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ADVANCEMENTS IN GAS TURBINE COMBUSTION SYSTEMS: PERFORMANCE, EFFICIENCY, AND EMISSION REDUCTION **STRATEGIES**

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ABSTRACT

Gas turbines play a pivotal role in aviation, power generation, and industrial applications, necessitating continuous advancements in combustion technology to enhance performance and reduce environmental impact. This paper comprehensively analyzes gas turbine combustion systems, covering diffuser aerodynamics, combustor configurations, flame stabilization mechanisms, and fuel injection techniques. Various diffuser geometries, including faired, dump, and vortex-controlled designs, are examined for their impact on flow stability and pressure recovery. The study further explores primary combustion chamber configurations—annular, can, and can-annular—highlighting their efficiency, maintenance considerations, and fuel-air mixing characteristics. Additionally, lean-premixed (LPM), rich-quench-lean (RQL), and trapped vortex combustion (TVC) strategies are discussed in the context of low-emission gas turbine operation. The paper also investigates catalytic combustion, fuel atomization processes, and emissions control technologies, including selective catalytic reduction (SCR) and water injection for NOx mitigation. With increasing emphasis on alternative fuels such as hydrogen, syngas, and biofuels, the study evaluates their combustion behavior and feasibility for future gas turbine applications. The findings suggest that integrated combustion design improvements, coupled with advanced fuel injection and emissions control strategies, are critical for achieving high efficiency, stable operation, and reduced environmental footprint in next-generation gas turbines.

Keywords: Gas turbine combustors, Fuel injection, Alternative fuels, Emissions control, Hydrogen combustion, Flame stabilization.

1. INTRODUCTION

Gas turbine combustion systems have undergone significant advancements to improve efficiency, reduce emissions, and enhance operational flexibility. Combustion is a critical process in gas turbines, where fuel is mixed with air and ignited to generate high-temperature gases. The evolution of combustor technology has been driven by stringent emission regulations, demand for fuel efficiency, and the need for durability in extreme operating conditions. Modern gas turbine combustors incorporate advanced designs, refined fuel injection and atomization techniques, and the integration of alternative fuels like hydrogen, syngas, biofuels, and synthetic fuels. Emission control strategies like lean-premixed combustion (LPM), Rich-Burn Quick-Mix Lean-Burn (RQL), and Trapped Vortex Combustion (TVC) have been developed to meet environmental standards while maintaining engine performance. Original Equipment Manufacturers (OEMs) continue to innovate in combustor design, using advanced materials and fuel-flexible technologies to optimize performance across various applications, including aviation, power generation, and industrial settings.

2. METHODOLOGY

The study examines gas turbine combustion technologies, focusing on combustor design, performance, diffuser configurations, flame stabilization techniques, fuel injection and atomization, and alternative fuels. It also examines emission control strategies, including lean-premixed combustion (LPM), Rich-Burn Quick-Mix Lean-Burn (RQL), and Trapped Vortex Combustion (TVC) systems. The study also examines Dry Low NOx (DLN) and Dry Low Emission (DLE) technologies implemented by OEMs and assesses catalytic combustion and exhaust gas treatment methods. The study also reviews combustion technologies developed by major gas turbine manufacturers, trends in fuel-flexible combustion systems for power generation and aviation applications, and advancements in high-temperature materials and cooling strategies to enhance combustor durability. The findings offer valuable insights into the future of lowemission, high-efficiency gas turbine combustion technologies.

3. DIFFUSERS IN GAS TURBINES

In axial-flow compressors, attaining the requisite stage pressure increase requires elevated axial velocities, frequently surpassing 170 m/s in aviation engines. Nonetheless, such elevated velocities are unfeasible for effective combustion owing to significant pressure loss, which may attain 25% of the compressor's pressure increase. A diffuser is positioned between the compressor outlet and the combustor input to reduce the airflow to approximately one-fifth of its initial velocity while augmenting static pressure.



Diffusers function by broadening the airflow across a diverging channel, transforming velocity head into an increase in static pressure. Achieving high efficiency is difficult due to pressure losses caused by skin friction in elongated diffusers and boundary-layer separation in shorter designs with large divergence angles. The ideal divergence angle generally ranges from 6° to 12° , optimizing the balance between frictional losses and boundary-layer stability.

The optimal diffuser must reduce pressure loss, ensure consistent outlet flow, and efficiently manage fluctuations in compressor discharge profiles, which are frequently asymmetric and significantly influenced by engine operating conditions. Despite comprehensive experimental investigations, the diffuser and combustor liner interplay generates further geometric complications, rendering general performance prediction models less dependable.



Fig 1: Diffuser in Gas Turbine configuration

3.1 Diffuser Geometry

Straight-walled diffuser performance is influenced by three geometric parameters: Area Ratio (AR), Nondimensional Length ($L/\Delta R$ or N/R), and Divergence Angle (2 θ). For conical and annular diffusers, optimal area ratio and length-to-radius ratio determine pressure recovery characteristics. Combusstor diffusers have additional complexities, such as liner position and flow redistribution effects, which conventional diffuser charts cannot fully capture.

3.2 Flow Regimes in Diffusers

Systematic studies on diffuser flow regimes have identified four primary behaviors based on increasing divergence angle:

- No appreciable stall: Flow remains attached with minor losses.
- Transitory stall: Formation of eddies that intermittently detach and reattach, assisting in turbulence-induced diffusion.
- Fully developed stall: Large-scale flow separation, leading to a triangular-shaped recirculation region.
- Jet flow: There was complete detachment from both walls, with reattachment occurring far downstream, causing significant losses.

Experiments indicate that conical diffusers exhibit superior performance due to delayed flow separation, while annular diffusers are more susceptible to stall under specific geometric configurations.

3.3 Performance Criteria

The effectiveness of a diffuser is evaluated using several dimensionless parameters, including the Pressure Recovery Coefficient (Cp), Ideal Pressure Recovery, Overall Effectiveness (η), Loss Coefficient (λ), and Kinetic Energy Coefficient (α). These metrics help optimize diffusers by minimizing losses and ensuring stable flow delivery to the combustor. The ideal pressure recovery is based on area ratio, while overall effectiveness is expressed as a fraction of the perfect pressure rise.

3.4 Influence of Inlet Flow Conditions

The inlet conditions at the compressor exit significantly impact diffuser performance. Key parameters include:

- Reynolds Number: Insensitive for Re > 5 × 10⁴, but lower values can affect boundary-layer thickness and turbulence levels.
- Mach Number: Performance is stable below 0.3, improves slightly between 0.3–0.6, but deteriorates above 0.6 due to increasing adverse pressure gradients.
- Turbulence: Levels up to 3.5% improve performance by delaying stall and enhancing flow mixing.
- Swirl: Swirl is generally undesirable, but a minor swirl (~3°) at the diffuser inlet can amplify downstream swirl effects, influencing combustor aerodynamics.

Variations in the inlet velocity profile can significantly affect flow stability for faired diffusers, while dump diffusers are more insensitive to inlet flow distortions.

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3.5 Diffuser Types and Design Considerations

Several diffuser designs exist, each with unique performance characteristics:

Faired Diffusers

- Designed for gradual velocity reduction without flow separation.
- Low pressure loss but highly sensitive to thermal distortions and manufacturing tolerances.
- Additional settling length is required to dissipate compressor wake effects.
- Used in early gas turbine combustors but largely replaced by more compact designs.

3.6 Dump Diffusers

- Features a sudden expansion to stabilize flow before entering the annular passages.
- Higher pressure loss (~50% more than faired diffusers) but significantly shorter length, making it favorable for aircraft applications.
- Insensitive to manufacturing variations and inlet velocity profile distortions.

3.7 Vortex-Controlled Diffusers (VCDs)

- Utilize boundary-layer bleed to inhibit separation and enhance diffusion efficiency.
- Require 4–5% bleed air but achieve near optimal pressure recovery.
- Promising for applications where cooling air is already required, such as high-temperature turbines.

3.8 Hybrid Diffusers

- Combine VCDs with conventional diffusers, minimizing bleed requirements while achieving high pressure recovery.
- Offer up to 25% higher efficiency compared to traditional conical diffusers.
- Additional length is required for integration with Rediffuses to increase bleed-air pressure.

3.9 Splitter-Vane Diffusers

- Introduce multiple passages within a single diffuser to reduce total divergence angle.
- Achieve higher pressure recovery (Cp > 0.5) with up to 50% shorter length than conventional diffusers.
- Successfully implemented in NASA/GE Energy Efficient Engine and GE LM6000 DLE combustors.

3.10 Diffusers for Tubular and Can-Annular Combustors

- Tubular combustors require complex transition sections to convert annular flow to circular cross-sections.
- Can-annular designs benefit from superior fuel-air mixing and lower emissions but suffer from severe flow asymmetry due to uneven diffusion.
- Wedge diffusers have been proposed to improve flow uniformity in can-annular systems.

Gas Turbine Combustion Chambers

Gas turbine combustion chambers are essential for the combustion process, enabling adequate fuel-air mixing and stable flame propagation. Three primary types of combustion chambers are typically employed in contemporary gas turbines:

- Annular Combustion Chambers
- Can (Multican) Combustion Chambers
- Can-Annular Combustion Chambers



Fig 2: Cross-Sectional View of a Gas Turbine Combustion Chamber This diagram depicts the internal architecture of a gas turbine combustion chamber, emphasizing essential elements such swirl vanes, secondary air apertures, flame tube, dilution air openings, and fuel spray nozzle. It offers a comprehensive overview of the major and secondary airflow zones, facilitating effective combustion and cooling.



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Fig 3 Airflow Pattern and Flame Stabilization in a Combustion Chamber This illustration depicts the airflow distribution and flame stabilization systems in a gas turbine combustor. The graphic highlights the process by which air enters the chamber, amalgamates with fuel, and advances towards the turbine while preserving ideal combustion conditions.



Fig 4 Multi-Can Combustion Chamber Configuration in Gas Turbines This illustration depicts a multiple-can combustion chamber configuration, featuring distinct combustors positioned around the engine. It emphasizes critical elements including the main fuel manifold, combustion chamber, interconnectors, and air casing, which facilitate efficient combustion and consistent heat distribution.



Fig 5 Annular Combustion Chamber with Integrated Cooling and Airflow Design



This illustration depicts an annular combustion chamber, highlighting the continuous ring structure that enhances airflow homogeneity and temperature regulation. Essential components are the flame tube, fuel manifold, diluting air apertures, and turbine nozzle guiding vanes, facilitating improved thermal efficiency and reduced emissions.

Each design is tailored to specific operational demands, thermal efficiency, and maintenance necessities. The combustor module contains the combustion chamber, igniter plugs, and fuel nozzles. The primary job is to initiate and sustain the combustion of a fuel-air mixture, providing high-temperature gases to the turbine while ensuring regulated thermal efficiency and emissions. Fuel is injected at the upstream end of the combustor in a finely atomized mist. Fuel nozzles may be classified as simplex-type, which manage solely gaseous or liquid fuel, or dual-fuel type, which can alternate between gas and liquid fuels. Specific gas turbines provide bi-fuel capability, enabling the burning of mixed fuel mixtures.

Management of Airflow and Temperature, where the combustion process depends on a complex airflow system. Primary Air (25%)—Utilized for blending with fuel to maintain combustion. The fuel-to-air ratio is often approximately 1:15. Secondary Air (75%) — Envelops the combustion gases, creating an insulating layer that regulates combustion temperature and improves efficiency. Contemporary gas turbine engines, particularly those engineered for airplane propulsion, may demonstrate flame temperatures over 3600°F (2000°C). Secondary air is utilized selectively to temper the flame and mitigate excessive thermal load on turbine components.

Types of Combustion Chambers

- Annular Combustion Chambers
- This design incorporates a singular ring-shaped combustion chamber encircling the engine. It is streamlined, enhances airflow dispersion, and provides superior fuel mixing. The annular gap between the chamber lining and housing enables cooling airflow.
- Benefits: Enhanced efficiency, lower weight, and even temperature distribution.
- Challenges: Necessitates intricate production and upkeep.
- Can Combustion Chambers
- Can combustors comprise discrete cylindrical combustion chambers positioned around the turbine's periphery? Air is supplied to each chamber from the compressor via a transition section. The combustion process transpires within an inner liner, where louvers and cooling apertures regulate airflow.
- Benefits: Simplified maintenance and chamber substitution.
- Challenges: Inconsistent temperature distribution and increased weight.

Ignition is initiated in the can closest to the igniter plug, and cross tubes rapidly propagate the flame to other chambers.

Can-Annular Combustion Chambers

- This hybrid design integrates characteristics of both annular and can-type chambers. It comprises several separate combustor cans contained within an annular shell.
- Benefits: Enhanced temperature consistency, longevity, and cooling effectiveness.
- Challenges: Increased complexity in structural needs.

Flame Stabilization and Airflow Management

- Gas turbines utilize swirler vanes adjacent to the fuel nozzle to maintain effective combustion by facilitating a wellmixed air-fuel mixture. Flame stabilization structures guarantee consistent ignition and avert flame blowout under fluctuating load circumstances.
- Airflow is additionally governed by cooling techniques, which include Film Cooling, in which thin layers of cooling air form an insulating film over the flame tube, and Transpiration Cooling, in Which Air is conveyed via porous substances to ensure consistent cooling. Splash Cooling, in Which Air is introduced through corrugated strips to enhance heat dissipation, is also used.

Low NOx Combustors and Environmental Considerations

Increasing turbine efficiency by raising the turbine inlet temperature (TIT) also leads to elevated NOx emissions. Modern gas turbines use Dry Low Emission (DLE) combustors to mitigate environmental impact, which optimize fuelair mixing to lower combustion temperature and emissions.

• Siemens SGT-600 DLE System – Achieves NOx levels below 25 ppm (15% O2) and operates efficiently across various environments.



• General Electric DLN Combustors – Designed for ultra-low emissions, meeting stringent regulatory requirements while maintaining operational flexibility.

Aerodynamic Processes in Gas Turbine Combustors

Aerodynamics plays a crucial role in gas turbine combustor design, ensuring efficient fuel combustion and minimizing emissions. A well-designed combustor achieves stable flame recirculation, effective fuel and air mixing, and controlled combustion gas dilution. The main aerodynamic goals are:

- Diffuser and Annulus: Reduce velocity and evenly distribute air without parasitic losses or recirculation.
- Combustion Liner: Achieve large-scale flow recirculation for flame stabilization, effective dilution, and efficient wall cooling.
- Mixing: Promote high burning rates in the primary zone while ensuring uniform temperature distribution in the dilution zone.

A thorough understanding of flow dynamics, jet penetration, and discharge coefficients is essential for effective combustor design.

Key Aerodynamic Parameters

Reference Quantities

Several aerodynamic parameters help analyze combustor flow characteristics:

- Reference Velocity (Uref): The mean velocity at the maximum casing cross-section in the absence of a liner.
- Reference Dynamic Pressure (qref): A function of the air density and reference velocity.
- Mach Number (Mref): Based on temperature and velocity to assess flow compressibility.

These parameters allow for comparing different combustor designs and optimizing performance.

Pressure Loss Considerations

Two dimensionless pressure-loss parameters are critical:

Overall Pressure Loss ($\Delta P3-4/P3$): Ratio of total combustor pressure drop to inlet pressure (typically 4–8%).

Pressure-Loss Factor: Represents flow resistance between the compressor and turbine.

The total pressure loss comes from:

- Diffuser Pressure Loss: Should be minimized as it does not contribute to combustion.
- Liner Pressure-Loss Factor (ΔPL): A high pressure drop across the liner enhances mixing and combustion efficiency.

Higher pressure loss improves turbulence and jet penetration, reducing combustor size. However, excessive loss negatively impacts fuel efficiency.

Relationship Between Size and Pressure Loss

The required pressure loss and combustor size influence the combustor casing area (Aref). A trade-off exists:

- A small combustor increases pressure loss but enhances mixing.
- A large combustor reduces pressure loss but may lead to inefficient mixing.

Fabel 1.	Typical	cold p	ressure	losses	for	different	combustor	types
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Chamber Type	Overall Pressure Loss (%)	Pressure-Loss Factor
Tubular	7%	37
Tuboannular	6%	28
Annular	6%	20

Annular combustors mix better due to lower diffuser losses and optimized liner air-inlet hole distribution.

Aerodynamics of Flow in Combustors

Flow in the Annulus

- The annulus airflow affects liner wall temperatures and hole discharge coefficients.
- A high annulus velocity aids cooling but can disrupt uniform air distribution.
- Flow disturbances near dilution holes can cause random recirculation if controlled improperly.
- Solutions include backstops and tapered liners to regulate airflow.



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editor@ijprems.com Flow Through Liner Holes

The discharge coefficient (CD) depends on hole geometry, pressure drop, and upstream flow conditions.

- Plunged holes (extended nozzles) have higher discharge coefficients than plain holes.
- Vortex formation at dilution holes affects jet penetration and mixing.
- Splitter plates and spectacle plates (dams) can prevent vortex-induced flow disturbances.

Jet Trajectories and Mixing

The penetration of air jets into the combustion zone is crucial for temperature uniformity.

- Key factors affecting penetration:
- Jet velocity and density ratio (momentum-flux ratio, J).
- Hole shape and angle of injection.
- Presence of opposing or staggered jets.
- Kidney-shaped vortices form due to pressure differences, enhancing air-fuel mixing.
- In-line vs. staggered jets:
- In-line jets promote better initial mixing.
- Staggered jets provide more uniform long-term mixing.

Mixing effectiveness depends on:

- Jet momentum ratio (J).
- Number of jets.
- Orifice shape and spacing.
- Converging vs. diverging liner designs.

Temperature Distribution in the Dilution Zone

Pattern Factor and Profile Factor

A critical combustor design goal is to achieve a uniform exit temperature distribution, which minimizes thermal stresses on turbine blades.

- Pattern Factor: Indicates maximum temperature variation in the combustor exit gases.
- Profile Factor: Describes radial temperature variations affecting turbine blade cooling.
- Turbine Profile Factor: Adjusted for cooling considerations, ensuring lower blade root and tip temperatures.

Dilution Zone Design

- The size and number of dilution holes determine the temperature profile at the combustor exit.
- Too many small holes cause under-penetration, while too few large holes lead to over-penetration and cold cores.
- The Cranfield Method and NASA Method provide guidelines for optimal hole sizing.

Swirler Aerodynamics and Flow Recirculation

Swirlers in Combustion Stabilization

Swirlers induce vortex breakdown, generating toroidal recirculation zones that stabilize the flame.

- Axial Swirlers: Vanes impart rotation to incoming air, enhancing shear and turbulence.
- Radial Swirlers: Air enters radially before turning axially, commonly used in low-emission combustors.
- Double Swirlers: Can be co-rotating or counter-rotating for enhanced mixing.

Swirl Number and Flow Reversal

- Swirl Number (SN): A non-dimensional measure of rotational flow.
- Weak Swirl (SN < 0.4): No flow recirculation.
- Strong Swirl (SN > 0.6): Induces a central recirculation zone.
- Higher swirl angles (above 38°) generate larger recirculation zones, improving mixing.

Influence of Swirler Geometry

- Curved vanes provide better flow turning and higher recirculation than flat vanes.
- Swirler exit geometry (diverging vs. straight passages) affects flame shape and combustion intensity.
- Reverse mass flow rate increases with swirl number, improving flame stability.

4. COMBUSTION EFFICIENCY & MODELING

The conventional gas turbine combustor is a fundamental component in the Brayton cycle, responsible for converting the chemical energy of fuel into thermal energy that is expanded through a turbine to generate mechanical power. It operates under a continuous combustion process at constant pressure, unlike the intermittent combustion in internal



combustion engines such as those following the Otto cycle. The combustor must efficiently mix fuel with air, maintain stable combustion, and ensure proper temperature distribution at the exit to protect turbine materials. These requirements make its design a complex interplay of fluid dynamics, chemical kinetics, and heat transfer.

4.1 Thermodynamic Basis and Combustor Inlet Conditions

The gas turbine operates on the Brayton cycle, where a compressor ingests and compresses ambient air to elevated pressures, increasing both pressure ratio (P_2/P_1) and temperature. A higher pressure ratio enhances the engine's overall thermodynamic efficiency. Compressed air and injected fuel (such as natural gas, syngas, or petroleum liquids) enter the combustor at high pressure and temperature. The combustor's role is to ignite and sustain combustion, ensuring complete energy release from the fuel.

4.2 Key Combustor Functions

The combustor achieves its goal through several critical functions:

- Fuel-Air Mixing: Proper mixing is necessary to ensure efficient combustion and minimize pollutants.
- Ignition and Flame Stability: The combustor must ignite the fuel-air mixture reliably and maintain a stable flame.
- Combustion Containment: The reaction must occur within a controlled volume to prevent loss of efficiency.
- Temperature Control: The exit gas temperature profile must be carefully managed to avoid excessive thermal stress on turbine blades.

4.3 Combustor Structure and Zones

The combustor consists of three primary zones: Primary Zone, Secondary Zone, and Dilution Zone, each serving a specific role in combustion efficiency and emission control.

4.4 Primary Zone: Fuel-Air Mixing and Ignition

- The primary zone is where the initial fuel-air mixing and ignition occur. Air enters through multiple injection points, primarily through:
- Swirler Vanes: These create a swirling motion that induces a recirculation zone, helping entrain hot combustion products to sustain the flame.
- Primary Air Jets: These regulate air mixing, contributing to the stabilization of combustion and reducing pressure oscillations.
- Recirculation Zone ("Aerodynamic Spark Plug"): Hot combustion products from downstream mix with fresh reactants, continuously igniting new fuel-air mixtures.
- The equivalence ratio (ϕ) in the primary zone is typically fuel-rich ($\phi > 1.0$) to prevent flame blowout and ensure reaction stability.
- Microscale Mixing and Turbulence: Mixing occurs at multiple scales, from macroscale recirculation zones down to turbulent eddies. These eddies dictate the local fuel-air ratio, which impacts combustion efficiency.
- Heat Release Process: Initially, hydrocarbon bonds break down into intermediate products (CO and H₂O), with twothirds of the fuel's energy released in the primary zone. The remainder is contained in CO, which requires further oxidation.

4.5 Secondary Zone: CO Oxidation and Efficiency Enhancement

- The secondary zone is critical for completing the oxidation of CO to CO₂, improving combustion efficiency and reducing harmful emissions.
 - The dominant reaction is:

 $\rm CO + OH \rightarrow \rm CO_2 + H$

•

• This zone must maintain an optimal temperature and residence time to ensure complete oxidation, typically by maintaining an equivalence ratio of $\phi \sim 0.8$.

4.6 Dilution Zone: Temperature Reduction and Uniformity

- The dilution zone introduces additional air jets to reduce the temperature of combustion gases before entering the turbine.
- This is necessary because excessively high temperatures would cause thermal damage to turbine blades.
- The temperature distribution must be controlled to prevent local hot spots, which can lead to material degradation.
- The Pattern Factor, Profile Factor, and Turbine Profile Factor are used to measure temperature uniformity at the exit.

4.7 Combustor Heat Transfer and Cooling Strategies

- Combustion generates high thermal radiation, which can overheat the combustor walls.
- Approximately 25% of the compressor air is used for liner cooling.



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- editor@ijprems.com Cooling Techniques:
- Film Cooling: Uses small perforations in the liner to direct cool air along the combustor walls.
- Effusion Cooling: Advanced liners with hundreds of small holes provide a uniform cooling layer.
- Convective Cooling: Uses dedicated cooling channels within the liner walls.

4.8 Combustor Configurations

Three primary combustor configurations exist, optimized for different applications:

- Can-Type Combustors:
- Individual cylindrical chambers, easy to maintain.
- Common in stationary gas turbines due to ease of replacement.
- Can-Annular Combustors:
- Multiple can combustors arranged in an annular housing.
- Used in some aero engines like the Pratt & Whitney JT8D.
- Annular Combustors:
- A continuous ring surrounding the engine core.
- Preferred in modern aircraft engines for compactness, efficiency, and better temperature distribution.

4.9 Environmental and Efficiency Considerations

- Traditional gas turbine combustors operate in a non-premixed (diffusion) combustion mode, where fuel and air mix within the combustor.
- Advanced designs aim to reduce NOx and CO emissions by approaching a premixed combustion regime.
- Strategies include:
- Rapid Mixing of Non-Premixed Reactants
- Spatially Distributed Injection
- Fully Premixed Injection (in select stationary applications)

High combustion efficiency is crucial for minimizing fuel waste and reducing emissions of unburned hydrocarbons (UHC) and carbon monoxide (CO). Modern aircraft engines achieve nearly 100% efficiency at takeoff and maintain at least 90% efficiency across the operational range. Regulatory requirements demand combustion efficiencies exceeding 99%, ensuring minimal pollutant emissions.

At high altitudes, achieving high efficiency is especially challenging due to reduced air pressure and temperature, leading to narrow stability limits. If efficiency drops too low, additional fuel injected to compensate may lead to rich extinction, causing a flameout. To ensure reliable restarts at high altitudes, combustors must be sized appropriately to maintain efficiency even in extreme conditions.



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4.10 The Combustion Process

The primary function of a combustion system is to raise the airflow temperature by efficiently burning fuel. However, the complexity of combustion processes makes precise theoretical modeling difficult. To estimate combustion efficiency, simplified models are used, which consider:

- Fuel evaporation rate
- Mixing rate of fuel vapor with air
- Chemical reaction rate

Since the available combustion time is inversely related to airflow rate, efficiency can be expressed as a function of these factors. The controlling mechanism varies under different conditions:

- Reaction-Controlled Combustion Limited by chemical kinetics.
- Mixing-Controlled Combustion Limited by turbulence and fuel-air interaction.
- Evaporation-Controlled Combustion Limited by fuel droplet evaporation.

Reaction-Controlled Systems

In cases where chemical reaction rates limit heat release, combustion performance is analyzed using two models:

4.11 Burning Velocity Model

This model assumes a turbulent flame brush similar to a Bunsen burner flame. The efficiency is dictated by the ratio of turbulent burning velocity to the incoming airflow velocity. If mixing and evaporation are infinitely fast, the only cause of inefficiency is fuel bypassing the flame front without burning.

Key insights from experimental studies:

- Combustion efficiency is proportional to turbulent burning velocity.
- Higher turbulence enhances flame propagation, improving efficiency.
- The θ parameter is introduced to correlate efficiency across different combustor designs:
- The theta parameter is a function of several key variables influencing combustion efficiency in gas turbine combustors. It depends on pressure, which affects reaction rates and flame stability, and the reference area, which determines the scale of the combustor and airflow distribution. Additionally, the diameter influences the combustion chamber's geometric proportions and mixing characteristics. The mass flow rate is another critical factor, as it dictates the available air for combustion and dilution, directly impacting efficiency and emissions. Finally, temperature is crucial in chemical reaction rates and fuel evaporation. Together, these parameters define the performance of a combustor, allowing engineers to assess and optimize its design for efficient and stable operation.
- The θ parameter is used to scale combustor dimensions and compare different designs, as shown in performance charts.

4.12 Stirred Reactor Model

This approach models the combustion chamber as a perfectly mixed reactor where fuel and air instantly blend. The system reaches a steady-state composition, with reaction rates governed by a single limiting chemical reaction.

Key findings:

- The reaction rate is linked to air temperature rather than reaction temperature.
- Experiments show pressure dependency, with an exponent between 1.75 to 1.8.
- The θ parameter remains applicable but focuses more on volume than cross-sectional area.

Both the Burning Velocity Model and Stirred Reactor Model accurately correlate experimental data and assist in scaling combustor design.

4.13 Mixing-Controlled Systems

If evaporation and chemical reactions occur at infinitely fast rates, combustion efficiency is determined by the mixing rate of air and fuel.

- Mixing rate is proportional to turbulence intensity, jet velocity, and density gradients.
- If the mixing process is inefficient, pockets of unburned fuel persist, lowering combustion efficiency.
- Equation-based models relate combustion efficiency to several key parameters. These include pressure, which influences reaction rates and overall combustor performance, and the reference area, which determines the size and airflow distribution within the chamber. The mass flow rate is also crucial, as it dictates the air volume available for combustion and dilution. The pressure loss across the liner is an essential design parameter affecting airflow dynamics, turbulence levels, and mixing efficiency. These factors help engineers develop models that predict combustion efficiency and optimize combustor design for improved performance and stability.

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• Industrial gas turbines, operating at constant pressures, are typically mixing-limited rather than reaction-limited.

4.14 Evaporation-Controlled Systems

In conditions where fuel evaporation is the slowest process, it becomes the rate-limiting step.

Factors Affecting Evaporation Rate

- Fuel volatility (λ_{eff})
- Mean droplet size (D_o)
- Turbulence intensity
- Combustor volume
- Gas pressure
- High-pressure environments enhance evaporation, improving efficiency.
- Larger droplet sizes impair efficiency, as droplets take longer to vaporize.
- A dimensionless efficiency ratio compares alternative fuels against a baseline:

4.15 Reaction- and Evaporation-Controlled Systems

In some cases, both chemical reaction rates and evaporation rates simultaneously limit combustion.

- Efficiency is a product of evaporation efficiency (η_e) and reaction efficiency (η_θ) .
- Equation-based correlations integrate fuel properties, air pressure, turbulence, and temperature.
- Studies on alternative fuels demonstrate the model's accuracy in predicting combustion efficiency across different engine conditions.

Flame Stabilization and Stability Performance

Flame stability is critical for reliable engine operation under various conditions, including:

- Low pressures & temperatures
- Rapid airspeed fluctuations
- Adverse weather conditions (rain, ice ingestion)

4.16 Measuring Stability Performance

- Stability is assessed using stability loops, mapping lean and rich blowout limits at different mass flow rates.
- The lean blowout limit (AFR > 250) is crucial for ensuring continuous combustion in aircraft engines.
- Rich blowout occurs at high fuel/air ratios, often limited by ignition system capabilities.

4.17 Practical Considerations

- Aircraft combustors require wide stability margins to prevent flameouts.
- Fuel injection design greatly impacts stability.
- In low-emission combustors, stability trade-offs may be necessary to achieve pollutant reduction goals.

5 LEAN PRE-MIXED COMBUSTION (LPM) IN GAS TURBINES

Gas turbine engineers consistently endeavor to improve cycle efficiency while reducing pollutant emissions. Nonetheless, these objectives frequently clash, as elevating working fluid temperatures enhances efficiency while also encouraging NOx generation. Significant NOx production occurs above 2800°F. Furthermore, diminishing the availability of oxygen to regulate NOx may result in elevated emissions of carbon monoxide (CO) and unburned hydrocarbons (UHC) due to incomplete combustion. Firing temperatures beyond 2350°F present material problems, constraining additional temperature elevations. To attain reduced NOx emissions, a range of pre-formation and postformation control strategies have been employed, including wet controls such as water or steam injection, dry combustion controls involving lean combustion and diminished residence time, selective catalytic reduction (SCR) systems, and catalytic combustion technologies like Xonon. Additionally, Rich-Quench-Lean (RQL) combustors and carbon monoxide oxidation catalysts have been implemented. Lean Pre-Mixed (LPM) combustion has emerged as the norm for natural gas turbines, owing to its capacity to achieve low NOx emissions and excellent combustion efficiency. LPM systems utilize surplus air to reduce flame temperature, thereby inhibiting NOx production. Fuel and air are meticulously blended prior to entering the combustor, hence averting localized hot spots that contribute to elevated NOx production. Numerous gas turbine manufacturers have created proprietary LPM systems under distinct trade names. General Electric and Siemens-Westinghouse implement Dry Low NOx (DLN) systems, Rolls-Royce adopts Dry Low Emissions (DLE) technology, and Solar Turbines employs the SoLoNOx method. These systems can attain NOx emissions as low as 15–25 parts per million by volume, dry (ppmvd), contingent upon the turbine model and application. Certain modern systems attain single-digit NOx emissions. This method not only diminishes NOx but also decreases

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CO and VOC emissions by optimizing the combustion process. The principal benefits of LPM encompass diminished NOx, CO, and UHC emissions, augmented combustion efficiency, and increased operational stability while sustaining low emissions.

Gas turbines predominantly release NOx, CO, and UHC, along with minor quantities of sulfur dioxide (SO₂), particulate matter (PM), and hazardous air pollutants during liquid-fuel combustion. Nitrogen oxides (NOx) are predominantly generated at elevated flame temperatures, whereas carbon monoxide (CO) and unburned hydrocarbons (UHC) arise from incomplete combustion. Emissions of sulfur dioxide and particulate matter are contingent upon the sulfur concentration of the fuel. Diverse strategies are employed to regulate these emissions. Lean combustion and water injection effectively reduce NOx emissions, whilst oxidation catalysts assist in minimizing CO emissions. The Environmental Protection Agency (EPA) identifies lean-premixed combustion as an optimal method for controlling NOx emissions, while simultaneously reducing CO and VOC emissions.

NOx emissions in gas turbines arise from two principal sources. Thermal NOx is produced when atmospheric nitrogen combines with oxygen at elevated temperatures. This reaction becomes critical above 2370°F, rendering flame temperature regulation essential for NOx mitigation. The second source is fuel NOx, generated when nitrogen-containing fuels, such syngas, undergo oxidation during combustion. Although fuel NOx is minimal for natural gas, it poses a significant issue when utilizing low-quality fuels. A variety of solutions are employed to mitigate NOx emissions, including as lean combustion methods that utilize surplus air to decrease flame temperature, flame cooling through water or steam injection, and post-combustion controls including SCR systems and oxidation catalysts.

The regulatory framework for NOx emissions in gas turbines has undergone substantial evolution. In the 1970s, the EPA's New Source Performance Standards (NSPS) restricted NOx emissions from major utility gas turbines to 75 ppmvd when utilizing natural gas. In the 1980s, Best Available Control Technology (BACT) was implemented, lowering NOx limits to 42 ppmvd. As technology progressed, NOx emissions were diminished to 25 ppmvd, with contemporary gas turbines attaining levels as low as 9 ppm through the use of LPM combustors. The BACT standard guarantees that emissions controls are perpetually revised in accordance with technological progress, whereas the Lowest Achievable Emission Rate (LAER) enforces the most stringent NOx restrictions grounded in industry best practices.

Diverse LPM combustor designs have developed to satisfy these regulatory and performance requirements. An example is the GE DLN-1 combustor, a dual-stage premixed system functioning in four separate modes. The primary mode is utilized during startup and low-load operations, whilst the lean-lean mode is applied during intermediate load levels. The secondary mode functions as a transitional phase, while the premix mode is employed at full load to attain minimal NOx emissions. Alstom created a sequential combustor, enhancing air premixing to further diminish emissions. These innovations illustrate the ongoing enhancements in LPM technology to optimize efficiency and comply with regulatory standards.

Notwithstanding its benefits, LPM combustion poses numerous problems. A critical concern is the CO/NOx tradeoff, wherein decreasing flame temperature to mitigate NOx emissions may elevate CO emissions as a result of incomplete combustion. This tradeoff is especially significant during partial-load operation, where sustaining ideal combustion conditions proves challenging. A further challenge is operating in chilly environmental conditions. Emissions warranties are typically not guaranteed below 0°F due to the impact of colder air on combustion dynamics. A potential approach is to employ inlet air heating or modify pilot fuel amounts to ensure steady combustion. Moreover, transient load problems may result in flame blowout during swift load fluctuations, which can be alleviated using fuel staging or air staging methods.

Future developments in LPM combustion technology concentrate on enhancing combustor lining configurations, fuel injectors, and fuel adaptability. Advanced combustor liners are shifting from film cooling to backside cooling techniques, which improve thermal control and longevity. Advanced turbulator designs are being developed to enhance cooling efficiency. Next-generation fuel injectors include enlarged swirlers to enhance air-fuel mixing and mitigate local hot spots. Enhanced injection patterns are being investigated to increase combustion stability and further diminish emissions. Moreover, the combustion of hydrogen and syngas presents distinct problems. The strong reactivity of hydrogen elevates the risk of NOx emissions, necessitating staged combustion techniques and sophisticated burner designs for enhanced control. LPM is acknowledged as the premier technology for low-emission gas turbines. Integrating lean combustion techniques substantially decreases NOx, CO, and UHC emissions while maintaining high efficiency. Nonetheless, ensuring combustion stability, accommodating transient loads, and addressing fuel variability continue to pose issues that necessitate continuous innovation. Advancements in combustor design, cooling methodologies, and fuel versatility will guarantee ongoing compliance with rigorous environmental standards while enhancing total gas turbine efficiency. Ongoing research is anticipated to advance LPM technology, rendering it a crucial element in the quest for cleaner and more efficient gas turbine operations.

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Rich Burn, Quick-Mix, Lean Burn (RQL) Combustor

The Rich-Burn, Quick-Mix, Lean-Burn (RQL) combustor concept was introduced in 1980 as an advanced strategy to reduce nitrogen oxides (NOx) emissions in gas turbine engines. By the 1990s, NASA had identified RQL technology as a key approach for minimizing NOx emissions in next-generation aero-propulsion engines. Today, RQL technology is a fundamental combustor design, particularly in commercial aero engines, where it is deployed under Pratt & Whitney's TALON (Technology for Advanced Low NOx) system. The preference for RQL combustors in aero engines is largely due to safety considerations and operational stability throughout the engine duty cycle, making it a more reliable choice than lean-premixed combustors for aviation applications.

In contrast, stationary gas turbines primarily rely on lean-premixed combustor (LPM) technology, as these applications do not face the same safety constraints and can achieve greater NOx reduction through lean combustion techniques. However, RQL technology is gaining increasing attention for stationary applications due to its advantages in processing fuels with complex compositions and varying fuel quality. This capability is becoming increasingly important as the global energy landscape shifts towards alternative fuels, including biomass-derived fuels, landfill gases, digester gases, wellhead gases, and liquefied natural gas (LNG). The California Energy Commission, in collaboration with the U.S. Department of Energy, is actively researching RQL strategies for niche power generation applications, particularly in areas where fuel variability is a significant concern.

Concept and Operation of RQL Combustion

The RQL combustor is based on the premise that a gas turbine's primary combustion zone functions most efficiently under fuel-rich conditions. The combustion process occurs in three distinct stages:

- Rich-Burn Zone In this initial stage, the combustion zone operates at a high equivalence ratio (typically $\Phi = 1.8$). This enhances flame stability by producing and sustaining a high concentration of energetic hydrogen and hydrocarbon radicals. Additionally, operating under rich conditions minimizes NOx formation due to lower temperatures and reduced oxygen availability, both of which suppress thermal NOx production.
- Quick-Mix Zone The effluent from the rich-burn zone contains high levels of partially oxidized hydrocarbons, hydrogen, and carbon monoxide (CO). Before being exhausted, this mixture must undergo further oxidation. To achieve this, air is rapidly injected through wall jets, ensuring effective mixing between the primary zone effluent and incoming air. This transition occurs rapidly to avoid conditions that promote excessive NOx formation.
- Lean-Burn Zone Once adequate air mixing is achieved, combustion shifts to lean conditions before reaching the combustor's exit plane. This phase is designed to ensure complete combustion while minimizing emissions, ideally resulting in an exhaust mixture composed primarily of carbon dioxide (CO₂), water vapor (H₂O), nitrogen (N₂), and excess oxygen (O₂), with minimal NOx, CO, and unburned hydrocarbons (UHCs). Despite the benefits of this approach, the transition from the rich-burn to the lean-burn zone presents significant

Despite the benefits of this approach, the transition from the rich-burn to the lean-burn zone presents significant engineering challenges, particularly in terms of combustor materials and aerodynamics.

- A significant design challenge for RQL combustors is selecting appropriate liner materials for the primary combustion zone. Unlike conventional combustors, the RQL primary zone does not allow for liner cooling via air injection because introducing air in this phase could create near-stoichiometric conditions that lead to excessive NOx formation. As a result, the combustor liner is exposed to an extremely harsh environment, characterized by: The Quick-Mix section of an RQL combustor is crucial for achieving lean combustion before combustion is completed. However, this process must be controlled precisely due to the rapid transition through stoichiometric conditions, were NOx formation peaks due to high temperatures and excess oxygen. Poor mixing can lead to localized regions of near-stoichiometric combustion, significantly increasing NOx emissions. Excessive jet air
 - penetration may result in flame instability, while insufficient penetration can cause incomplete combustion and elevated CO emissions.
- Research efforts have focused on optimizing jet penetration and mixing dynamics through the geometry of the air injection orifices, including factors such as jet entry angle, orifice shape and size, and axial staggering of injection points. Over the past two decades, extensive jet-in-crossflow studies have been conducted to enhance the design of the Quick-Mix section. Key findings from Quick-Mix research include single jet behavior, multiple jet interactions, and optimized orifice configurations. The NASA Holdeman correlation provides an empirical relationship for determining the optimal number of air injection orifices in the Quick-Mix zone to achieve maximum mixing efficiency.
- Recent research has challenged the assumption that an aerodynamically "optimal" mixer does not necessarily yield the lowest NOx emissions. The formation of nitrogen-based species in the Rich-Burn zone significantly impacts NOx emissions. NOx levels tend to be higher in the wake of the air jets, suggesting that NOx formation occurs downstream of the mixing zone, rather than within the primary zone itself. Air preheating also impacts NOx formation, with preheat primarily affecting NOx chemistry rather than jet penetration.

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Fig 7 Rich Burn, Quick-Mix, Lean Burn (RQL) Combustor

Trapped Vortex Combustion (TVC)

The Trapped Vortex Combustion (TVC) technology represents a significant advancement in gas turbine combustor design, particularly for Integrated Gasification Combined Cycle (IGCC) applications. This innovative combustion approach offers multiple benefits, including the ability to burn a wide variety of low and medium-BTU fuels, such as hydrogen-rich syngas from gasified coal, biomass products, and landfill gases. Additionally, TVC allows gas turbines to operate in a low NOx lean premixed combustion mode, even with hydrogen-rich fuels, which typically present challenges due to their high flame speeds.



Conceptual Rendering

Fig 8 Trapped Vortex Combustion (TVC)

Key advantages of TVC for IGCC gas turbines include:

- Reduced NOx Emissions TVC achieves ultra-low NOx emissions without the need for costly exhaust gas aftertreatment technologies, such as Selective Catalytic Reduction (SCR).
- Elimination of Diluent Requirements Conventional gas turbines operating on syngas require the injection of steam, nitrogen, or CO₂ to suppress flame temperatures and reduce NOx formation. TVC eliminates this costly requirement.
- Improved Efficiency By reducing the pressure drop through the combustor, TVC enhances overall cycle efficiency, leading to lower operational costs.
- Better Load Flexibility TVC extends the lean blowout limit, which improves turndown capability, allowing for stable operation under varying load conditions.
- Compatibility with a Broader Range of Gas Turbines By decreasing the mass flow rate through the turbine section, TVC allows IGCC systems to integrate with more gas turbine models, enhancing system flexibility.

These advantages make TVC a promising next-generation combustor technology for IGCC power plants, addressing both efficiency and environmental concerns.

Challenges of IGCC Gas Turbine Combustion

While IGCC technology is regarded as one of the most efficient and environmentally friendly methods for utilizing lowquality fuel sources (such as coal and oil), there are still significant challenges that need to be addressed:

- Fuel Characteristics Unlike natural gas, syngas has a low calorific value (100-300 BTU/scf) compared to natural gas (800-1200 BTU/scf). This results in higher fuel mass flow requirements, which can be four to five times greater than those for natural gas turbines.
- NOx Emissions Control Conventional dry low NOx (DLN) combustors rely on premixed combustion to reduce NOx. However, this is not feasible for hydrogen-rich syngas due to the high flame speed, which leads to flashback and potential hardware failure.
- Dilution Challenges Syngas turbines often use dilution techniques (steam, nitrogen, or CO₂ injection) to control NOx emissions. However, excessive dilution can cause flame instabilities and potential flame blowout.



• Backpressure and Surge Risks – The increased mass flow through the turbine due to fuel dilution can lead to backpressure issues, potentially pushing the compressor towards surge conditions, which can impact overall system performance.

These challenges highlight the need for alternative combustion technologies, such as Trapped Vortex Combustion, which can efficiently handle hydrogen-rich syngas without excessive dilution or flashback issues.

Combustion of Syngas and Emission Control

Syngas combustion in IGCC power plants presents unique NOx emission challenges, primarily due to differences in fuel composition compared to natural gas:

- Higher Flame Speed The high hydrogen content (up to 60% by volume) in syngas results in a flame speed up to six times faster than natural gas, making premixed combustion impractical.
- Limited NOx Reduction via Dilution—Unlike natural gas, syngas cannot be diluted indefinitely without causing flame instabilities. The practical NOx reduction limit for syngas combustion is typically 10-20 ppm NOx.
- Incompatibility with Selective Catalytic Reduction (SCR) The presence of sulfur compounds in syngas can interfere with SCR catalysts, leading to unwanted deposits on heat recovery steam generator (HRSG) tubes and potential system failure.

These constraints make alternative NOx control strategies, such as TVC, an attractive solution for syngas-fueled IGCC turbines.

DOE NETL IGCC Turbine Program and TVC Research

In response to the challenges of syngas combustion, the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) has initiated a multi-year program to develop new turbine technologies capable of efficiently operating on high-hydrogen fuels. The program focuses on three key approaches:

- Hydrogen Premixing Exploring methods to safely mix hydrogen with air before combustion without flashback risks.
- Catalytic Combustion Investigating the use of catalysts to lower combustion temperatures and suppress NOx formation.
- Trapped Vortex Combustion (TVC) Developing advanced vortex-based stabilization techniques to enhance combustion efficiency while maintaining low NOx emissions.

Among these approaches, TVC is emerging as a breakthrough technology, offering unparalleled flame stability, fuel flexibility, and lower emissions without requiring exhaust gas treatment.

Trapped Vortex Combustion – A Breakthrough Technology

The Trapped Vortex Combustion (TVC) concept was originally developed in the early 1990s for aero-propulsion applications, where it was designed to handle high-throughput velocity flows. In the early 2000s, research efforts expanded TVC applications into industrial and power generation sectors.

Key Advantages of TVC:

- Superior Flame Stability By using recirculation zones, TVC ensures continuous ignition, promoting stable combustion under varying operating conditions.
- Lower Emissions TVC eliminates hot spots within the combustor, leading to significantly lower NOx emissions compared to traditional designs.
- Fuel Flexibility Unlike diffusion flame or DLN combustors, TVC can handle hydrogen-rich fuels without flashback risks.
- Compact and Efficient Design TVC reduces combustor pressure drop, leading to higher cycle efficiency and better fuel utilization.

Instead of relying on swirl stabilization, as seen in traditional gas turbines, TVC stabilizes the flame using cavity flows, leveraging insights from aerospace fluid dynamics.

TVC Stabilization Mechanism

TVC employs a stable vortex region within a cavity adjacent to the main combustion zone. This trapped vortex serves as a continuous ignition source, allowing for efficient fuel-air mixing without relying on turbulent shear layers, which are prone to instability and NOx formation.

TVC Development and Research Efforts

Key Organizations Advancing TVC Technology:

1. Air Force Research Laboratory (AFRL) – Initiated research in the 1990s, focusing on military aero-propulsion applications.

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- 2. General Electric (GE) Developing TVC concepts for both military and industrial gas turbines, with a focus on sub-9 ppm NOx emissions.
- 3. DOE NETL Investigating TVC for stationary gas turbines, aiming for NOx levels below 3 ppmvd.
- 4. Ramgen Power Systems (RPS) Developed Advanced Vortex Combustion (AVC) technology, achieving <3 ppm NOx emissions in gas turbine operating conditions.
- 5. ALM Turbines Focused on microturbines and large industrial-scale turbines, with proprietary TVC designs.

Low Swirl Combustion (LSC)

Industrial gas turbine manufacturers have widely adopted lean-premixed (LP) combustion technologies as a Dry Low NOx (DLN) solution to meet emissions regulations worldwide. However, as ultra-low emissions standards become increasingly stringent, DLN combustors face challenges operating near the lean stability limits, where noise, instability, flame blowoff, and flashback can severely impact engine performance. Efforts to mitigate these challenges include passive control techniques (fuel and air staging), active control strategies (feedback loops), and costly exhaust gas cleanup methods like catalytically assisted combustion.

These solutions often lead to more complex combustion devices requiring sensors, actuators, and auxiliary components. The variability of fuel compositions in coal-based Integrated Gasification Combined Cycle (IGCC) systems further exacerbates instability problems, necessitating the optimization or re-engineering of fuel injectors and combustors. Since most turbine combustors are designed for natural gas, they may not be easily adaptable for IGCC fuels.

A promising solution to fuel flexibility challenges in IGCC turbines is the Low Swirl Combustion (LSC) concept. Originally developed at Lawrence Berkeley National Laboratory, LSC operates on aerodynamic principles that control the propagation of premixed flames. This simple and robust combustion method offers low NOx emissions without significantly modifying system configurations, efficiency, or costs. LSC has been successfully commercialized in industrial process burners under the name Low Swirl Burners (LSB), with products ranging from 150 kW to 7.5 MW, delivering ultra-low NOx emissions (4-7 ppm).

LSC technology has been adapted as Low Swirl Injectors (LSI) for gas turbine applications. Rig tests for 10 MW-class gas turbines have demonstrated its ability to achieve < 5 ppm NOx (@15% O₂), making it a promising plug-and-play solution for upgrading existing DLN turbines. Furthermore, LSC is adaptable for burning various fuels, including hydrogen-enriched fuels and synthetic gases, making it a versatile and cost-effective alternative for low-emission gas turbines.

Principle of Low Swirl Combustion (LSC) and Technology Transfer History

High-Swirl vs. Low-Swirl Combustion

Swirl-stabilized combustion has traditionally been used in premixed and non-premixed combustion systems due to its benefits in flame stability, combustion intensity, and overall combustor performance. Conventional high-swirl burners generate a strong recirculation zone, which enhances turbulent mixing and flame anchoring. However, this can also lead to increased NOx formation due to prolonged residence times at high temperatures.

In contrast, Low Swirl Combustion (LSC) deliberately reduces swirl intensity to avoid vortex breakdown and recirculation zones. Instead of a strong central vortex, LSC produces a divergent flow field, allowing the premixed turbulent flame to self-propagate. This approach minimizes thermal NOx emissions while maintaining flame stability and robust combustion characteristics.

Development and Commercialization of Low Swirl Burners (LSB)

The LSC concept was initially developed in small-scale laboratory burners before being scaled up for industrial process applications. Commercial LSBs have been implemented in residential pool heaters, industrial furnaces, and boilers, with sizes ranging from 15 kW to 7.5 MW. The Maxon Corporation commercialized the M-PAKT burner line, offering 4–7 ppm NOx and CO emissions with a 10:1 turndown ratio, demonstrating the practical viability of LSC technology.

Flow Field Characteristics and Flame Stabilization

Flame Anchoring Mechanism

The LSC flame stabilization mechanism is unique compared to high-swirl combustion. The key principles include:

- Divergent Flow Field: The central flow expands outward instead of forming a recirculation zone, ensuring that the flame propagates freely without being trapped.
- Self-Stabilizing Mechanism: The flame automatically positions itself at the point where the local flow velocity matches the turbulent flame speed. This prevents flashback while mitigating blow-off risks.
- Linear Velocity Decay: Unlike high-swirl flames that rely on hot gas recirculation, LSC flames remain stabilized through fluid mechanics rather than thermal feedback.



Impact on NOx Emissions

LSC achieves ultra-low NOx emissions by:

- 1. Reducing Residence Time in High-Temperature Zones Unlike high-swirl combustors, LSC prevents hot gases from lingering in the flame zone, significantly reducing NOx formation.
- 2. Operating at Lower Flame Temperatures LSC flames burn at ultra-lean conditions, minimizing thermal NOx production.
- 3. Minimizing Shear Stresses and Flame Instabilities Absent steep velocity gradients ensures a uniform and smooth combustion process, avoiding local hot spots that could trigger NOx formation.

Development of Low Swirl Injectors (LSI) for Gas Turbines

Proof-of-Concept and Gas Turbine Integration

The first proof-of-concept LSI prototype was successfully tested in a Solar Turbines gas turbine combustion rig, demonstrating:

- Stable operation at high temperatures (220–341°C) and pressures (5–10 atm)
- Easy light-off and reliable ignition
- Lean blow-off prevention, even at low equivalence ratios

Following initial tests, a vane-type LSI prototype was developed as a drop-in replacement for existing high-swirl DLN injectors. The LSI was retrofitted into a standard film-cooled combustor liner and tested at pressures of 5-15 atm and airflows of 0.4-1.33 kg/s, representative of 5-7 MW gas turbines.

Key Performance Results

- NOx emissions of < 5 ppm (@ 15% O₂), a 2.5× reduction compared to high-swirl DLN technology
- No flashback or combustion instabilities
- Maintained CO emissions below 5 ppm
- Compatible with standard DLN combustion systems without hardware modifications

Development of LSI for IGCC Gas Turbines

Challenges of Burning Syngas in LSI

IGCC turbines operate on variable syngas compositions, requiring adaptation of LSI to different fuel properties:

- Low Heating Value Syngas (25% H₂, 40% CO, 20% H₂O):
- Lower flame speed than natural gas
- Requires optimized flow divergence to prevent flame quenching
- High Hydrogen Syngas (65–85% H₂, 15–35% H₂O):
- Faster burning than natural gas
- Requires relaxed flow divergence to avoid flashback

Optimization Strategy

- Adjusting swirl intensity (S) based on fuel properties
- Developing fuel-flexible LSI prototypes
- Performing high-pressure rig tests with preheated air to simulate gas turbine conditions
- Early proof-of-concept experiments confirmed that LSC can successfully burn 100% hydrogen flames, demonstrating its potential for next-generation hydrogen-fueled turbines.

Catalytic Combustion (CC) for Gas Turbines

Catalytic combustion, initially developed by Pfefferle at Engelhard Corporation in the 1970s, involves catalytic and non-catalytic combustion reactions within a temperature range that enables both processes. The original catalytic combustor consists of a ceramic honeycomb monolith with catalytically coated parallel channels placed within a combustion chamber. In this setup, surface reactions generate heat and reactive intermediates, inducing gas-phase reactions that allow stable combustion at leaner fuel conditions than conventional combustion. This results in ultra-low emissions, making catalytic combustion an attractive option for gas turbines.



Fig 9 Catalytic combustion

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The 1990s resurgence in catalytic combustion was driven by stricter emissions regulations that could not be met with conventional combustors alone. New developments, including partial fuel conversion in catalyst beds and the use of metal catalyst substrates to mitigate thermal shock, contributed to successful applications in gas turbines.

Two distinct catalytic combustion systems emerged:

- Fuel-lean catalytic systems (developed by Catalytica, Inc.)
- Fuel-rich catalytic systems (developed by Precision Combustion, Inc.)

Both have been engine-tested and are discussed further in the handbook's later sections.

Role of Catalysis in Combustion

1

Catalysts are used in combustion turbines to promote three primary reactions:

- 1. Fuel reforming (before combustion)
- 2. Fuel oxidation with heat release (catalytic combustion)
- 3. Pollutant destruction (exhaust gas cleanup)

In catalytic combustion, a catalyst lowers the ignition temperature, enabling complete combustion at lower temperatures, thereby reducing NOx emissions. Conventional gas turbines require flame temperatures above $1525^{\circ}C$ (2780°F) for stability, leading to NOx levels exceeding 3 ppm (@ 15% O₂). However, catalytic combustion enables stable operation at much lower flame temperatures, improving emissions control and combustor turndown capabilities.

Catalyst Materials for Combustion Applications

A catalyst facilitates chemical reactions without being consumed in the process. In catalytic combustors, precious metal catalysts (such as platinum (Pt), palladium (Pd), and rhodium (Rh)) are used and fixed to a substrate to prevent degradation. The reactants (fuel and air) come into contact with the catalyst surface, promoting complete combustion at lower temperatures.

Key Catalyst Substrate Considerations:

- High surface area (to maximize reaction rates)
- High thermal durability (to withstand gas turbine operating conditions)
- Resistance to thermal shock and thermal gradients

Two primary types of catalyst substrates exist:

- 1. Metal substrates: These are preferred for gas turbines due to their durability, but their operating temperature must be below 950°C (1750°F).
- 2. Ceramic substrates: Can withstand higher temperatures but are susceptible to thermal shock failure.

A common feature in modern catalytic combustor designs is limiting catalyst temperature without sacrificing engine performance. This is achieved by controlling mass transfer rates, adjusting fuel-air equivalence ratios, and optimizing catalyst placement.

Catalyst Lightoff and Reaction Mechanisms

Catalyst light off refers to the transition from low-temperature catalytic surface reactions to high-temperature masstransfer-limited operation, in which reactants are consumed as quickly as they arrive at the catalyst surface.

Key insights from lightoff temperature studies include:

- Palladium-based (Pd) catalysts show the lowest lightoff temperatures for methane oxidation (~340–460°C).
- Platinum-based (Pt) catalysts require higher lightoff temperatures (~590–710°C) but offer longer operational stability.
- Fuel-rich catalytic reactions generally exhibit higher reaction rates than fuel-lean conditions.

Recent studies at Precision Combustion, Inc. demonstrated that syngas catalytic combustion can achieve lightoff temperatures as low as 180°C (350°F). This is particularly beneficial for gas turbine applications, as it allows stable ignition without a preburner.

Flame Temperature Considerations and NOx Emissions

- Temperature Constraints in Catalytic Combustion Systems
- 1. Minimum flame temperature (~1100°C / 2000°F)
- Required for complete burnout of hydrocarbons and CO.
- 2. Maximum flame temperature (~1525°C / 2780°F)
- Above this threshold, NOx emissions increase significantly.



Catalytic combustion systems operate within this temperature window to achieve ultra-low NOx emissions while maintaining combustor efficiency.

Tabel 2 Turbine Classifications and Catalytic Combustion Applicability

Turbine Type	Flame Temperature (°C)	Catalytic Combustion Approach	NOx Emissions
Microturbines	< 1000°C	Single-stage total conversion	Ultra-low NOx
Industrial turbines (E, F-Class)	1100–1480°C	Two-stage partial conversion	< 3 ppm NOx
Ultra-high temperature turbines (G-Class, FB-Class)	> 1525°C	Advanced cooling strategies needed	Moderate NOx

For high-firing-temperature turbines, alternative approaches, such as exhaust gas recirculation (EGR) and advanced cooling methods, are being investigated to maintain low NOx emissions.

Catalytic Combustion System Designs

1. Single-Stage (Total Conversion) System

- Fuel and air are premixed before passing over a catalyst bed.
- The catalyst sustains combustion, but gas-phase reactions are needed for complete fuel oxidation.
- Used in microturbines and low-temperature applications.
- 2. Two-Stage (Partial Conversion) System
- First stage (Catalytic Reactor): Only a portion of the fuel is oxidized at <950°C (1750°F).
- Second stage (Gas-Phase Combustion): Remaining fuel is burned in a traditional combustor at >1100°C (2000°F).
- Used in industrial gas turbines (E, F-Class machines).

Table 5 Leading Catalytic Combustion Systems

Company	System Type	Fuel Mixing Strategy	Primary Features
Catalytica, Inc.	Fuel-lean catalytic system	Full premixing before catalyst	Uses autoignition to sustain gas-phase combustion
Precision Combustion, Inc.	Fuel-rich catalytic system	Partial premixing, staged cooling	Uses recirculation for flame stabilization

Both systems have been successfully engine-tested and demonstrated ultra-low NOx emissions (<3 ppm @ 15% O₂).

Challenges and Future Developments

1. Catalyst Durability and Contamination

- Syngas fuels contain contaminants (e.g., sulfur, alkali metals) that degrade catalyst performance.
- Long-term durability studies are needed for IGCC applications.
- 2. Scaling for High-Volume Fuel Flow
- Syngas has a low lower heating value (LHV), requiring larger catalytic reactors to handle high volumetric fuel flow rates.

3. Advanced Cooling Strategies for High-Firing-Temperature Turbines

- New high-temperature catalyst materials are required for >1525°C applications.
- Exhaust gas recirculation (EGR) may help lower NOx emissions in ultra-high-temperature gas turbines.

Fuel-rich catalytic combustion

Fuel-rich catalytic combustion presents a highly effective approach for achieving ultra-low NOx emissions in gas turbines, particularly through the Rich-Catalytic Lean-burn (RCL®) combustion system developed by Precision Combustion, Inc. (PCI). Conventional lean-premixed combustion systems, such as those used in F-class industrial gas turbines, have achieved NOx emissions below 9 ppm (at 15% O₂), with some systems demonstrating emissions as low as 5 ppm. However, further reductions are necessary, prompting research into catalytic combustion, which offers NOx emissions below 3 ppm and in some cases as low as 1 ppm. The RCL® combustor, thereby preheating and partially reacting a portion of the fuel in a fuel-rich environment upstream of the combustor, thereby preheating and partially oxidizing the fuel-air mixture. This reaction enhances combustion stability, particularly at low flame temperatures,



enabling ultra-low NOx emissions by reducing peak flame temperatures while avoiding flame instability issues common in lean-premixed systems. A critical design challenge is limiting the extent of reaction within the catalyst bed to prevent excessive heat that could damage the catalyst or substrate, while simultaneously ensuring that sufficient heat is released to stabilize downstream gas-phase combustion. For this purpose, catalyst-bed temperatures are carefully controlled, typically maintaining operating temperatures below 780°C (1430°F) in full-scale tests.

Initial research focused primarily on methane due to its unique oxidation characteristics and practical application in gas turbines. Palladium (Pd)-based catalysts were identified as the most suitable option for methane oxidation under fuellean conditions due to their high activity, light-off temperature, and resistance to volatilization. However, Pd-based catalysts exhibit complex behaviors, including deactivation above 750°C (1380°F), hysteresis in reaction rate over heating and cooling cycles, and light-off/extinction temperatures exceeding 300°C (570°F), necessitating the use of a preburner in many applications. In contrast, fuel-rich catalytic combustion circumvents these issues by enabling the use of non-Pd catalysts, reducing catalyst operating temperatures, and eliminating the need for a preburner. Fuel-rich catalysts exhibit light-off temperatures as low as 260–280°C at 15 atm and can remain active down to temperatures below 200°C without deactivating, significantly improving catalyst durability.

PCI has conducted extensive experimental validation of fuel-rich catalytic combustion across multiple scales, including sub-scale laboratory rigs, full-scale single-injector rigs, and modified industrial gas turbines. Full-scale combustion tests at Solar Turbines confirmed the feasibility of RCL® combustion at gas turbine conditions, achieving NOx emissions below 3 ppm and CO emissions below 10 ppm over a wide operating window. At pressures of 16–17 atm and total airflow of 4 pounds per second (pps) in a single-injector Taurus 70 combustor, NOx emissions as low as 1 ppm were measured at an adiabatic flame temperature of approximately 1450°C (2650°F). Furthermore, the system exhibited ultralow NOx and CO emissions across a 110°C (200°F) range of flame temperatures, demonstrating robust emissions control. These tests also confirmed that fuel-rich catalyst effluent could be directly mixed with additional combustion air without triggering autoignition. For example, at a catalyst effluent temperature of 700°C, the estimated autoignition delay time is approximately 25 ms (calculated using Spadaccini and Colket's correlation for a representative natural gas mixture at 15 atm and equivalence ratio of 0.5), which is significantly longer than the 2–5 ms required for mixing with final combustion air and the typical 10–20 ms residence time in gas turbine combustors. Thus, autoignition is effectively avoided while imparting greater combustion stability to the system.

To further evaluate RCL® combustion's fuel flexibility, PCI conducted sub-scale high-pressure tests with alternative hydrocarbon fuels, including methane, simulated landfill gas, Diesel No. 2, gasoline, and syngas. A single catalytic reactor was tested at 10–15 atm in a ceramic-lined combustor, with NOx, CO, and unburned hydrocarbons (UHC) emissions measured after a 30–50 ms residence time. Results demonstrated that NOx emissions remained below 3 ppm for flame temperatures below 2600°F (1427°C) for all tested fuels, including biomass-derived fuels. Diesel fuel, which contained 188 ppm nitrogen by weight, exhibited NOx emissions of approximately 10 ppm, with 8.1 ppm attributed to fuel-bound nitrogen. CO emissions were consistently below 2 ppm across all fuel types. Catalyst surface temperatures remained stable across different fuels, confirming that reaction rates under fuel-rich conditions are primarily controlled by oxygen flow rather than fuel chemistry. This insensitivity to fuel composition is a key advantage of RCL® combustion, enabling its application to diverse fuel sources.

PCI further validated RCL® combustion in a modified Solar Turbines Saturn engine, fitted with a cluster of four RCLinjectors to evaluate controls compatibility, transient response, and long-term operational stability. Engine start-up was initiated with a preburner operating at 350°C (660°F) to ensure catalyst light-off, after which the preburner was deactivated and the catalyst remained active at compressor discharge temperatures as low as 191°C (376°F). The engine was successfully operated over a speed range of 82% to 89% gas producer shaft speed (Ngp), with NOx emissions averaging 2.2 ppm and CO emissions below 10 ppm. Combustion-driven pressure oscillations (CDPO) remained below 0.7 kPa (0.1 psi) peak-to-peak, demonstrating quiet operation. Power output ranged from 237 kW (318 hp) at 82% Ngp to 453 kW (607 hp) at 89% Ngp. The RCL® injectors successfully replaced conventional Dry Low NOx (DLN) premixer/swirler assemblies while maintaining stable combustion across the full operating range.

In addition to hydrocarbon fuels, RCL® combustion has been demonstrated for coal-derived syngas and other highhydrogen fuels, which pose significant challenges for lean-premixed combustion due to their high reactivity and susceptibility to flashback. For example, tests with syngas containing 20% H₂, 20% CO, 10% CO₂, and 50% N₂ (LHV = 117 Btu/ft³) at 10 atm achieved NOx emissions of 2.0 ppm (0.011 lbs/MMBtu) at a flame temperature of 2550°F (1400°C). Even for highly diluted low-Btu syngas (88 Btu/ft³), stable combustion was maintained at flame temperatures as low as 2300°F (1260°C), with CO emissions below 5 ppm. Tests with blast furnace gas (23% CO, 22% CO₂, 1.4% H₂, 0.6% CH₄, and 53% N₂) demonstrated stable operation with NOx emissions below 1 ppm at flame temperatures



below 2500°F (1370°C). Similarly, refinery fuel gas (30% H₂, 70% CH₄) exhibited NOx emissions below 3 ppm at flame temperatures below 2800°F (1540°C), confirming RCL® combustion's applicability to high-hydrogen fuels.

Future development challenges for RCL® combustion include addressing long-term catalyst durability in syngas applications, mitigating autoignition risks in premixing hardware for high-hydrogen fuels, and optimizing catalytic reactor designs for high-volume, low-Btu fuels. Field demonstrations in commercial gas turbines are the next step in technology validation, particularly for IGCC applications where syngas composition variability and contaminant effects must be assessed over extended operation. Despite these challenges, RCL® combustion offers compelling advantages over conventional DLN systems, including lower NOx emissions, greater combustion stability, fuel flexibility, and simplified control strategies. The ability to achieve sub-3 ppm NOx emissions while avoiding common issues such as flashback and autoignition makes RCL® combustion a transformative technology for next-generation low-emission gas turbines.

Catalytic Combustion in Large Frame Industrial Gas Turbines

The Rich Catalytic Lean-burn (RCL®) combustion approach has been adapted for application in Siemens gas turbines, particularly the SGT-6-3000E and SGT-6-5000F engines, with extensive rig testing confirming its capability to deliver ultra-low emissions. The catalytic combustor design incorporates multiple catalytic modules arranged around a central pilot, as seen in the full-scale combustor basket configuration tested in Siemens' full-pressure single-basket test facility in Italy. The central pilot ensures stable operation at low loads but is designed to be minimized or completely deactivated at baseload conditions, thus reducing NOx emissions associated with diffusion pilots. The combustor basket includes six catalytic modules, each featuring a fuel-rich catalytic reactor where a fraction of the fuel is reacted upstream to preheat and stabilize combustion. This arrangement maintains catalyst temperatures within operational limits while allowing emissions control across a range of firing temperatures corresponding to both E-class and F-class engines.

Experimental testing in the Siemens facility provided emissions data across different firing temperature conditions. For the SGT-6-3000E engine, additional dilution air was required to achieve complete CO burnout. Under these conditions, the catalytic combustor achieved emissions of 3.3 ppm NOx and 7 ppm CO. At the higher firing temperatures of the SGT-6-5000F engine, the combustor demonstrated improved stability, enabling a lower pilot fraction. As a result, emissions remained nearly identical, with NOx at 3.6 ppm and CO at 9 ppm. Throughout testing, combustor pressure oscillations, basket metal temperatures, and catalyst temperatures remained well below design limits, confirming the robustness of the catalytic module design. Furthermore, an over-firing test was conducted to assess the system's structural integrity, with no observable damage to the catalytic components, indicating durability under extreme operating conditions.

The RCL® combustion approach is now undergoing further development, with a primary focus on fuel flexibility, particularly for syngas and hydrogen applications. This aligns with industry trends towards decarbonization and alternative fuel integration in power generation. The rig test results indicate that rich catalytic combustion can achieve emissions in the range of 2–3 ppm NOx even at the high firing temperatures associated with F-class turbines. The system has demonstrated resilience to variations in air and fuel flow, making it a viable candidate for next-generation low-emissions gas turbine engines. Future work will refine the design for enhanced emissions reduction while improving adaptability to a broader range of fuel compositions, including hydrogen-enriched fuels, without sacrificing performance, stability, or reliability.

Water Injection Technique for Stability Testing

The water injection technique is a cost-effective alternative for assessing the stability performance of full-scale combustors. This method allows engineers to construct complete stability loops while operating within the normal range of fuel-to-air ratios and velocity conditions. Unlike conventional methods that rely on high-altitude testing or complex experimental setups, this approach provides a controlled and replicable environment for evaluating combustor stability at various operating conditions. The underlying principle of the technique is based on the equivalence between a reduction in combustion pressure and a reduction in reaction temperature, which is achieved by introducing water into the combustion zone.

Principle of Operation

The water injection technique's theoretical foundation relies on global reaction rate theory. In combustion systems, lower pressures reduce the overall reaction rate, affecting flame stability. Since directly decreasing the pressure in a ground-based test facility is impractical, adding water is a practical substitute. Water injection effectively reduces the reaction temperature, simulating the stability challenges at lower pressures.

This technique has been widely used to study the blowout characteristics of various flame holder designs. By systematically varying the water-to-fuel ratio, engineers can determine the amount of cooling required to induce flame

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extinction under different conditions. The assumption behind this method is that the flame holder requiring the highest amount of water to extinguish the flame possesses the greatest stability margin.

Experimental Setup

The standard experimental setup for stability testing using water injection consists of the following key components:

- Air Supply System: A fan supplies air at atmospheric pressure to simulate normal combustion conditions.
- Preheat Chamber: The incoming air is heated to a predetermined temperature to ensure complete vaporization of the fuel-water mixture before it enters the combustor.
- Fuel and Water Injection System: A duplex atomizer or similar injector ensures uniform distribution of the fuelwater mixture within the combustion chamber.
- Flameholder: The stabilizer, which is the test subject, is mounted in a pipe where airflow and temperature conditions are controlled.
- Measurement System: Sensors monitor airflow, temperature, equivalence ratios, and flame stability.

Stability Loop Analysis

- Equivalence Ratio (Φ): The ratio of the actual fuel-to-air mixture to the stoichiometric fuel-to-air ratio.
- Water-to-Fuel Mass Ratio: The amount of water added per unit fuel mass.

The stability loop illustrates the operating envelope within which stable combustion is possible. The area inside the loop represents conditions where combustion is maintained, while points outside indicate flame extinction. A key advantage of this technique is its ability to compare the stability performance of different flame holder designs. The flame holder that requires the highest water-to-fuel mass ratio for extinction is deemed to have the best stability performance.

Pressure Simulation Using Water Injection

One of the most valuable applications of the water injection technique is its ability to simulate the effects of reduced combustion pressure. Global reaction rate theory has established this relationship and validated it through experimental studies.

Figure 5.15 shows an empirical correlation between the water-to-fuel mass ratio and the equivalent reduction in combustion pressure. For example:

- Injecting an equal mass of water and fuel into the combustor is approximately equivalent to halving the combustion pressure.
- A higher water-to-fuel ratio results in more significant pressure reduction, allowing engineers to model the impact of high-altitude conditions without requiring expensive low-pressure test facilities.

Comparison with Other Low-Pressure Simulation Techniques

While water injection is an effective tool for pressure simulation, alternative methods have also been explored:

- Nitrogen Dilution: Nitrogen gas is injected into the combustion zone to reduce the oxygen concentration and simulate low-pressure conditions instead of water. Researchers such as Norster and Sturgess et al. have successfully used this method. While nitrogen is more expensive than water, it eliminates the need for a preheat combustor and is particularly useful for small-scale flame holder studies.
- Direct Pressure Reduction: Some facilities use vacuum chambers or altitude test rigs to simulate low-pressure environments directly. However, these setups are significantly more expensive and complex than water injection.

6 ADVANTAGES AND LIMITATIONS OF WATER INJECTION

Advantages

- Cost-Effective: The method requires only a fan, water supply, and basic combustion instrumentation, making it far cheaper than high-altitude test facilities.
- Controlled Testing Environment: Allows stability testing under normal operating conditions while systematically introducing destabilizing factors.
- Scalability: Can be applied to full-scale combustion systems and used for different flameholder geometries and fuel types.
- Pressure Simulation Capability: Enables simulation of high-altitude conditions without requiring a low-pressure chamber.

6.1 Limitations

- Requires Precise Control: The water-to-fuel ratio must be carefully controlled to ensure accurate pressure simulation.
- Potential for Water Condensation: In some cases, incomplete water vaporization can affect measurements and introduce uncertainties.

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• Limited Applicability to Certain Fuels: While practical for hydrocarbon fuels like kerosene and octane, the technique may require modifications for alternative fuels.

6.2 Mechanisms of Flame Stabilization

Flame stabilization is crucial to combustion systems, particularly in gas turbines, afterburners, and high-speed combustion applications. A stable flame ensures efficient combustion, prevents blowout, and reduces emissions. Understanding the mechanisms of flame stabilization helps optimize flameholder designs and improve overall combustion performance.

Theoretical Models of Flame Stabilization

Two primary theories explain how flames remain stable in turbulent, high-velocity flows.

• Homogeneous Reactor Model

This model treats the wake region behind a bluff body as a well-mixed chemical reactor. The assumption is that the reaction zone maintains a uniform temperature and composition, meaning the flame will only stabilize if the rate of heat release from combustion is sufficient to preheat incoming fresh fuel-air mixtures. If the time required to ignite the fresh mixture exceeds the available reaction time, the flame extinguishes.

• Shear Layer Model

The second approach focuses on the turbulent shear layer that forms between the wake region and the main airflow. Fresh fuel-air mixtures ignite when they interact with hot combustion products from the recirculation zone. The burning mixture spreads downstream, igniting adjacent pockets of fresh fuel. A stable flame is maintained as long as hot combustion products continuously mix with the shear layer, ensuring sustained ignition. Extinction occurs when the time available for ignition in the shear layer is too short.

Both models highlight different aspects of flame stabilization, but they lead to similar conclusions. The stability of a flame depends on factors such as airflow velocity, pressure, temperature, flameholder size, and the fuel-air equivalence ratio.

Key Factors Affecting Flame Stabilization

Multiple parameters influence flame stability, including airflow dynamics, fuel properties, and flameholder design.

• Air Velocity

The speed of air moving past the flame holder significantly affects flame stability. Higher velocities can lead to blowout, reducing the time available for ignition. Lower velocities allow for better mixing and longer residence times, improving stability.

• Pressure

Increasing the operating pressure enhances flame stability by promoting faster chemical reactions. Higher pressures also improve fuel atomization, ensuring better mixing of fuel and air, which further supports stable combustion.

• Temperature

Higher inlet air temperatures contribute to stability by reducing ignition delay. A hotter incoming mixture requires less ignition energy, making the flame more resistant to disturbances.

• Flameholder Size and Shape

The size and design of the flame holder play a crucial role in stabilizing the flame. Larger flame holders create bigger recirculation zones, which help trap hot combustion gases and sustain ignition. The shape of the flame holder also affects turbulence and wake formation, influencing how well it stabilizes the flame.

• Fuel-Air Mixing

Proper fuel and air mixing is essential for a stable flame. Poor mixing can create regions with too much or too little fuel, leading to localized extinction or excessive emissions. Swirl stabilizers and bluff bodies are commonly used to enhance mixing and create favorable conditions for ignition.

Experimental Observations on Flame Stabilization

Extensive experimental studies have confirmed the influence of the above factors on flame stability.

- Larger flameholders improve stability by increasing the residence time of combustion gases in the recirculation zone.
- Higher air temperatures enhance flame stabilization by reducing the ignition delay.
- Lower air velocities promote flame stability by allowing more time for combustion reactions to develop.
- Optimized fuel-air mixing prevents localized extinction and ensures consistent combustion.

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• Swirl and recirculation zones help maintain stability by promoting continuous ignition. Flame Stabilization in Gas Turbine Combustors

In practical gas turbines, flame stabilization is achieved through specific design features.

• Swirl-Stabilized Combustors

These use strong vortex motion to create a central recirculation zone where hot gases are trapped. This ensures continuous ignition and stabilizes the flame under varying conditions.

• Bluff-Body Flameholders

These create a wake region where combustion gases recirculate, maintaining a stable flame. They are commonly used in afterburners and ramjet engines. The performance of bluff-body flame holders depends on the blockage ratio, flame holder shape, and airflow conditions.

• Air Distribution in Combustors

Air is introduced through various apertures to maintain flame stability in gas turbines. The arrangement of these air passages influences combustion efficiency and stability.

Practical Considerations for Flame Stability

From experimental and theoretical studies, several best practices emerge for improving flame stability:

- Using Larger Flameholders: Increasing the flame holder's characteristic dimension improves stability by creating a larger recirculation zone.
- Raising Inlet Temperature: Higher temperatures enhance stability by reducing ignition delay.
- Controlling Air Velocity: Lower velocities allow better flame anchoring and prevent blowout.
- Optimizing Fuel-Air Mixing: Ensuring proper atomization and fuel distribution prevents instability.
- Employing Swirl and Recirculation: These enhance mixing and extend the residence time of combustion gases.

7 FUEL INJECTION AND ATOMIZATION

Introduction to Atomization

Atomization is the process of breaking bulk liquid fuel into small droplets to enhance mixing with air for efficient combustion. The key challenge is overcoming surface tension forces, which naturally pull liquids into spherical shapes, by applying disruptive aerodynamic and internal forces. The quality of atomization impacts combustion efficiency, emissions, and overall engine performance.

Atomization typically consists of two main stages:

- Primary Atomization The initial breakup of the fuel stream into large shreds or ligaments.
- Secondary Atomization Further fragmentation of larger droplets into finer spray particles.

The overall spray characteristics are influenced by the atomizer's design, the surrounding gas properties, and the physical properties of the fuel.

Breakup of Drops

A fundamental aspect of atomization is the disintegration of liquid drops due to aerodynamic forces. The balance between disruptive aerodynamic drag and consolidating surface tension determines whether a drop remains intact or breaks apart. This is quantified using the Weber number, which is the ratio of aerodynamic forces to surface tension forces.

For low-viscosity fuels, experimental studies suggest a critical Weber number threshold beyond which breakup occurs. The size of the largest stable drop can be determined by this threshold, providing insights into spray formation and evaporation characteristics.

In practical turbulent flows, fuel droplets experience fluctuating forces that affect their stability. Under such conditions, turbulent velocity fluctuations in the surrounding air dictate the drop breakup process, leading to more complex droplet size distributions.

Jet and Sheet Breakup Mechanisms

Fuel is typically injected as either a liquid jet or a thin sheet, and different atomization mechanisms apply to each:

- Jet Breakup
- o Low-velocity jets break into drops due to natural oscillations.
- Higher velocities lead to aerodynamic interaction, forming ligaments that break into smaller drops.
- \circ At even higher velocities, the breakup process accelerates, forming fine droplets almost immediately after injection.



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- Sheet Breakup
- o Fuel sheets disintegrate due to wave instabilities forming at their surface.
- o Low relative velocity between the sheet and air results in drop formation at the sheet's leading edge.
- Increasing velocity reduces the wavelength of disturbances, leading to faster and finer atomization.
- Extremely high velocities cause immediate fragmentation into small droplets, a phenomenon known as prompt atomization.

Classical vs. Prompt Atomization

Atomization follows two primary mechanisms:

- Classical Atomization Involves the gradual development of surface instabilities leading to the formation of ligaments and then droplets.
- Prompt Atomization Occurs when high-speed air or fuel jets cause immediate fuel fragmentation, producing fine droplets independent of fuel viscosity or initial jet diameter.

At low Weber numbers, classical atomization dominates, with drop sizes being influenced by viscosity and initial fuel sheet dimensions. At high Weber numbers, prompt atomization takes over, with surface tension being the primary factor affecting droplet formation.

Drop-Size Distribution in Sprays

Atomized fuel does not form uniform droplets but rather a range of sizes. The drop-size distribution is a key parameter in combustion performance. Common statistical models describe this distribution:

- Rosin-Rammler Distribution Used widely in spray analysis, it characterizes the spread of droplet sizes based on experimentally determined parameters.
- Modified Rosin-Rammler Distribution An improvement that better fits large droplet sizes.
- Sauter Mean Diameter (SMD) Represents the droplet size that maintains the same surface-area-to-volume ratio as the entire spray.

Drop-size distributions vary based on atomizer type, fuel properties, and injection conditions.

Types of Fuel Atomizers

Fuel injection systems are designed to optimize atomization under various operating conditions. Different types of atomizers are used depending on the application:

- Pressure Atomizers
- Convert pressure energy into kinetic energy to break fuel into droplets.
- o Include plain-orifice, simplex, and dual-orifice injectors.
- o Common in gas turbines and afterburners.
- Air-Assisted Atomizers
- Use compressed air to enhance fuel breakup.
- o Include internal-mixing and external-mixing configurations.
- Useful for atomizing high-viscosity fuels.
- Airblast Atomizers
- o Utilize high-speed air to shear fuel into fine droplets.
- o Preferred for low-smoke, high-efficiency combustion.
- Includes plain-jet, prefilming, and piloted airblast designs.
- Effervescent Atomizers
- Introduce air bubbles into the fuel upstream of the nozzle.
- Provide fine atomization even at low injection pressures.
- Suitable for alternative fuels and low-emission applications.
- Rotary Atomizers
- Use centrifugal forces to disperse fuel.
- Common in industrial combustion systems.
- Vaporizers
- Heat liquid fuel to convert it into a vapor before combustion.
- Used in low-emission applications where complete fuel vaporization is feasible.

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Performance Requirements for Atomizers An ideal atomizer should:

- Provide fine and uniform fuel droplets.
- Operate efficiently across varying fuel flow rates.
- Minimize susceptibility to clogging and carbon buildup.
- Ensure stable combustion and low emissions. Causes of Fuel Nozzle Coking:
- High Fuel Temperature:
- The fuel absorbs heat from the airframe, avionics, and engine lubrication system, significantly increasing its temperature before injection.
- The compressor efflux air further heats the fuel feed arm, intensifying the issue.
- Fuel Chemistry and Oxidation Reactions:
- Higher fuel temperatures reduce viscosity, which aids in atomization but also accelerates oxidation reactions.
- These reactions lead to the formation of gums and insoluble materials that deposit within the nozzle, obstructing the passages.
- Nozzle Design Sensitivity:
- Pressure-swirl atomizers: More susceptible due to small internal passages that easily clog with coke deposits.
- Airblast atomizers: Less prone to coking due to larger fuel passages but may face cold-starting issues. Consequences of Fuel Nozzle Coking:
- 1. Non-Uniform Fuel Spray:
- Deposits distort the spray pattern, leading to uneven combustion and inefficiencies.
- 2. Engine Damage & Operational Issues:
- Some fuel nozzles may experience increased fuel flow due to blockage in others, causing localized overheating and potential damage.
- 3. Pollutant Emissions:
- o Distorted fuel-air mixing can lead to higher NOx and soot emissions.

Mitigation Strategies:

The U.S. Navy's High-Temperature Fuel Nozzle Program has proposed several design improvements to counter fuel coking:

- Heat Transfer Reduction Strategies:
- o Smaller fuel passage area: Increases fuel velocity, reducing heat absorption.
- Air gaps: Act as thermal barriers to minimize conductive heat transfer.
- o Ceramic components: Substituting metal parts with ceramics lowers wetted-wall temperatures.
- Avoiding bends and steps: Reduces fuel residence time in heated regions.
- Surface Finish Improvement:
- \circ Reducing surface roughness from 3.1 to 0.25 μm decreased deposition rates by 26%.
- Thermal Modeling Insights:
- Studies by Myers et al. revealed that heat flux from flame radiation is 20 times greater than heat absorbed through conduction and convection.
- Using simple air gaps and improved thermal barriers significantly reduces wetted-wall temperatures.

Future Considerations:

- Improved Fuel Chemistry: Developing fuel blends with higher thermal stability.
- Advanced Coatings: Anti-coking coatings for fuel passages.
- Active Cooling Mechanisms: Utilizing fuel recirculation or controlled cooling pathways.

Gas Turbine Emissions and Reduction Techniques

Pollutant emissions from gas turbines have become a significant concern due to their impact on air quality, human health, and climate change. Over the past decade, regulatory bodies have introduced stringent emission limits, prompting advancements in combustion technology. Gas turbines are widely used in aviation, power generation, and industrial



applications, making their emissions a significant environmental issue. The focus of emissions reduction efforts has primarily been on nitrogen oxides (NOx), carbon monoxide (CO), unburned hydrocarbons (UHC), and particulate matter (soot).

This document provides an in-depth explanation of the formation of these pollutants, their effects, and various techniques used to minimize them in gas turbine operation.

Pollutant Emissions and Their Impact

Gas turbines emit various pollutants, primarily due to incomplete combustion and high-temperature oxidation of air and fuel. The key pollutants include:

- Carbon Monoxide (CO): Produced due to incomplete combustion, especially at low power settings. It is toxic and reduces oxygen transport in the bloodstream.
- Unburned Hydrocarbons (UHC): Consist of partially oxidized fuel and byproducts of thermal decomposition. They contribute to smog formation and are harmful to health.
- Particulate Matter (Soot): Forms in fuel-rich combustion zones with insufficient oxygen for complete oxidation. It contributes to air pollution and visibility issues.
- Oxides of Nitrogen (NOx): This category includes nitric oxide (NO) and nitrogen dioxide (NO₂), which are formed in high-temperature regions of the combustor. NOx emissions contribute to acid rain, smog, and ozone depletion.

Mechanisms of Pollutant Formation

Each pollutant is formed under different combustion conditions:

Carbon Monoxide (CO) Formation

CO emissions are primarily the result of incomplete combustion caused by:

- Low temperatures in the primary combustion zone, leading to slow oxidation rates.
- Poor fuel-air mixing, resulting in local regions with insufficient oxygen.
- Quenching of combustion reactions by excess cooling air.

CO emissions are highest at low power settings because the burning rates and temperatures are lower, preventing complete oxidation of CO-to-CO₂.

Unburned Hydrocarbon (UHC) Formation

Unburned hydrocarbons result from:

- Poor atomization of liquid fuels, leading to large fuel droplets that do not completely burn.
- The presence of cooling air that lowers flame temperature and prevents complete oxidation.
- Localized fuel-rich regions where combustion is incomplete.
- 8 UHC EMISSIONS ARE MORE COMMON IN OLDER COMBUSTORS WITH POOR FUEL-AIR MIXING.

8.1 Soot and Smoke Formation

Soot particles form when fuel burns in oxygen-deficient regions. Factors that influence soot production include:

- High combustion pressures, which promote fuel-rich conditions near the fuel injector.
- Heavy hydrocarbons, especially aromatic compounds that resist oxidation, are present.
- Poor fuel atomization, leading to large droplets that burn in a diffusion mode rather than a premixed flame.
 Modern combustors minimize soot formation by improving fuel-air mixing and using advanced injection technologies.

NOx Formation Mechanisms

NOx emissions occur primarily due to the high-temperature oxidation of nitrogen in the air. The key factors affecting NOx production include:

- Flame Temperature: NOx formation increases exponentially with temperature.
- Residence Time: Longer exposure to high temperatures increases NOx production.
- Oxygen Availability: NOx formation is highest at near-stoichiometric conditions, where there is enough oxygen for complete combustion but also high temperatures.

Lean combustion technologies reduce NOx by lowering flame temperature while maintaining combustion efficiency. Emission Control Strategies

Several approaches have been developed to reduce gas turbine emissions, focusing on modifying combustion conditions and post-combustion treatment.



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8.2 Primary Combustion Modifications

Lean Premixed Combustion

- This technique involves premixing fuel and air before combustion to achieve a uniform, lean mixture.
- A lower flame temperature results in reduced NOx formation.
- Modern Dry Low NOx (DLN) combustors use this principle.

Staged Combustion

- Fuel is injected in multiple stages to control flame temperature and optimize combustion.
- The primary stage operates fuel-rich, producing minimal NOx, while secondary air injections complete the combustion process.
- This technique helps balance NOx and CO/UHC emissions.

Catalytic Combustors

- A catalytic reactor is used to partially oxidize the fuel at lower temperatures before full combustion.
- This allows combustion to occur below the NOx formation threshold.
- Catalyst materials like platinum and palladium facilitate oxidation without requiring high temperatures.

Variable Geometry Combustors

- Adjustable fuel nozzles and airflow control systems help optimize fuel-air ratios under varying load conditions.
- This improves efficiency and reduces emissions across the engine's operating range.

8.3 Post-Combustion Emissions Control

Water or Steam Injection

- Water or steam is injected into the combustion chamber to absorb heat and lower flame temperature.
- This technique effectively reduces NOx emissions but increases fuel consumption and requires purified water to prevent corrosion.

8.4 Selective Catalytic Reduction (SCR)

- A post-combustion treatment that injects ammonia (NH₃) into the exhaust gas stream.
- The ammonia reacts with NOx over a catalyst to form harmless nitrogen (N₂) and water vapor (H₂O).
- This method is widely used in stationary power plants.

8.5 Exhaust Gas Recirculation (EGR)

- A portion of the exhaust gas is cooled and reintroduced into the combustion chamber.
- This lowers the oxygen concentration and reduces peak flame temperature, thereby limiting NOx formation.

8.6 Regulatory Standards

Different regions have implemented strict emissions regulations for gas turbines:

- Aviation (ICAO Standards)
- o The International Civil Aviation Organization (ICAO) sets emission limits for commercial aircraft engines.
- Emission restrictions focus on reducing NOx, CO, and UHC levels during takeoff, landing, and cruise operations.
- Stationary Gas Turbines (EPA and EU Standards)
- The Environmental Protection Agency (EPA) in the U.S. and European regulations impose limits on NOx, CO, and SOx emissions for power plants.
- NOx limits for large gas turbines have been reduced to as low as 9 parts per million (ppm) in certain locations.

8.7 Future Trends in Low-Emission Gas Turbines

With increasing environmental concerns, the future of gas turbine emissions control is focused on:

- Hydrogen and Ammonia Fuels: Switching from hydrocarbon-based fuels to hydrogen or ammonia to eliminate CO₂ and reduce NOx.
- Advanced Thermal Barrier Coatings: Improving combustor materials to allow for leaner combustion without durability concerns.
- Hybrid Systems: Integrating gas turbines with renewable energy sources and battery storage to reduce reliance on fossil fuels.

Pollutant Reduction by Control of Flame Temperature in Gas Turbines

Controlling flame temperature is one of the most effective ways to reduce pollutant emissions in gas turbine combustors. Among the many factors that influence emissions, the temperature in the combustion zone plays the most significant



role. Gas turbines operate at a wide range of temperatures, from about 1000 K at low power to 2500 K at full power, with emissions varying significantly across this range.

Research has shown that the optimal temperature range for minimizing both carbon monoxide (CO) and nitrogen oxides (NOx) emissions lies between 1670 K and 1900 K. Below 1670 K, incomplete combustion leads to high CO emissions, while above 1900 K, thermal NOx formation increases exponentially. This narrow temperature band represents a critical operational window for designing low-emission gas turbine combustors.

To maintain combustion temperatures within this ideal range across various power levels, several strategies are employed. The most notable approaches include variable geometry combustors and staged combustion systems.

Variable Geometry Combustors

Variable geometry combustors control airflow distribution dynamically to keep combustion temperatures within the optimal emission range. This approach involves adjusting the amount and location of air entering different combustion zones, depending on engine load.

How Variable Geometry Works

- At maximum power, large amounts of air are introduced into the primary combustion zone to lower the temperature and prevent excessive NOx formation.
- At lower power settings, more air is directed into the dilution zone, ensuring that the primary-zone temperature does not drop too low, which would increase CO and unburned hydrocarbon (UHC) emissions.

8.8 Practical Implementations

- Variable-area swirlers control airflow into the combustion zone, adjusting the air-fuel mixture dynamically.
- Adjustable dilution air openings regulate the cooling and dilution process.
- Combined air distribution techniques optimize combustion efficiency at different engine loads.

Challenges and Drawbacks

Despite its benefits, variable geometry technology presents challenges:

- Complex control systems: Requires precise electronic controls to adjust airflow dynamically.
- Increased cost and weight: Additional moving components add to the turbine's complexity.
- Potential reliability concerns: Mechanical systems that regulate airflow must withstand extreme temperatures and pressures.

Despite these issues, variable geometry systems offer a balanced approach to reducing NOx, CO, and UHC emissions simultaneously, making them an attractive option for next-generation gas turbines.

8.9 Staged Combustion

Staged combustion is another effective technique for controlling flame temperature. Unlike variable geometry systems, which manipulate airflow distribution, staged combustion controls the fuel distribution to maintain an optimal flame temperature.

How Staged Combustion Works

- At low power settings, fuel is injected into a single combustion zone, ensuring complete combustion and reducing CO and UHC emissions.
- As power increases, additional fuel is injected into a secondary combustion zone to maintain a stable, lower-temperature flame and prevent excessive NOx formation.

8.10Types of Staged Combustion

- Selective Fuel Injection
- Fuel is injected into specific fuel nozzles depending on engine load.
- At low power, only a subset of injectors operates, ensuring complete combustion in a smaller volume.
- o As power increases, additional injectors are activated to distribute fuel more evenly.
- Series Staging (Axial Staging)
- Fuel is introduced progressively along the combustion chamber.
- \circ The primary zone provides stable ignition and partial combustion.
- The secondary zone completes the combustion process at lower temperatures, minimizing NOx.
- Parallel Staging (Radial Staging)
- o Uses dual-annular combustors (concentric combustion zones).

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o The inner combustor operates at low power, ensuring low CO and UHC emissions.

• The outer combustor activates at high power, maintaining a lean combustion process to limit NOx.

8.11Challenges of Staged Combustion

- Complex fuel management: Requires precise control over multiple fuel injection points.
- Flame instability risks: Transitioning between different stages must be carefully managed to avoid unstable combustion.
- Turbine efficiency concerns: Uneven combustion can lead to non-uniform temperature distributions at the turbine inlet, affecting performance.

Despite these limitations, staged combustion has been widely adopted in modern gas turbines due to its effectiveness in achieving low emissions while maintaining efficiency.

8.12Combining Variable Geometry and Staged Combustion

For maximum emissions reduction, variable geometry and staged combustion can be used together. This hybrid approach offers:

- Greater control over combustion temperatures across all power levels.
- Optimized flame stability, reducing both CO and NOx simultaneously.
- Improved turbine performance, preventing hot streaks that could damage turbine blades.

Aircraft gas turbines, such as those in the General Electric CFM56 and GE90 engines, have successfully implemented dual-annular combustors with fuel staging to meet stringent emissions regulations while maintaining high efficiency.

9 GAS TURBINE FUELS AND ALTERNATIVE FUEL TECHNOLOGIES

Gas turbines were once considered "omnivorous" machines, operating efficiently on various fuels, including solid, liquid, and gaseous options. However, the choice of fuel is dictated by factors such as cost, availability, and handling ease, particularly important in aviation applications where strict requirements related to fuel properties must be met.

The increasing cost of petroleum-based fuels drives the search for alternative fuel sources. Factors influencing this shift include economic considerations, geopolitical stability, and infrastructure compatibility. The optimal fuel choice for a specific application depends on various trade-offs: Civil Aircraft, Military Aircraft, Industrial and Marine Gas Turbines, and Heavy Oil. Gaseous Fuels generally pose fewer operational problems but may require specialized storage and handling. Residual Oils tend to produce large amounts of ash and exhaust smoke, which can be damaging to turbines. Pulverized Solid Fuels have historically been unsuccessful in open-cycle gas turbines, though advancements in Integrated Gasification Combined Cycle (IGCC) technology are changing this.

Several alternative fuel sources have emerged as the aviation and power generation industries explore sustainable fuel options. Biomass, coal, oil shale and tar sands, heavy oil, and methane and hydrogen are major sources of alternative fuels. Hydrocarbon fuel classification is crucial for understanding these fuels.

Gas turbine fuels are primarily hydrocarbons, consisting of hydrogen and carbon. Based on their molecular structure and carbon atom count, they exist in gaseous, liquid, or solid states. Four primary hydrocarbon groups define fuel characteristics: paraffins (alkanes), olefins (alkenes), naphthenes (cycloalkanes), aromatics, and water.

Fuel production involves three key steps: separation (distillation), upgrading, and conversion. Impurities in gas turbine fuels, including sulfur compounds, asphaltenes, gum and sediments, ash, and water, must be minimized. Fuel additives, such as antioxidants, corrosion inhibitors, lubricity improvers, anti-icing agents, static dissipators, and smoke suppressants, are commonly used to enhance fuel performance and safety.

As environmental concerns and fuel costs rise, alternative fuels are being explored: hydrogen, methane (natural gas), biofuels (ethanol, biodiesel, synthetic kerosene), and liquefied petroleum gas (LPG). The future of gas turbine fuel technology depends on factors such as fuel compatibility with existing engines and infrastructure, environmental sustainability, and economic viability. Governments and industries are improving the efficiency of synthetic aviation fuels and hydrogen-based propulsion to reduce dependency on fossil fuels while maintaining aircraft and power generation efficiency.

9.1 Ammonia as a Fuel

- Ammonia has a low heat of combustion, about 40% that of kerosene.
- Its primary advantage lies in its potential as a heat sink rather than as a main fuel.
- Due to its low heat release, it is unlikely to be used as the primary fuel for aircraft.
- It may be utilized as a secondary fuel where its high cooling capacity is advantageous.
- Similar to propane, ammonia can be stored as a pressurized liquid at ambient temperatures.



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9.2 Alcohols as Fuels

- Alcohols are hydrocarbons containing oxygen atoms within their molecular structure.
- They are categorized into:
- Alkanes with a hydroxyl radical, such as methanol (CH3OH) and ethanol (C2H5OH).
- Ethers with an internal oxygen atom, such as methyl ether (CH3–O–CH3) and methyl tertiary butyl ether (MTBE).
- Commercial bioethanol consists of 98.5% ethanol, water, and methanol.
- The United States and Brazil produce bioethanol at lower costs than gasoline.
- Alcohols are impractical for long-range aircraft due to their high oxygen content and low calorific value.
- Methanol and ethanol are safer than gasoline due to their higher flash points and water-extinguishable fires.
- Alcohols can be corrosive to certain metals, necessitating special handling precautions.

9.3 Methanol and Ethanol in Industry

- Methanol is an attractive fuel for industrial gas turbines due to:
- o Ash-free combustion
- o Low soot formation
- Low-luminosity blue flame
- Wide flammability limits
- o Low flame temperature, leading to lower NOx emissions
- Ethanol is used in a 10% gasoline mixture in Brazil and parts of the U.S.
- Production methods:
- o Methanol: Derived from biomass distillation, direct oxidation of natural gas, or coal gasification.
- Ethanol: Produced via fermentation of wood, corn, and grain. Advantages of Alcohol Fuels
- Carbon neutrality as they originate from vegetable matter.
- Lower carbon content and freezing point.
- Higher flash point, latent heat of vaporization, and octane rating.
- Reduced emissions of particulates, CO, and NOx.
- Lean mixture operation due to higher flame speed. Disadvantages of Alcohol Fuels
- Methanol is toxic.
- Lower specific energy and energy density.
- High corrosiveness and poor lubricity in pumps and injectors.
- Low vapor pressure makes cold starting and transient operation difficult.
- Methanol can cause spark knock and has a lower cetane rating.
- Generates aldehyde emissions, which contribute to ozone pollution.

9.4 Supplemental Fuels

- Includes non-petroleum fossil fuel sources such as tars and shale oil.
- Canadian Athabasca tar sand-derived fuel has combustion characteristics like high-quality petroleum-derived JP-5.
- Oil shale heating decomposes resinous content into an oily liquid, producing syncrude.
- Refinement can yield a Jet A-like product with high aromatic content.
- Higher nitrogen content in these fuels increases NOx emissions.

9.5 Slurry Fuels

- Comprise powdered metals like beryllium, boron, aluminum, and magnesium suspended in gasoline or kerosene.
- Offer potential for more excellent flight range or higher thrust than conventional hydrocarbons.
- Magnesium slurries burn readily, even in conditions where liquid hydrocarbon fuels do not.
- Boron slurries are more difficult to burn and leave deposits in combustors.
- Challenges include preparation, storage, and abrasion-related wear in fuel systems.



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9.6 Synthetic Fuels

- Derived from non-petroleum sources such as coal and biomass.
- Two primary methods of coal conversion:
- Direct coal liquefaction: Uses catalytic hydrogenation (Bergius process) to produce liquid fuel.
- Coal gasification: Produces syngas (CO + H2), which undergoes Fischer–Tropsch (FT) synthesis to form liquid hydrocarbons.

9.7 Fischer–Tropsch Fuels

- South Africa's Sasol Corporation operates FT synthesis commercially, producing 40,000 barrels/day.
- Uses iron, cobalt, nickel, ruthenium, and molybdenum as catalysts.
- Shell's SMDS process converts natural gas to kerosene and gas oil using an FT slurry bubble column reactor.
- FT fuels are cleaner, with low nitrogen, aromatics, and sulfur content.
- FT processes generate high CO2 emissions, but biomass integration can reduce emissions.

9.8 Biofuels

- Gas turbines can use biofuels, which have low sulfur and ash content.
- Biofuels are carbon-neutral since they absorb CO2 during biomass growth.
- Common biofuels include biodiesel, bioethanol, biomethanol, vegetable oils, and biodimethyl ether (bio-DME).
- Biofuels have lower energy density than coal or petroleum-based fuels.
- Organic salts in vegetable oils can cause contamination and operational issues.

9.9 Advantages of Biofuels

- Carbon neutrality and lower carbon content.
- Higher flash point for improved fire safety.
- Lower sulfur content.
- Higher cetane number for biodiesel, reducing hydrocarbon and particulate emissions.

9.10Disadvantages of Biofuels

- High viscosity and cold filter plugging necessitate gum removal.
- Lower specific energy leads to higher fuel consumption.
- Higher solidification temperature (SIT) results in a lower cetane number.
- Greater corrosivity, leading to carbon deposits and injector coking.

9.11Alternative Fuel Properties

- In 2002, DEF STAN 91-91/Issue 4 approved synthetic paraffinic kerosene (IPK) blending up to 50% with petroleum-derived kerosene.
- Sasol's semisynthetic Jet A-1 meets commercial jet fuel specifications.
- FT fuels contain no aromatics or sulfur and have a high iso/standard paraffinic ratio.
- FT-blended fuels exhibit good elastomer compatibility and combustion performance.
- U.S. Air Force initiated the "OSD Assured Fuels Initiative" for coal-related military fuels.

9.12Combustion and Emissions Performance

Fischer-Tropsch Fuels

- Performance tests indicate FSJF (fully synthetic jet fuel) matches Jet A-1 in:
- Engine endurance
- o Low-temperature atomization
- Cold-day ignition and altitude relight
- Lean blowout
- Exhaust emissions
- FSJF shows slightly reduced NOx emissions (4%) and lower CO emissions (19%) than Jet A.
- Smoke emissions are lower due to reduced aromatic content.
- FT-blended fuels produce fewer particulates.

9.13Biodiesel Fuels



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- Combustion studies show minimal chemical differences between diesel and biodiesel blends.
- Biodiesel ignition performance varies with air pressure and temperature.
- At high combustor pressure, biodiesel emits less NOx than diesel.
- Increasing combustor pressure drop enhances mixing, reducing NOx emissions.
- Higher combustion pressures improve ignition reliability.
- Biodiesel blends exhibit lower unburned hydrocarbon emissions than diesel.
- Biodiesel's combustion dynamics are stable, with lower dynamic pressure amplitudes than diesel.

9.14Highly Aromatic Alternative Fuels

- Increasing jet fuel aromatic content to 35% enhances soot formation.
- Smoke point decreases with increased aromatics.
- Lower hydrogen content correlates with higher liner wall temperatures.
- High-aromatic fuels may shorten combustor liner lifespan.
- Studies on high-aromatic fuels like Benzene Heart Cut (BHC) and light cycle oil (LCO) show increased NOx and smoke emissions.
- Industrial gas turbines can burn these fuels but require emission controls.

10 CONCLUSION

The evolution of gas turbine combustion technology continues to be driven by the need for improved efficiency, reduced emissions, and adaptability to alternative fuels. This study has explored the aerodynamic principles of diffusers, combustor configurations, flame stabilization mechanisms, and advanced fuel injection techniques, emphasizing their collective impact on turbine performance. Low-emission combustion strategies such as LPM, RQL, and TVC have demonstrated their ability to significantly reduce NOx emissions while maintaining operational stability. The adoption of catalytic combustion and novel atomization techniques further enhances combustion efficiency and pollutant control. Additionally, alternative fuels, including biofuels, hydrogen, and syngas, offer promising pathways for sustainable gas turbine operation, though challenges such as fuel compatibility and emissions variability must be addressed. Future advancements will likely focus on hybrid combustion models, adaptive combustor geometries, and fuel-flexible turbine designs to meet stringent environmental regulations while sustaining high power output. The integration of advanced computational modeling and experimental validation will play a crucial role in optimizing combustion processes for next-generation gas turbines.

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