a visible 'corona discharge'—a plasma region where free electrons and positive ions are generated.
- Electrons rapidly migrate away from the negative electrode, attaching to electronegative gas molecules (like O2 and SO2) to form negative ions.

Particle Charging Mechanisms

- Field Charging (Bombardment): Dominant for larger particles (¿1 µm). Negative ions driven by the electric field collide with and transfer charge to the particles.
- Field charging rate decreases as the particle's acquired charge repels further ions, reaching a 'saturation charge'.
- Diffusion Charging: Dominant for sub-micron particles (¡0.2 µm). Driven by the random thermal motion (Brownian motion) of gas ions colliding with particles.
- Unlike field charging, diffusion charging does not have a distinct saturation limit, but the rate of charging decreases exponentially.

Particle Migration Velocity

- Once charged, particles experience a Coulombic force (Fe = qE) directed toward the collection plates.
- This force is opposed by aerodynamic viscous drag (Stokes' drag), proportional to the particle's velocity.
- Particles rapidly reach terminal velocity, known as the Migration Velocity (w).
- For small particles obeying Stokes' Law: w = (q * E * C) / (3 * pi * μ * d), where μ is gas viscosity, d is particle diameter, and C is the Cunningham correction factor.

The Deutsch-Anderson Equation

- The fundamental equation relating ESP design parameters to collection efficiency (\ensuremath{\eta}).
- \ensuremath{\eta} = 1 - exp(-w * A / Q)
- Where: w = effective migration velocity (m/s).
- A = total surface area of collection plates (m\ensuremath{^2}).
- Q = volumetric gas flow rate (m\ensuremath{^3}/s).
- The ratio (A/Q) is known as the Specific Collection Area (SCA). Increasing SCA exponentially increases theoretical efficiency.

Mechanical Systems: Rapping

- Collected ash forms an insulating layer on the collection plates, which must be removed to maintain electrical efficiency.
- Rapping involves mechanically striking the plates (using drop hammers or electromagnetic vibrators) to impart a shear force.
- The ash layer ideally dislodges in coherent sheets (agglomerates) that fall into the hopper without re-entrainment.
- Rapping intensity and frequency must be optimized: too frequent causes re-entrainment; too infrequent causes excessive sparkover and back corona.

Electrical Supply: Transformer-Rectifier (TR) Sets

- TR sets step up the low plant AC voltage (e.g., 415 V) to high AC voltage, then rectify it to full-wave negative DC (up to 100 kV).
- Modern ESPs use High-Frequency Switched-Mode Power Supplies (SMPS) which offer faster spark response and higher average operating voltages compared to conventional 50/60 Hz TR sets.
- Automatic Voltage Control (AVC) units continuously adjust the voltage just below the sparkover limit to maximize the electric field strength.
- When a spark occurs, the AVC rapidly quenches the arc and ramps the voltage back up.

Performance Factors: Fly Ash Resistivity

- Resistivity (measured in ohm-cm) determines how easily the collected ash layer conducts charge to the grounded plate.
- Ideal Range: 10ˆ8 to 10ˆ10 ohm-cm. Allows charge to dissipate steadily.
- Low Resistivity (¡10ˆ8 ohm-cm): Typical of high-carbon unburned ash. Particles lose charge too quickly and re-entrain into the gas stream.
- High Resistivity (¿10ˆ11 ohm-cm): Typical of low-sulfur coal ash. Charge cannot dissipate, creating a strong opposing electric field in the ash layer. Leads to 'Back Corona' (positive ion emission from plates) which destroys efficiency.

Summary

- ESPs are highly efficient particulate control devices relying on ionization, charging, migration, and collection via electrostatic forces.
- Particle charging utilizes both field and diffusion mechanisms depending on particle size.
- The Deutsch-Anderson equation mathematically relates efficiency to Specific Collection Area (A/Q) and migration velocity.
- Optimizing TR set voltage, rapping frequency, and managing ash resistivity are critical for maintaining ¿99% emission capture.

Next Lecture Preview

- Having addressed particulate emissions with the ESP, we will next tackle gaseous pollutants.
- Topic: Flue Gas Desulfurization (FGD) Systems.
- We will cover wet limestone scrubbing, dry sorbent injection, and the chemistry of converting harmful SO2 into synthetic gypsum.