

COMPREHENSIVE REVIEW OF COMBUSTION STABILITY AND INSTABILITIES IN PREMIXED SYSTEMS: MECHANISMS, CONTROL STRATEGIES, AND FUEL FLEXIBILITY FOR CLEAN COMBUSTION IN GAS TURBINES

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ABSTRACT

Combustion stability in premixed gas turbine systems is crucial for achieving high efficiency, reduced emissions, and reliable operation. This review paper explores the fundamental mechanisms of combustion instabilities, including static instabilities such as blow-off and flashback and dynamic instabilities driven by thermo-acoustic coupling. The influence of operating conditions, such as Reynolds number (Re), equivalence ratio, swirl stabilization, and oxygen fraction, on flame structure and stability is examined. Hydrogen enrichment is identified as a potential strategy for extending lean blowout limits, improving flame anchoring, and reducing carbon emissions. However, challenges such as increased flashback risk and NO_x emissions require advanced combustor designs and control strategies. The paper also discusses oxy-fuel combustion as an alternative approach for carbon-neutral power generation, highlighting its challenges and operability limits. Large Eddy Simulations (LES) are reviewed as a predictive tool for modeling turbulent premixed flames and guiding the development of low-emission combustion technologies. The findings provide insights into optimizing gas turbine combustor designs for enhanced stability, fuel flexibility, and emissions control in the transition toward sustainable energy systems.

Keywords: Combustion stability, premixed systems, blow-off, flashback, thermo-acoustic instabilities, hydrogen enrichment, swirl stabilization, oxyfuel combustion, Large Eddy Simulation (LES).

1. INTRODUCTION

Premixed combustion is widely used in gas turbines to enhance thermal efficiency and reduce pollutant emissions. However, achieving stable premixed combustion presents significant challenges due to complex interactions between flow dynamics, turbulence-chemistry coupling, and heat-release variations. Combustion instabilities can be broadly classified into:

1. **Static Instabilities:** Blow-off and flashback, which result from an imbalance between flame propagation and local flow velocity, leading to flame detachment or upstream propagation.
2. **Dynamic Instabilities:** Thermo-acoustic coupling, which arises when pressure oscillations align with combustor resonance frequencies, leading to self-sustaining pressure fluctuations and potential hardware damage.

Hydrogen-enriched fuels and oxy-fuel combustion are emerging as promising alternatives for achieving low-carbon energy conversion in gas turbines. However, hydrogen's high flame speed increases the risk of flashback, requiring innovative burner designs and control strategies. Similarly, oxy-fuel combustion, which uses pure oxygen instead of air, offers simplified CO₂ capture but introduces new challenges related to flame stability and high-temperature operation.

This review explores the underlying mechanisms of combustion instabilities in premixed gas turbines, strategies for controlling them, and the implications of fuel flexibility, including hydrogen enrichment and oxy-fuel combustion. Numerical modeling approaches, such as Large Eddy Simulation (LES), are also examined as tools for optimizing combustor performance.

2. METHODOLOGY

This review is based on an extensive survey of experimental and numerical studies on premixed combustion instabilities. The methodology follows a structured approach:

3. LITERATURE REVIEW

- Identification of key studies focusing on blow-off, flashback, and thermo-acoustic instabilities in premixed combustion.
- Analysis of experimental findings related to Reynolds number effects, equivalence ratio variations, and swirl stabilization.

Theoretical Framework:

- Discussion of governing equations for combustion instabilities, including Damköhler number for blow-off predictions and flow-acoustic coupling mechanisms.
- Examination of NO_x formation pathways in lean premixed flames and mitigation strategies.

Computational Modeling:

- Review of LES and other computational fluid dynamics (CFD) techniques used to predict flame dynamics, stability limits, and emissions behavior.
- Comparative evaluation of modeling approaches for different fuels, including methane, syngas, and hydrogen-enriched blends.

Technology Assessment:

- Evaluation of fuel-flexible combustor designs, including Dry Low NO_x (DLN) and Dry Low Emission (DLE) burners.
 - Assessment of the feasibility and operational challenges of oxy-fuel combustion for gas turbines.
- The findings are synthesized to provide a comprehensive understanding of combustion stability challenges and potential solutions for next-generation gas turbine systems.

3.1 Combustion Stability and Instabilities in Premixed Systems

Maintaining a stable premixed flame in gas turbines is a multifaceted challenge, influenced by burner and combustor design, fuel and oxidizer composition, turbulence severity, and air-fuel mixing dynamics. Premixed combustion instabilities are classified into static and dynamic categories.

3.2 Static Instabilities: Blow-Off and Flashback

Static instabilities, primarily blow-off and flashback, occur when the flame deviates from its intended anchor position, potentially leading to combustor failure and equipment damage.

3.3 Blow-Off

Blow-off transpires when the flame moves downstream due to an excessive flow velocity of the combustible mixture relative to the flame speed, leading to inadequate residence time for chemical reactions.

A key metric for predicting blow-off is the **Damköhler number (Da)**, which represents the ratio of residence time to chemical time.

- Hydrogen-enriched fuels have lower blow-off limits, reducing operability at low equivalence ratios.
- CO₂ dilution prolongs chemical timescales, diminishing flame stability.

3.4 Flashback

Flashback occurs when the flame propagates upstream due to local flow velocity being lower than the burning velocity, posing serious hardware risks.

• Flashback mechanisms:

- Boundary layer propagation
- Turbulent flame propagation in swirling flows
- Dynamic instability-driven flame propagation
- Combustion-induced vortex breakdown (CIVB)
- Hydrogen enrichment, while reducing blow-off, increases flashback risks due to hydrogen's high flame speed.
- **CFD studies** reveal that flashback risk is significantly influenced by fuel composition, combustor pressure, and mass flow rates.
- Swirl stabilization can mitigate blow-off but complicates flashback management.

3.5 Dynamic Instabilities and Thermo-Acoustic Coupling

Dynamic instabilities arise from the interaction between heat-release variations and combustor acoustics, leading to thermo-acoustic coupling.

3.6 Mechanisms of Dynamic Instabilities

Thermo-acoustic coupling occurs when pressure oscillations constructively align with combustor resonance frequencies, amplifying pressure waves and potentially causing hardware damage.

- Pressure fluctuations should remain below **5% of the average combustor pressure** to ensure stable operation.

- Lean premixed combustion (LPM) is particularly susceptible due to its operation near blow-off limits, exacerbating pressure oscillations through flame extinction and re-ignition cycles.
- Hydrogen-enriched syngas affects dynamic instabilities by modifying flame velocity and equivalence ratios, altering pressure oscillation frequencies.

3.7 Control Strategies for Dynamic Instabilities

Control strategies are categorized into active and passive approaches:

- **Active Controls:** Modify fuel injection rates or use real-time feedback systems to regulate heat-release rates.
- **Passive Controls:** Alter combustor acoustics via design modifications, such as perforated liners, acoustic dampers, or tailored fuel injection strategies.

Although passive methods are more practical, active strategies like phase-modulated spray injection show promise in reducing high-amplitude pressure oscillations. Research continues to refine these techniques to enhance combustor performance and reduce emissions, especially in hydrogen-enriched and oxy-fuel combustion scenarios.

4. NOX EMISSIONS IN LEAN PREMIXED COMBUSTION

4.1 Prompt NOx and Fuel NOx Formation

NOx emissions in LPM combustion arise from two primary mechanisms:

- **Prompt NOx (Fenimore NOx):** Results from rapid interactions between nitrogen (N_2) and hydrocarbon radicals (CH , CH_2) in fuel-rich conditions. In lean systems, its impact is minimal.
- **Fuel NOx:** Occurs when nitrogen-containing fuels (e.g., ammonia, biomass-derived fuels) oxidize. Fuel NOx production depends on fuel nitrogen content and combustion kinetics.

4.2 NOx Control Strategies

Effective NOx reduction requires:

- Optimized fuel selection
- Combustion staging
- Advanced emissions control techniques

Future research should enhance predictive NOx models for hydrogen-enriched and ammonia-based combustion systems.

5. STRATEGIES FOR OPTIMIZED COMBUSTION

5.1 Fuel/Oxidizer Flexibility Strategy

Fuel adaptability is critical in modern gas turbines due to increasing reliance on alternative fuels like syngas, biomass, and liquefied petroleum gas. Variations in fuel composition affect:

- Chemical timeframes
- Ignition delay
- Blow-off limits
- Dynamic stability

5.2 Hydrogen-Enrichment Methodology

Hydrogen is a promising clean fuel due to its high energy density and zero carbon emissions.

- Enhances flame stability by increasing reaction rates and reducing the Lewis number.
- Improves mixing and diffusion properties.
- However, increased NOx emissions at constant equivalence ratios require leaner operation to maintain emissions control.

5.3 Oxy-Fuel Combustion as an Alternative

Oxy-fuel combustion, using pure oxygen instead of air, significantly reduces NOx emissions.

- **Challenges:**
 - Requires pure oxygen supply
 - Introduces flame stability issues
 - Limits operational flexibility
- Research focuses on advanced burner designs and computational modeling to optimize oxy-fuel combustion.

6. SWIRL STABILIZATION IN GAS-TURBINE COMBUSTION

6.1 Swirl Generation Techniques

Swirl stabilization enhances flame stability, prevents blow-off, and improves turndown performance.

- **Techniques:**

- Tangential injection
- Axial vane swirlers
- Radial vane swirlers
- Mechanical spinners

6.2 Swirl Number and Its Impact on Stability

The **swirl number** (ratio of axial flux of angular momentum to axial thrust) quantifies swirl intensity.

- **Types of swirlers:**

- Axial swirlers: Moderate swirl numbers
- Radial swirlers: High swirl numbers with minimal pressure loss
- Hybrid swirlers: Enhanced efficiency at lower engine loads
- Excessive swirl can cause vortex breakdown, disrupting stability.

6.3 Effects of Swirl on Stability and Emissions

- Expands lean-premixed flame operability by increasing blow-off resistance.
- Swirl numbers > 0.6 create well-defined recirculation zones, enhancing flame stability.
- Higher swirl numbers reduce blow-off limits for hydrogen but improve flashback resistance.
- Trade-off: Increased residence time improves CO oxidation but raises NO_x emissions.
- Advanced combustor designs, such as **vortex generators**, reduce NO_x and CO emissions by 20%.

7. NUMERICAL SIMULATION OF PREMIXED COMBUSTION

7.1 Modeling Approaches

Numerical simulations are essential for predicting combustion performance and guiding burner design.

- **Direct Numerical Simulation (DNS):** Highest accuracy but computationally expensive.
- **Reynolds-Averaged Navier-Stokes (RANS):** Common in engineering but lacks resolution of turbulent eddies.
- **Large Eddy Simulation (LES):** Balances accuracy and cost, effectively capturing transient combustion dynamics.

7.2 LES Governing Equations

LES models filter flow variables to separate large and small turbulence scales, incorporating conservation laws for mass, momentum, and energy.

7.3 LES Applications in Premixed Combustion

LES is widely used to study:

- Lean premixed swirl flames
- Flashback and blow-off dynamics
- Effects of heat flux and burner configurations
- Impact of swirl generator placement on combustion stability

Studies reveal that LES provides accurate predictions of flame propagation and stability, guiding the design of low-emission gas turbine combustors. Further refinements are necessary for unstable combustion conditions, particularly hydrogen-air premixed flames, due to hydrogen's high diffusivity and propensity for combustion instabilities.

8. ADVANCED BURNER DESIGNS FOR PREMIXED COMBUSTION IN GAS TURBINES

8.1 Introduction

Advanced burner designs have been developed to enhance combustor stability and performance in gas turbines using premixed combustion techniques. These designs aim to improve flame stability, reduce emissions, and increase efficiency. Key technologies include:

- **Stagnation Point Reverse Flow (SPRF) burner**
- **Internal flue gas recirculation (IFGR)**

- Dry low-NOx (DLN) or dry low-emission (DLE) combustors
- Environmental (EV) burners
- Micromixer (MM) combustors
- Perforated plate (PP) burner
- Syngas-fueled micromixing gas turbine burners

These innovations play a significant role in optimizing gas turbine combustion performance and sustainability.

8.2 Emission Reduction and Carbon Capture Strategies

Despite progress in reducing NO_x and CO emissions through advanced combustion technologies, lean premixed air combustion alone does not achieve complete emission control. Carbon capture technologies must be integrated to further mitigate emissions. CO₂ is a major greenhouse gas, with annual emissions exceeding 30 gigatonnes. Carbon capture systems are classified into:

- Pre-combustion capture
- Oxy-fuel combustion
- Post-combustion capture

Oxy-fuel combustion, in particular, is advantageous for gas turbines as it simplifies CO₂ separation by producing only CO₂ and H₂O. However, combustion stability and efficiency remain challenges in oxy-fuel systems.

8.3 Fuel Flexibility and Hydrogen Enrichment

Fuel-flexible burners are essential for ensuring stable combustion under varying fuel compositions. Hydrogen-enriched combustion is a promising approach to improve combustor performance and reduce emissions. Hydrogen enrichment influences:

- Flame stability
- NO_x emissions
- Flashback risk

By adjusting the hydrogen concentration, engineers can balance performance and emission control.

8.4 Oxy-Fuel Combustion for Zero-Emission Power Plants

Oxy-fuel combustion is recognized as a key technology for zero-emission power plants (ZEPPs). However, its viability is hindered by the high energy demand of cryogenic air separation units (ASUs) for pure oxygen production. Alternative oxygen separation methods include:

- Membrane-based oxygen separation
- High-temperature membrane reactors (HTMRs)

Research aims to reduce the economic and energy burden of ASUs while maintaining the benefits of oxy-fuel combustion.

8.5 Future Outlook on Gas Turbine Combustion Technologies

With rising global energy demand and stricter emission regulations, innovative combustion solutions are crucial. The focus of future burner designs will be on:

- Optimizing combustion stability
- Enhancing fuel adaptability
- Reducing NO_x and CO₂ emissions

Comparisons between oxy-fuel and air-combustion environments provide insights into their operational efficiency and emission characteristics.

9. COMBUSTION OF SYNGAS: CHALLENGES AND CHARACTERISTICS

9.1 Introduction to Syngas as a Fuel

Syngas is a mixture of hydrogen (H₂), carbon monoxide (CO), and carbon dioxide (CO₂). It is produced through:

- Gasification of hydrocarbons and waste materials
- Industrial byproducts such as coke-oven gas
- Fossil fuel reforming

Its hydrogen-rich nature makes it an attractive alternative fuel for gas turbines.

9.2 Integrated Gasification Combined Cycle (IGCC) Technology

IGCC plants utilize syngas combustion with pre-combustion carbon capture. The **water-gas shift reaction** converts CO into CO₂, enabling its removal before combustion, resulting in a hydrogen-rich syngas fuel.

9.3 Challenges in Transitioning to Syngas in Gas Turbines

Natural gas-fired gas turbines must undergo modifications to burn syngas due to: efficiently

- **Increased flashback risk from high flame speeds**
- **Higher fuel flow rates to match natural gas power output**
- **Lower Wobbe Index (WI), requiring larger fuel injectors**

Research focuses on combustion dynamics, emissions, and operational safety to enable syngas adoption.

9.4 Impact of Syngas Composition on Flame Stability

Studies have examined the effects of **H₂ and CO variations**, but limited research exists on **H₂O and CO₂ dilution**. These components influence:

- **Flame temperature**
- **Radiative heat transfer**
- **Ignition delay**

Higher hydrogen concentrations improve stability, while CO₂ and H₂O dilution impact ignition delay and flame behavior.

10. AMMONIA COMBUSTION AS A LOW-CARBON ENERGY SOURCE

10.1 Advantages and Challenges of Ammonia as a Fuel

Ammonia (NH₃) is gaining attention as a carbon-free fuel, but its combustion faces obstacles due to:

- **High ignition energy requirements**
- **Slow reaction kinetics**
- **High NO_x emissions**

10.2 Research Efforts to Improve Ammonia Combustion

Methods to enhance NH₃ combustion include:

- **Hydrogen blending** for better reaction rates
- **Ammonia-methane mixtures** to enhance flame stability
- **Advanced burner designs** for optimized air-fuel mixing

Further research is needed to ensure reliable NH₃ combustion for large-scale applications.

11. FUEL-FLEXIBLE PREMIXED OXY-FUEL COMBUSTION

11.1 Integration of Hydrogen-Enriched Fuels

The demand for low-carbon fuels has led to increased research on **hydrogen-enriched gas turbines**. Key findings include:

- **Water vapor dilution** reduces flame speed
- **CO₂ dilution** alters flame velocity and stability
- **Hydrogen enrichment** lowers CO emissions and improves efficiency

11.2 Hydrogen-Enriched Syngas in Gas Turbines

Hydrogen-enriched syngas is a **low-carbon, high-reactivity** fuel alternative. Advantages include:

- **Higher reaction rates** improving thermal efficiency
- **Lower CO emissions**
- **Expanded flammability limits** for operational flexibility

However, challenges such as **high NO_x emissions, flashback risks, and combustion instabilities** require innovative burner designs.

12. PROSPECTS AND RESEARCH DIRECTIONS

12.1 Advancing Fuel-Flexible Combustion Technologies

To achieve **sustainable power generation**, research is focused on:

- **Developing advanced burners** for multi-fuel adaptability

- **Optimizing turbulence-chemistry interactions**
- **Hybrid combustion methods, such as hydrogen-biofuel co-firing**

Future gas turbines will incorporate hydrogen-enriched syngas, ammonia combustion, and oxy-fuel techniques for **low-emission, high-efficiency performance**.

13. GLOBAL DEVELOPMENTS IN CCS/CCUS TECHNOLOGIES

13.1 Strategies for CO₂ Utilization

Carbon Capture, Utilization, and Storage (CCUS) is essential for **reducing industrial emissions**. However, global CO₂ utilization remains **below 1%** due to thermodynamic stability and energy costs.

13.2 CO₂ Utilization Methods

- **Direct Utilization:**
 - **Water treatment, beverage carbonation, enhanced oil recovery (EOR)**
- **Chemical Conversion:**
 - **Hydrogenation, carbonylation, polymer production**
 - **Biological carbon fixation via microalgae cultivation**

Microalgae cultivation, for example, can absorb **1.8 tons of CO₂ per ton of biomass**, highlighting its potential.

13.3 Research Focus

Current efforts integrate CO₂ capture with conversion processes to establish **closed-loop, carbon-neutral solutions**. Research priorities include:

- **Reducing energy consumption in CO₂ capture**
- **Enhancing catalyst efficiency**
- **Improving scalability for commercial applications**

14. INNOVATIONS IN GAS TURBINE COMBUSTION TECHNOLOGIES

14.1 Recent Advances

Gas turbines have evolved to meet demands for **higher efficiency, lower emissions, and greater fuel flexibility**. Innovations include:

- **SPRF combustors for enhanced stability**
- **DLN/DLE burners for NO_x reduction**
- **Micromixer combustion for uniform fuel-air mixing**

14.2 Future Research Areas

- **Hybrid combustor designs for alternative fuels**
- **Optimizing oxygen separation for oxy-fuel systems**
- **Advancements in low-swirl injectors for hydrogen-rich fuels**

As global energy demands evolve, continued research in **low-carbon combustion strategies** will shape the future of gas turbine technology.

15. FLAME STRUCTURE AND OXYGEN FRACTION EFFECTS ON COMBUSTION INTENSITY

15.1 Reynolds Number Influence on Flame Configuration

Flame images captured at different Reynolds numbers (Re) revealed key trends in combustion dynamics:

- **Higher Re broadened operability**, allowing flames to sustain leaner conditions before blowout.
- **Larger flame structures at higher Re** indicated enhanced turbulence-induced mixing and increased reactant residence times.
- **Flame morphology remained similar at constant adiabatic flame temperature (T_{ad}) and Re**, confirming their predictive reliability for flame behavior.

These findings highlight the strong interplay between flow properties (Re) and combustion characteristics (T_{ad}) in defining flame behavior.

15.2 Oxygen Fraction (OF) Effects on Flame Stability and Heat Release

Oxygen fraction (OF) significantly impacts flame stability and reaction kinetics:

- **Higher OF (30% to 40%) increased flame speed by 2.4 times.**

- **Flames with higher OF anchored closer to the burner throat**, enhancing stability.
- **Thermal Distributions:**
- Higher OF raised flame temperature by **200 K at an axial distance of 6.35 cm**.
- Increasing Re from **7000 to 9000** led to a **smaller 100 K temperature increase**, demonstrating that OF exerts a stronger influence on combustion intensity than Re.

These results suggest that while oxygen fraction primarily governs combustion intensity and stability, Re enhances fuel-air mixing and turbulence effects.

16. OPERABILITY OF FUEL/OXIDIZER-FLEXIBLE GAS TURBINE COMBUSTORS

16.1 Oxidizer Flexibility and Oxy-Combustion

Modern gas turbines must accommodate fuel/oxidizer flexibility to support low-emission power generation and carbon capture (CCS) integration.

Air-Fuel Combustion Challenges:

- Produces **diluted CO₂ exhaust**, complicating post-combustion carbon capture.
- **Oxy-Fuel Combustion Advantages:**
- Uses **pure O₂**, generating an exhaust stream of only **CO₂ and H₂O**, simplifying carbon capture.
- **CO₂ dilution regulates flame temperature**, preventing material degradation.
- Requires **Exhaust Gas Recirculation (EGR)** to maintain flame stability.

Transitioning from **air-based to oxy-fuel combustion** introduces challenges due to lower flame speeds and changes in recirculation zone behavior.

16.2 Hydrogen Enrichment and Fuel Flexibility

Hydrogen as a Stability Enhancer

Hydrogen-enriched flames exhibit:

- **Higher flame speed**, extending lean stability limits.
- **Lower NO_x emissions** due to reduced adiabatic flame temperature.
- **Increased flashback risk**, requiring swirl-stabilization.

Stability Maps for Hydrogen-Enriched Oxy-Fuel Flames

- Increasing **hydrogen fraction (HF)** shifts blowout limits toward leaner conditions.
- Higher **oxygen fractions (OF)** extend operability but **mainly affect blowout over flashback**.
- Elevated **throat velocity (U_{in})** mitigates blowout but accelerates flashback, underscoring the importance of flow control.

Large-Eddy Simulations (LES) confirm that hydrogen enrichment:

- **Enhances radical production** and accelerates flame propagation.
- **Reduces ignition delay**, improving combustion stability.

17. FUTURE DIRECTIONS IN GAS TURBINE COMBUSTOR DESIGN

1. **Optimizing O₂/CO₂ Ratios for Oxy-Combustion** – Fine-tuning dilution levels for stability and emissions control.
2. **Hydrogen Enrichment for Extended Operability** – Ensuring flashback mitigation through swirl-stabilization and injector design.
3. **Dynamic Combustion Control Systems** – Real-time fuel-oxidizer composition adjustments for stable operation.
4. **Integration with Carbon Capture (CCS)** – Leveraging oxy-fuel combustion for efficient CO₂ sequestration.
5. **Advancing LES Modeling** – Refining numerical simulations for predictive analysis and design optimization.

Modern gas turbines can achieve stable, low-emission combustion by addressing Re effects, fuel flexibility, and oxidizer composition, facilitating the transition to **carbon-neutral power generation**.

18. FLAME SHAPE ANALYSIS IN HYDROGEN-ENRICHED OXY-METHANE COMBUSTION

18.1 Effect of Hydrogen Enrichment on Flame Shape

The impact of **hydrogen fraction (HF)** on the flame structure was analyzed at a fixed equivalence ratio ($\phi = 1.0$) across different **throat velocities (U_{in})**. Hydrogen enrichment significantly altered **flame shape, brightness, and turbulence levels**, revealing enhanced combustion dynamics.

Key Observations:

1. Flame Compactness and Reaction Kinetics

- At 0% HF (pure methane combustion), flames spread across the combustor, conforming to confinement boundaries.
- With increasing HF, flames became shorter, brighter, and highly turbulent, signifying:
 - Increased chemical reaction rates.
 - Higher flame speed.
- Higher hydrogen content reduced flame height, enhancing combustion intensity and increasing audible combustion noise.

2. Flashback Occurrence

- At a throat velocity of 4.4 m/s, flashback occurred at HF > 50%.
- At 5.2 m/s and 6.0 m/s, flashback occurred at HF > 40%.
- Higher turbulent flame speeds at increased hydrogen fractions led to premature upstream flame propagation.
- Audible noise intensified as flashback conditions were approached, indicating instability buildup.

18.2 Equivalence Ratio Influence on Flame Transition

At HF = 50%, three distinct flame configurations emerged based on ϕ :

1. Cup-shaped flames ($\phi < 0.75$) – Elongated, less luminous flames with lower reaction rates.
2. V-shaped Flames ($0.75 < \phi < 0.85$) – Intermediate stability regime with increased brightness and turbulence.
3. Vase-Shaped Flames ($\phi > 0.85$) – Shorter, high-intensity flames with enhanced chemical kinetics.

18.3 Velocity Influence on Flame Transition

Throat velocity significantly affected flame shape at $\phi < 0.8$:

- At 4.4 m/s, transition from cup-shaped to vase-shaped flames occurred at $\phi = 0.75 - 0.80$.
- At 5.2 m/s, transition occurred at $\phi = 0.65 - 0.70$.
- At 6.0 m/s, transition occurred at $\phi = 0.60 - 0.65$.

Higher velocity reduced equivalence ratio transition points, indicating that increased turbulence enhances flame compactness and stability.

18.4 Flame Stabilization and Outer Recirculation Zone (ORZ)

A shift from Inner Shear Layer (ISL) stabilization to Outer Recirculation Zone (ORZ) anchoring was observed:

- 4.4 m/s: $\phi = 0.7$
- 5.2 m/s: $\phi = 0.6$
- 6.0 m/s: $\phi = 0.6$

This shift suggests that hot recirculating gases play a crucial role in flame retention and stability.

18.5 Effect of Adiabatic Flame Temperature (AFT) on Flame Shape

At AFT = 2000 K, findings indicate:

- Flame structure is primarily governed by hydrogen fraction and velocity, not AFT.
- Higher HF resulted in shorter flames, confirming faster combustion kinetics.
- Similar flame configurations were observed in pure hydrogen and hydrogen-enriched flames.

18.6 Flame Behavior Near Stability Limits

- Near Blowout: Flames shrank but remained confined within the combustor.
- Near Flashback: Flame brightness decreased, but structure remained compact.

These results contribute to the development of hydrogen-enriched combustors, optimizing stability, turbulence, and emissions control for next-generation gas turbines.

19. CONCLUSION

This review highlights the critical role of combustion stability in premixed gas turbines and the challenges associated with managing blow-off, flashback, and thermo-acoustic instabilities. The key findings include:

1. **Static Instabilities:** The Damköhler number influences blow-off and is more pronounced in hydrogen-enriched flames due to their higher reaction rates. High hydrogen fractions exacerbate flashback but can be mitigated through swirl stabilization and injector design modifications.

2. **Dynamic Instabilities:** Thermo-acoustic coupling is particularly severe in lean premixed combustion due to its proximity to blow-off limits. Active and passive control strategies can mitigate instability effects, including phase-modulated fuel injection and acoustic damping.
3. **Fuel Flexibility:** Hydrogen enrichment improves lean blowout resistance but increases flashback risk, requiring optimized fuel-air mixing and flame anchoring techniques. Oxy-fuel combustion presents a pathway to zero-emission power generation but necessitates advanced recirculation strategies for maintaining flame stability.
4. **Numerical Simulations:** LES provides a robust framework for understanding turbulence-chemistry interactions and predicting combustion instability trends. Further refinement of modeling techniques is needed to improve predictive accuracy under real-world operating conditions.

Future research should focus on integrating adaptive combustion control systems, refining low-swirl injectors for hydrogen-enriched fuels, and optimizing oxy-fuel combustor designs to balance efficiency, emissions, and stability. The continued advancement of premixed combustion technologies will play a crucial role in the transition to sustainable, low-emission power generation.

20. REFERENCES

- [1] Xie Y, Wang J, Zhang M, Gong J, Jin W, Huang Z (2013) Experimental and numerical study on laminar flame characteristics of methane oxy-fuel mixtures highly diluted with CO₂. *Energy Fuels*, 27:6231–6237. DOI: 10.1021/ef401220h
- [2] Oh J, Noh D (2012) Laminar burning velocity of oxy-methane flames in atmospheric condition. *Energy*, 45(1):669–675. DOI: 10.1016/j.energy.2012.07.027
- [3] Abubakar Z, Shakeel MR, Mokheimer EMA (2018) Experimental and numerical analysis of non-premixed oxycombustion of hydrogen-enriched propane in a swirl stabilized combustor. *Energy*, 165:1401–1414.
- [4] Gu X, Huang Z, Wu S, Li Q (2010) Laminar burning velocities and flame instabilities of butanol isomers-air mixtures. *Combust Flame*, 157(12):2318–2325.
- [5] Vagelopoulos CM, Egolfopoulos FN (1998) Direct experimental determination of laminar flame speeds. *Symp (Int) Combust*, 27(1):513–519.
- [6] Tseng LK, Ismail MA, Faeth GM (1993) Laminar burning velocities and Markstein numbers of hydrocarbon/air flames. *Combust Flame*, 95(4):410–426.
- [7] Toporov D, Bocian P, Heil P, Kellermann A, Stadler H, Tschunko S et al. (2008) Detailed investigation of a pulverized fuel swirl flame in CO₂/O₂ atmosphere. *Combust Flame*, 155(4):605–618.
- [8] Metghalchi M, Keck JC (1980) Laminar burning velocity of propane-air mixtures at high temperature and pressure. *Combust Flame*, 38:143–154.
- [9] Yi B, Zhang L, Huang F, Mao Z, Zheng C (2014) Effect of H₂O on the combustion characteristics of pulverized coal in O₂/CO₂ atmosphere. *Appl Energy*, 132:349–357.
- [10] Kim HK, Kim Y, Lee SM, Ahn KY (2007) NO reduction in 0.03–0.2 MW oxy-fuel combustor using flue gas recirculation technology. *Proc Combust Inst*, 31:3377–3384.
- [11] Liu CY, Chen G, Sipöcz N, Assadi M, Bai XS (2012) Characteristics of oxy-fuel combustion in gas turbines. *Appl Energy*, 89(1):387–394.
- [12] Glarborg P, Bentzen LLB (2008) Chemical effects of a high CO₂ concentration in oxy-fuel combustion of methane. *Energy Fuels*, 22(1):291–296.
- [13] Wang J, Huang Z, Tang C, Miao H, Wang X (2009) Numerical study of the effect of hydrogen addition on methane-air mixtures combustion. *Int J Hydrogen Energy*, 34(2):1084–1096. DOI: 10.1016/j.ijhydene.2008.11.010
- [14] Shy SS, Chen YC, Yang CH, Liu CC, Huang CM (2008) Effects of H₂ or CO₂ addition, equivalence ratio, and turbulent straining on turbulent burning velocities for lean premixed methane combustion. *Combust Flame*, 153:510–524. DOI: 10.1016/j.combustflame.2008.03.014
- [15] Boushaki T, Dhué Y, Selle L, Ferret B, Poinot T (2012) Effects of hydrogen and steam addition on laminar burning velocity of methane-air premixed flame: Experimental and numerical analysis. *Int J Hydrogen Energy*, 37(11):9412–9422.
- [16] Guo H, Smallwood GJ, Liu F, Ju Y, Gülder ÖL (2005) The effect of hydrogen addition on flammability limit and NO_x emission in ultra-lean counterflow CH₄/air premixed flames. *Proc Combust Inst*, 30(1):303–310.

- [17] Kim HS, Arghode VK, Gupta AK (2009) Flame characteristics of hydrogen-enriched methane-air premixed swirling flames. *Int J Hydrogen Energy*, 34(2):1063–1073. DOI: 10.1016/j.ijhydene.2008.10.035
- [18] Schefer RW (2002) Reduced turbine emissions using hydrogen-enriched fuels. *DOE Hydrogen Program Review 2002*, pp 1–16.
- [19] Yu G, Law CK, Wu CK (1986) Laminar flame speeds of hydrocarbon + air mixtures with hydrogen addition. *Combust Flame*, 63(3):339–347.
- [20] Aliyu Mansur, Nemitallah MA, Said Syed A, Habib MA (2016) Characteristics of H₂-enriched CH₄-O₂ diffusion flames in a swirl-stabilized gas turbine combustor: Experimental and numerical study. *Int J Hydrogen Energy*, 41:2041.
- [21] Imteyaz BA, Nemitallah MA, Abdelhafez AA, Habib MA (2018) Combustion behavior and stability map of hydrogen-enriched oxy-methane premixed flames in a model gas turbine combustor. *Int J Hydrogen Energy*, 43.
- [22] Tang C, Huang Z, Jin C, He J, Wang J, Wang X et al. (2008) Laminar burning velocities and combustion characteristics of propane–hydrogen–air premixed flames. *Int J Hydrogen Energy*, 33(18):4906–4914. DOI: 10.1016/j.ijhydene.2008.06.063
- [23] Riahi Z, Bounaouara H, Hraiech I, Ali Mergheni M, Sautet J-C, Ben Nasrallah S (2017) Combustion with mixed enrichment of oxygen and hydrogen in lean regime. DOI: 10.1016/j.ijhydene.2016.06.232
- [24] Rezgui Y, Guemini M (2017) Effect of hydrogen addition on equimolar dimethyl ether/iso-octane/oxygen/argon premixed flames. *Int J Hydrogen Energy*, 42:29557–29573. DOI: 10.1016/J.IJHYDENE.2017.10.063
- [25] Shi B, Hu J, Ishizuka S (2015) Carbon dioxide diluted methane/oxygen combustion in a rapidly mixed tubular flame burner. *Combust Flame*, 162:420–430. DOI: 10.1016/j.combustflame.2014.07.022
- [26] Konnov AA, Dyakov IV (2005) Measurement of propagation speeds in adiabatic cellular premixed flames of CH₄ + O₂ + CO₂. *Exp Therm Fluid Sci*, 29:901–907. DOI: 10.1016/j.expthermflusci.2005.01.005
- [27] Li J, Huang H, Kobayashi N, He Z, Nagai Y (2014) Study on using hydrogen and ammonia as fuels: combustion characteristics and NO_x formation. *Int J Energy Res*, 38:1214–1223. DOI: 10.1002/er.3141