Undergraduate Certificate in Advanced Combustion Engineering

Emissions Control Technologies

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_2 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_2.
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, NOx 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 NOx formation.
Example: A natural-gas boiler employing air-staged combustion reduces NOx emissions from 150 ppm to below 30 ppm without additional post-combustion controls.
Practical application: Common in industrial furnaces and boiler designs where NOx 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, NOx 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 NOx 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, NOx, 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_{10}, 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 NOx emissions of 200 ppm are established for a turbine before installing a low-NOx 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_2 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_2 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_2 and H_2O 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-NOx 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 NOx, CO, and unburned hydrocarbons.
Example: Implementing flue-gas recirculation (FGR) in a boiler reduces peak flame temperature, achieving a 60 % NOx 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 NOx production compared to a premixed flame due to elevated local temperatures.
Practical application: Understanding diffusion flame behavior assists in designing burners that minimize NOx 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_2, 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/10^6 Btu, achieving 70 % SO_2 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 $PM_{2.5}$ 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, NOx formation, thermal NOx, temperature control
Definition: The peak temperature reached within the combustion zone, a primary driver of thermal NOx production according to the Zeldovich mechanism.
Example: Reducing flame temperature from 2100 K to 1800 K in a furnace lowers NOx emissions by approximately 50 %.
Practical application: Temperature management is central to NOx 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_2 from flue gases, typically using a wet scrubbing system where a limestone slurry reacts with SO_2 to form calcium sulfite, which is later oxidized to gypsum.
Example: A utility plant's FGD system removes 95 % of SO_2, 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, NOx 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 NOx to N_2 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 % NOx 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, NOx 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 NOx 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_2 and H_2O.
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 NOx 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, NOx 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 NOx formation.
Example: An industrial furnace recirculates 20 % of its flue gas, achieving a 45 % reduction in NOx emissions.
Practical application: Provides a flexible method for NOx 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-NOx Burner
Related terms: staged combustion, flame temperature control, NOx 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 NOx.
Example: A low-NOx natural-gas burner installed in a boiler reduces NOx from 300 ppm to 30 ppm without additional downstream controls.
Practical application: Commonly used in boiler retrofits and new installations where NOx 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 NOx 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: $PM_{2.5}$, PM_{10}, 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^3 of $PM_{2.5}$, 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 NOx Control
Related terms: low-NOx burners, fuel staging, natural gas dilution, temperature management
Definition: Strategies that reduce NOx formation directly within the combustion zone without the need for additional downstream treatment equipment.
Example: Implementing fuel staging in a boiler reduces NOx 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 NOx 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 NOx Reduction
Related terms: SCR, SNCR, selective catalytic reduction, non-catalytic reduction
Definition: Technologies applied to the flue gas after combustion to convert NOx 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 NOx 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, NOx reduction, staged combustion, secondary fuel injection

Definition: A NOx 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 NOx to N_2.
Example: Reburning in a coal-fired boiler achieves a 40 % reduction in NOx while maintaining overall combustion efficiency.
Practical application: Provides a cost-effective alternative to SCR for moderate NOx 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, NOx reduction, urea, ammonia slip
Definition: A catalytic process where ammonia (or urea) reacts with NOx over a catalyst at temperatures typically between 300–400 °C, converting NOx to N_2 and H_2O with high efficiency.
Example: An SCR unit on a diesel locomotive reduces NOx emissions by 90 % while maintaining engine performance.
Practical application: The most effective post-combustion NOx 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, NOx reduction, thermal NOx
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 NOx to N_2 without a catalyst.
Example: An SNCR system installed in a cement kiln reduces NOx 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_2, 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_2 stream.

Steam Injection
Related terms: flue-gas recirculation, temperature control, NOx 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 NOx formation.
Example: A gas turbine employs steam injection to achieve a 20 % reduction in NOx 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_2) Removal
Related terms: acid gas scrubbing, limestone slurry, dry sorbent injection, gypsum production
Definition: Technologies designed to capture and convert SO_2 from flue gases, thereby preventing acid rain and complying with sulfur emission limits.
Example: A wet FGD system removes 98 % of SO_2 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 NOx
Related terms: Zeldovich mechanism, flame temperature, high-temperature oxidation, NOx formation
Definition: NOx 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 NOx may account for 80 % of total NOx emissions.
Practical application: Understanding thermal NOx 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-NOx (ULN) Burner
Related terms: advanced combustion, multi-stage staging, flame shaping, NOx 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_2 and H_2O, 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

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 NOx, high-temperature chemistry, nitrogen oxidation, reaction kinetics
Definition: The set of elementary reactions describing the formation of NOx from atmospheric nitrogen and oxygen at high temperatures, primarily responsible for thermal NOx 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 NOx mitigation strategies such as flame-temperature reduction and staged combustion.
Challenges: Accurately modeling the mechanism in CFD simulations, especially under transient operating conditions.