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Undergraduate Certificate in Advanced Combustion Engineering

## Emissions Control Technologies

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### Acid Gas Scrubber

Related terms: flue gas desulfurization, wet scrubber, limestone slurry, spray tower

Definition: A wet-scrubbing system that removes acidic gases such as SO<sub>2</sub> and HCl from combustion exhaust by contacting the flue gas with a liquid absorbent. The absorbent reacts chemically to form neutral salts, which are collected as a sludge.

Example: A coal-fired power plant uses a limestone-based acid gas scrubber to achieve >95 % removal of SO<sub>2</sub>.

Practical application: Widely employed in utility boilers, petroleum refineries, and waste-to-energy facilities to meet sulfur emissions limits.

Challenges: High water consumption, disposal of spent sludge, corrosion of equipment, and the need for precise pH control to maintain reaction efficiency.

### Activated Carbon

Related terms: adsorption, mercury control, porous media, regeneration

Definition: A form of carbon processed to have a high surface area and porosity, enabling it to adsorb volatile organic compounds (VOCs), mercury, and other trace pollutants from flue gases.

Example: An activated carbon injection system captures elemental mercury in the flue gas of a municipal solid-waste incinerator, achieving removal efficiencies of 80–90 %.

Practical application: Used in conjunction with baghouses or electrostatic precipitators for post-combustion pollutant control.

Challenges: Limited capacity for high-temperature streams, the need for periodic replacement or regeneration, and potential for carbon dust release if not properly managed.

### Air-Staged Combustion

Related terms: staged combustion, reburning, NO<sub>x</sub> reduction, oxygen-enrichment

Definition: A combustion strategy where the air supply is divided into primary and secondary stages, creating a fuel-rich zone followed by a lean zone, which suppresses peak flame temperatures and consequently reduces thermal NO<sub>x</sub> formation.

Example: A natural-gas boiler employing air-staged combustion reduces NO<sub>x</sub> emissions from 150 ppm to below 30 ppm without additional post-combustion controls.

Practical application: Common in industrial furnaces and boiler designs where NO<sub>x</sub> limits are stringent.

Challenges: Requires precise control of airflow distribution, may affect combustion stability, and can lead to increased CO emissions if the fuel-rich zone is not properly balanced.

### Ammonia Slip

Related terms: selective catalytic reduction, SCR, ammonia slip catalyst, NO<sub>x</sub> control

Definition: The unreacted ammonia that passes through an SCR system and is emitted with the flue gas, potentially forming secondary pollutants such as ammonium salts.

Example: In a coal-fired power plant, ammonia slip is monitored and kept below 10 ppm by adjusting the urea injection rate and installing an ammonia slip catalyst downstream of the SCR reactor.

Practical application: Monitoring and controlling ammonia slip is essential to avoid downstream fouling and to comply with ambient air quality standards.

Challenges: Balancing sufficient ammonia for NO<sub>x</sub> reduction while minimizing slip, dealing with variability in flue-gas composition, and ensuring catalyst durability.

#### Atmospheric Plasma Reactor

Related terms: plasma oxidation, non-thermal plasma, VOC destruction, dielectric barrier discharge

Definition: A device that generates a high-energy plasma field to oxidize and decompose pollutants such as VOCs, NO<sub>x</sub>, and CO at relatively low temperatures, leveraging energetic electrons rather than bulk gas heating.

Example: A pilot-scale atmospheric plasma reactor treats the exhaust of a metal-working shop, achieving >99 % VOC destruction with a power input of 5 kW.

Practical application: Offers a compact, rapid-response solution for intermittent or low-volume emission sources.

Challenges: High electrical energy consumption, electrode wear, and limited scalability for large-scale industrial applications.

#### Baghouse (Fabric Filter)

Related terms: particulate control, dust collector, filter cake, pulse-jet cleaning

Definition: A filtration device that captures particulate matter from flue gases by passing the gas through fabric filter media, where particles accumulate as a filter cake and are periodically removed by a cleaning pulse.

Example: A cement plant uses a baghouse to remove >99 % of PM<sub>10</sub>, meeting the strictest particulate standards.

Practical application: Serves as a primary particulate control device and can be combined with sorbent injection for acid gas removal.

Challenges: Filter media wear, potential for filter rupture under high-temperature conditions, and the need for regular maintenance to prevent pressure drop increases.

#### Baseline Emissions

Related terms: emissions inventory, regulatory baseline, performance benchmarking, stack testing

Definition: The measured or estimated emissions levels of a facility before the implementation of control technologies, used as a reference point for evaluating reduction effectiveness.

Example: Baseline NO<sub>x</sub> emissions of 200 ppm are established for a turbine before installing a low-NO<sub>x</sub> burner.

Practical application: Provides a basis for compliance reporting, permits, and the calculation of emission credits.

Challenges: Accurate baseline determination requires comprehensive testing, accounting for operational variability, and may be subject to regulatory revisions.

#### Carbon Capture and Storage (CCS)

Related terms: CO<sub>2</sub> sequestration, post-combustion capture, amine scrubbing, geological storage

Definition: A suite of technologies that capture carbon dioxide from flue gases, compress it, transport it, and permanently store it in geological formations to mitigate climate change.

Example: A natural-gas combined-cycle plant captures 90 % of its CO<sub>2</sub> using a monoethanolamine (MEA) solvent and injects it into a depleted oil reservoir.

Practical application: Enables continued use of fossil fuels while reducing net greenhouse-gas emissions.

Challenges: High capital and operating costs, energy penalty (typically 10–15 % of plant output), solvent degradation, and public acceptance of storage sites.

### Catalytic Oxidation

Related terms: catalyst, oxidation reactor, VOC abatement, temperature window

Definition: A process where a catalyst promotes the oxidation of pollutants (e.g., VOCs, CO) to CO<sub>2</sub> and H<sub>2</sub>O at temperatures lower than would be required for thermal oxidation alone.

Example: A catalytic oxidizer reduces VOC concentrations from 500 ppm to Combustion Modification

Related terms: low-NO<sub>x</sub> burners, staged combustion, flue-gas recirculation, flame temperature control

Definition: Engineering adjustments to the combustion process that aim to reduce pollutant formation at the source, primarily targeting NO<sub>x</sub>, CO, and unburned hydrocarbons.

Example: Implementing flue-gas recirculation (FGR) in a boiler reduces peak flame temperature, achieving a 60 % NO<sub>x</sub> reduction.

Practical application: Often the first line of defense in emission control strategies, complementing downstream technologies.

Challenges: Potential loss of combustion efficiency, increased CO emissions if not properly tuned, and the need for sophisticated control systems.

### Diffusion Flame

Related terms: laminar flame, premixed flame, flame speed, flame stability

Definition: A flame where the fuel and oxidizer mix by diffusion rather than being premixed, leading to a characteristic shape and temperature profile that influences pollutant formation.

Example: A diffusion flame in a gas turbine combustor exhibits higher NO<sub>x</sub> production compared to a premixed flame due to elevated local temperatures.

Practical application: Understanding diffusion flame behavior assists in designing burners that minimize NO<sub>x</sub> while maintaining stable combustion.

Challenges: Controlling flame anchoring and preventing flashback in high-temperature environments.

### Dry Sorbent Injection (DSI)

Related terms: calcium carbonate, sodium bicarbonate, particulate control, flue-gas desulfurization

Definition: A technique where dry alkaline sorbent powders are injected into the flue gas stream to react with acidic gases (SO<sub>2</sub>, HCl) and form solid salts that are captured by downstream particulate control devices.

Example: An industrial boiler injects calcium carbonate at a rate of 2 lb/10<sup>6</sup> Btu, achieving 70 % SO<sub>2</sub> removal.

Practical application: Offers a low-cost, retrofit-friendly option for acid gas reduction without the need for liquid handling systems.

Challenges: Sorbent handling and storage, increased particulate loading on downstream filters, and limited

removal efficiency for high sulfur-content fuels.

#### Electrostatic Precipitator (ESP)

Related terms: particulate removal, corona discharge, collection plates, particle charging

Definition: An electrostatic device that charges particles in the flue gas and collects them on oppositely charged plates, allowing for continuous removal of fine particulates.

Example: An ESP in a steel mill captures >99 % of sub-micron particles, reducing PM<sub>2.5</sub> emissions to regulatory limits.

Practical application: Provides high-efficiency particulate control for high-temperature, high-volume gas streams.

Challenges: Plate fouling, reduced efficiency with low-resistivity particles, and the need for periodic re-conditioning to maintain performance.

#### Flame Temperature

Related terms: adiabatic flame temperature, NO<sub>x</sub> formation, thermal NO<sub>x</sub>, temperature control

Definition: The peak temperature reached within the combustion zone, a primary driver of thermal NO<sub>x</sub> production according to the Zeldovich mechanism.

Example: Reducing flame temperature from 2100 K to 1800 K in a furnace lowers NO<sub>x</sub> emissions by approximately 50 %.

Practical application: Temperature management is central to NO<sub>x</sub> mitigation strategies such as staged combustion and flue-gas recirculation.

Challenges: Maintaining combustion efficiency while lowering temperature, and avoiding excessive CO or unburned hydrocarbon formation.

#### Flue-Gas Desulfurization (FGD)

Related terms: wet scrubber, limestone slurry, sulfur dioxide removal, by-product gypsum

Definition: A set of processes that remove SO<sub>2</sub> from flue gases, typically using a wet scrubbing system where a limestone slurry reacts with SO<sub>2</sub> to form calcium sulfite, which is later oxidized to gypsum.

Example: A utility plant's FGD system removes 95 % of SO<sub>2</sub>, producing marketable gypsum for the construction industry.

Practical application: Essential for compliance with sulfur emission regulations on coal-fired power plants.

Challenges: High water usage, disposal of waste sludge, corrosion, and the need for continuous monitoring of slurry chemistry.

#### Fuel-Rich Zone

Related terms: staged combustion, reburning, NO<sub>x</sub> reduction, reducing atmosphere

Definition: The region in a combustion system where the fuel-to-air ratio exceeds stoichiometric, creating a reducing environment that can help convert NO<sub>x</sub> to N<sub>2</sub> during subsequent stages.

Example: In a reburning system, a fuel-rich zone is created by injecting natural gas downstream of the primary burner, achieving up to 60 % NO<sub>x</sub> reduction.

Practical application: Used in conjunction with reburning or selective non-catalytic reduction (SNCR) to enhance nitrogen oxide control.

Challenges: Managing CO emissions, ensuring stable flame, and avoiding flame blow-off.

### Gas-Phase Catalysis

Related terms: homogeneous catalysis, SCR, NO<sub>x</sub> reduction, catalyst promoter

Definition: Catalytic reactions that occur in the gaseous phase, often involving transition-metal compounds that facilitate pollutant conversion without a solid support.

Example: A homogeneous SCR system using ammonia and a copper-based catalyst reduces NO<sub>x</sub> at temperatures between 250–350 °C.

Practical application: Offers flexibility in reactor design and can be integrated into compact emission control units.

Challenges: Catalyst recovery, potential for catalyst deactivation, and handling of toxic or corrosive catalyst species.

### Halogenated Hydrocarbon

Related terms: chlorinated VOCs, HCl emissions, flame retardants, pollutant source

Definition: Organic compounds containing halogen atoms (Cl, Br, F) that can be released during combustion, contributing to corrosive acid formation and ozone depletion.

Example: Burning PVC waste releases HCl, which can corrode downstream equipment if not properly scrubbed.

Practical application: Identifying halogenated hydrocarbon emissions helps in selecting appropriate scrubber chemistries (e.g., alkaline sorbents).

Challenges: Accurate detection, managing corrosivity, and ensuring compliance with hazardous air pollutant regulations.

### High-Temperature Oxidation

Related terms: thermal oxidation, incineration, VOC destruction, temperature threshold

Definition: A method of destroying organic pollutants by heating the flue gas to temperatures typically above 850 °C, where oxidation reactions proceed rapidly, converting pollutants to CO<sub>2</sub> and H<sub>2</sub>O.

Example: A hazardous waste incinerator operates at 950 °C, achieving >99.9% VOC destruction efficiency.

Practical application: Used for the treatment of high-strength waste streams where low-temperature technologies are insufficient.

Challenges: High energy consumption, formation of nitrogen oxides at elevated temperatures, and the need for robust materials to withstand thermal stress.

### Hydrocarbon (HC) Emissions

Related terms: unburned hydrocarbons, VOCs, incomplete combustion, flame quenching

Definition: Emissions consisting of organic compounds that have not been fully oxidized during combustion, often indicating poor flame stability or insufficient residence time.

Example: A gas turbine operating at low load may emit 10 ppm of unburned HC, exceeding the permitted limit.

Practical application: Monitoring HC emissions helps optimize combustion parameters and detect fuel-rich conditions.

Challenges: Balancing low NO<sub>x</sub> operation with HC control, and ensuring reliable detection in the presence of other pollutants.

### Inert Gas Recirculation (IGR)

Related terms: flue-gas recirculation, nitrogen dilution, NO<sub>x</sub> control, combustion stability

Definition: The process of recirculating a portion of the exhaust gas back into the combustion zone to lower peak flame temperatures and reduce thermal NO<sub>x</sub> formation.

Example: An industrial furnace recirculates 20 % of its flue gas, achieving a 45 % reduction in NO<sub>x</sub> emissions.

Practical application: Provides a flexible method for NO<sub>x</sub> control that can be adjusted in real time.

Challenges: Potential increase in CO emissions, need for robust mixing equipment, and impact on furnace heat transfer.

### Low-NO<sub>x</sub> Burner

Related terms: staged combustion, flame temperature control, NO<sub>x</sub> reduction, fuel staging

Definition: A burner design that incorporates air staging, fuel staging, or swirl to limit peak flame temperatures and reduce the formation of thermal NO<sub>x</sub>.

Example: A low-NO<sub>x</sub> natural-gas burner installed in a boiler reduces NO<sub>x</sub> from 300 ppm to 30 ppm without additional downstream controls.

Practical application: Commonly used in boiler retrofits and new installations where NO<sub>x</sub> limits are stringent.

Challenges: Maintaining combustion efficiency, avoiding excessive CO formation, and ensuring reliable operation across a range of loads.

### Mercury (Hg) Emission Control

Related terms: activated carbon injection, oxidation catalysts, elemental mercury, mercury speciation

Definition: Technologies aimed at capturing and converting mercury species in flue gases, typically involving oxidation of elemental mercury to oxidized forms followed by adsorption onto sorbents.

Example: A coal plant injects activated carbon downstream of an oxidation catalyst, achieving 85 % mercury removal.

Practical application: Essential for compliance with mercury emission regulations, especially for coal-fired units.

Challenges: Variability in mercury speciation, sorbent cost, and the need for precise control of catalyst temperature and flue-gas composition.

### Non-Thermal Plasma

Related terms: dielectric barrier discharge, plasma oxidation, VOC abatement, low-temperature plasma

Definition: A plasma technology that generates energetic electrons at near-ambient gas temperatures, enabling the oxidation of pollutants without raising bulk gas temperature.

Example: A non-thermal plasma reactor treats diesel exhaust, reducing NO<sub>x</sub> by 40 % with a modest power input.

Practical application: Suitable for mobile sources and intermittent emission streams where thermal methods are impractical.

Challenges: Energy efficiency, electrode degradation, and scale-up to industrial flow rates.

### Oxidation Catalyst

Related terms: catalyst support, noble metals, VOC oxidation, catalyst deactivation

Definition: A solid catalyst, often based on platinum or palladium, that facilitates the oxidation of VOCs, CO,

and other reducible gases at moderate temperatures.

Example: An oxidation catalyst placed before a baghouse reduces VOC concentrations from 200 ppm to Particulate Matter (PM)

Related terms: PM<sub>2.5</sub>, PM<sub>10</sub>, aerosol, filter cake, coarse particles

Definition: Solid or liquid particles suspended in the flue gas, ranging from sub-micron to several micrometers in diameter, which can impact human health and visibility.

Example: A cement kiln emits 0.1 g/Nm<sup>3</sup> of PM<sub>2.5</sub>, requiring control to meet stringent local air quality standards.

Practical application: Measurement and control of PM are central to compliance with particulate emission limits.

Challenges: Capturing ultrafine particles, handling ash disposal, and maintaining filter efficiency under variable operating conditions.

#### Passive NO<sub>x</sub> Control

Related terms: low-NO<sub>x</sub> burners, fuel staging, natural gas dilution, temperature management

Definition: Strategies that reduce NO<sub>x</sub> formation directly within the combustion zone without the need for additional downstream treatment equipment.

Example: Implementing fuel staging in a boiler reduces NO<sub>x</sub> emissions by 30% without installing an SCR system.

Practical application: Cost-effective initial step in emission reduction plans, especially for new installations.

Challenges: Limited reduction potential compared to active controls, and the need for precise combustion tuning.

#### Plasma-Assisted Combustion

Related terms: plasma ignition, flame stabilization, low-temperature combustion, electric field enhancement

Definition: The use of plasma discharges to generate radicals and ions that promote combustion, allowing stable flame operation at lean mixtures and lower temperatures.

Example: A plasma-assisted burner operates at an equivalence ratio of 0.6, achieving stable combustion with reduced NO<sub>x</sub> emissions.

Practical application: Enables ultra-lean combustion regimes for high-efficiency, low-emission burners.

Challenges: Power supply integration, electrode erosion, and ensuring uniform plasma distribution.

#### Post-Combustion NO<sub>x</sub> Reduction

Related terms: SCR, SNCR, selective catalytic reduction, non-catalytic reduction

Definition: Technologies applied to the flue gas after combustion to convert NO<sub>x</sub> to nitrogen and water, typically using reductants such as ammonia or urea.

Example: A selective catalytic reduction (SCR) system installed on a coal-fired boiler reduces NO<sub>x</sub> from 500 ppm to below 30 ppm.

Practical application: Widely adopted in power generation, industrial boilers, and marine engines.

Challenges: Reductant handling, catalyst poisoning, temperature control, and ammonia slip management.

#### Reburning

Related terms: fuel-rich zone, NO<sub>x</sub> reduction, staged combustion, secondary fuel injection

Definition: A NO<sub>x</sub> control technique where a secondary fuel (often natural gas) is injected downstream of the primary combustion zone to create a fuel-rich environment that reduces NO<sub>x</sub> to N<sub>2</sub>.

Example: Reburning in a coal-fired boiler achieves a 40 % reduction in NO<sub>x</sub> while maintaining overall combustion efficiency.

Practical application: Provides a cost-effective alternative to SCR for moderate NO<sub>x</sub> reductions.

Challenges: Managing increased CO emissions, ensuring thorough mixing, and controlling the temperature profile to avoid excess unburned carbon.

#### Selective Catalytic Reduction (SCR)

Related terms: ammonia injection, catalyst, NO<sub>x</sub> reduction, urea, ammonia slip

Definition: A catalytic process where ammonia (or urea) reacts with NO<sub>x</sub> over a catalyst at temperatures typically between 300–400 °C, converting NO<sub>x</sub> to N<sub>2</sub> and H<sub>2</sub>O with high efficiency.

Example: An SCR unit on a diesel locomotive reduces NO<sub>x</sub> emissions by 90 % while maintaining engine performance.

Practical application: The most effective post-combustion NO<sub>x</sub> control technology for large stationary and mobile sources.

Challenges: Catalyst cost, ammonia slip, need for precise temperature control, and sensitivity to sulfur and particulate fouling.

#### Selective Non-Catalytic Reduction (SNCR)

Related terms: ammonia injection, high-temperature reduction, NO<sub>x</sub> reduction, thermal NO<sub>x</sub>

Definition: A non-catalytic process where ammonia or urea is injected into the flue gas at temperatures of 850–1100 °C, causing direct reduction of NO<sub>x</sub> to N<sub>2</sub> without a catalyst.

Example: An SNCR system installed in a cement kiln reduces NO<sub>x</sub> by 30 % with a simple injection system.

Practical application: Offers a lower-cost alternative to SCR where catalyst installation is impractical.

Challenges: Narrow temperature window, lower reduction efficiency, and the risk of ammonia slip if the reaction is incomplete.

#### Soot Oxidation

Related terms: carbon burnout, oxidation catalyst, high-temperature oxidation, particulate removal

Definition: The process of converting carbonaceous particles (soot) in the flue gas to CO<sub>2</sub>, often using elevated temperatures or catalytic aids to ensure complete burnout.

Example: Adding a copper-based oxidation catalyst to a furnace exhaust stream increases soot oxidation efficiency from 70 % to 95 %.

Practical application: Improves the performance of particulate control devices and reduces visible emissions.

Challenges: Catalyst deactivation, temperature management, and handling of the resulting CO<sub>2</sub> stream.

#### Steam Injection

Related terms: flue-gas recirculation, temperature control, NO<sub>x</sub> reduction, combustion dilution

Definition: The injection of steam into the combustion zone to increase the mass flow, lower flame temperature, and dilute the oxygen concentration, thereby reducing NO<sub>x</sub> formation.

Example: A gas turbine employs steam injection to achieve a 20 % reduction in NO<sub>x</sub> while maintaining power output.

Practical application: Often used in combined-cycle plants where waste steam is readily available.

Challenges: Additional water consumption, potential for increased corrosion, and the need for precise control to avoid flame instability.

#### Sulfur Dioxide (SO<sub>2</sub>) Removal

Related terms: acid gas scrubbing, limestone slurry, dry sorbent injection, gypsum production

Definition: Technologies designed to capture and convert SO<sub>2</sub> from flue gases, thereby preventing acid rain and complying with sulfur emission limits.

Example: A wet FGD system removes 98 % of SO<sub>2</sub> from a coal plant's flue gas, producing gypsum for use in wallboard manufacturing.

Practical application: Integral to coal-fired power plant emission control trains.

Challenges: High water usage, disposal of waste by-products, and maintaining high removal efficiency under variable load conditions.

#### Thermal NO<sub>x</sub>

Related terms: Zeldovich mechanism, flame temperature, high-temperature oxidation, NO<sub>x</sub> formation

Definition: NO<sub>x</sub> generated from the oxidation of atmospheric nitrogen at high temperatures (typically >1800 K) during combustion, following the kinetic pathways described by Zeldovich.

Example: In a furnace operating at 2100 K, thermal NO<sub>x</sub> may account for 80 % of total NO<sub>x</sub> emissions.

Practical application: Understanding thermal NO<sub>x</sub> guides the design of temperature-control strategies such as staged combustion.

Challenges: Reducing flame temperature without sacrificing combustion efficiency or increasing CO emissions.

#### Ultra-Low-NO<sub>x</sub> (ULN) Burner

Related terms: advanced combustion, multi-stage staging, flame shaping, NO<sub>x</sub> VOC (Volatile Organic Compound) Destruction

Related terms: catalytic oxidizer, thermal oxidizer, plasma oxidation, destruction removal efficiency (DRE)

Definition: The removal or conversion of VOCs from exhaust streams to CO<sub>2</sub> and H<sub>2</sub>O, typically measured by destruction removal efficiency.

Example: A catalytic oxidizer achieves a DRE of 99.5 % for a mixture of aromatic VOCs at 300 °C.

Practical application: Critical for compliance with hazardous air pollutant (HAP) regulations in solvent-intensive industries.

Challenges: Catalyst poisoning, high inlet VOC concentrations, and the need for reliable temperature control to avoid incomplete oxidation.

#### Water-Cooled Scrubber

Related terms: wet scrubber, heat recovery, acid gas removal, limestone slurry

Definition: A scrubber design where the absorbent liquid is cooled by water, allowing efficient removal of acidic gases while minimizing the temperature rise of the flue gas.

Example: A water-cooled FGD unit reduces the temperature of the flue gas by 30 °C, improving downstream heat-exchange efficiency.

Practical application: Used where downstream temperature constraints are critical, such as in

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combined-cycle plants.

Challenges: Managing water usage, preventing scaling on heat-exchange surfaces, and ensuring adequate residence time for chemical reactions.

#### Zeldovich Mechanism

Related terms: thermal NO<sub>x</sub>, high-temperature chemistry, nitrogen oxidation, reaction kinetics

Definition: The set of elementary reactions describing the formation of NO<sub>x</sub> from atmospheric nitrogen and oxygen at high temperatures, primarily responsible for thermal NO<sub>x</sub> generation in combustion.

Example: The rate of NO formation increases exponentially with temperature according to the Zeldovich mechanism, emphasizing the importance of flame-temperature control.

Practical application: Forms the theoretical basis for NO<sub>x</sub> mitigation strategies such as flame-temperature reduction and staged combustion.

Challenges: Accurately modeling the mechanism in CFD simulations, especially under transient operating conditions.