Research Insight: The Critical Impact of Operational Modes on Gas Turbine Combustor Performance

1. Introduction: The Thermal Challenge of Liner Durability

In the pursuit of increased power density and thermal efficiency, liner durability has solidified as the primary technical bottleneck for gas turbine longevity. The mechanical integrity of the combustor hardware is dictated by the synergy between absolute maximum metal temperatures and steep temperature gradients, which together catalyze mechanical stress and material fatigue. A pivotal 2012 investigation analyzed these variables, demonstrating that the "mode of operation"—defined by fuel phase and injection method—is the dominant driver of liner life.

This research provides an analytical evaluation of how non-premixed natural gas, dry liquid fuel, and wet liquid fuel modes influence localized heat loading, emissions profiles, and acoustic operability. Analysis of these high-fidelity experimental data points yields essential design parameters for predicting hardware degradation and managing operational margins in F-class systems.

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2. Experimental Methodology: The Single Nozzle Rig (SNR) Framework

To isolate the effects of operational modes under realistic F-class conditions, a Single Nozzle Rig (SNR) was utilized. This framework provides a high-fidelity environment for data acquisition, allowing for the precise measurement of internal aerodynamics and chemical kinetics without the confounding variables of a multi-nozzle engine configuration.

A critical aspect of the experimental design was the maintenance of a constant residence time of approximately 18ms across all test points, effectively isolating the impact of inlet pressure (P3) and temperature (T3) on performance metrics. The study contrasted two primary loading conditions:

Parameters	Load 1 (Part Load)	Load 2 (Full Load)
Inlet Pressure (P3)	140 psia	225 psia
Inlet Temperature (T3)	715°F	865°F
Residence Time	~18 ms	~18 ms

The experimental fuels included a methane-rich Natural Gas (~96% CH_4) and Distillate No. 2 (DistII). To map the thermal loading across the hardware, the liner was instrumented with over 30 thermocouples. Per the hardware nomenclature, the rig was divided into a square-profile **Primary Zone** (head-end) and a cylindrical-profile **Liner Zone** (tail-section), enabling a granular assessment of zone-specific thermal shifts.

3. Key Insight 1: Flame Shape Dynamics and Thermal Loading Profiles

Flame stabilization is the fundamental driver of localized heat flux. The physical "seat" of the flame—where it anchors within the swirler-induced flow field—determines the proximity of the highest thermal release to the metal walls. The study identifies stark thermal differentiators between Natural Gas (NG) and Dry Liquid Fuel (DistII) based on their respective stabilization mechanisms.

Primary Zone Impact Operation on DistII increases average metal temperatures in the Primary Zone by approximately 100°F relative to NG. This elevation is driven by the higher luminosity of liquid fuel flames, which intensifies radiation heat transfer, and a robust flame shape that occupies the Primary Zone more fully.

Liner Zone Divergence Conversely, the Liner Zone exhibits temperatures roughly 50°F lower during DistII operation than with NG. This inverse relationship suggests that while liquid fuel stabilizes and releases heat more aggressively in the upstream Primary Zone, Natural Gas carries a higher thermal burden into the downstream Liner Zone.

Corner Recirculation Zone (CRZ) Interaction Aerodynamic stabilization is dictated by the Corner Recirculation Zone (CRZ). Liquid fuels exhibit deeper involvement in the CRZ, shifting the heat load toward the head-end. Natural Gas operation, however, shows higher temperature variability (streaking) in the Liner Zone due to a non-homogeneous flame structure. While average temperatures may be lower, individual hot streaks in NG mode can create localized thermal gradients that threaten material integrity.

4. Key Insight 2: The Emissions Trade-off and the Homogenizing Effect of Wet Operation

Liquid fuel combustion presents an inherent challenge to environmental compliance due to the droplet burning mode, which creates locally stoichiometric regions that produce higher emissions than the gaseous phase of Natural Gas.

The Pressure Exponent and Baseline Performance Natural Gas yields significantly lower emissions, with CO levels ~80 ppm lower and NOx levels 35–80% lower than dry liquid fuel. Crucially, the study identifies a pressure sensitivity that exceeds standard industry assumptions. While the industrial standard for pressure effect on NOx is an exponent of 0.5, this investigation found an exponent of **0.9 to 1.05** for these diffusion flames, indicating a much more aggressive NOx rise at high-power conditions.

Mechanisms of Wet Operation The transition to Wet Liquid Fuel (water injection) achieves an 80% reduction in NOx through peak flame temperature suppression. However, it introduces complex thermal shifts:

- **Primary Zone:** A massive ~300°F reduction in maximum metal temperature is achieved specifically through **water impingement** on the liner walls.
- **Liner Zone:** Maximum temperatures increase by 50–100°F, a result of **flame length extension** associated with water injection.

Despite the localized temperature rise in the tail-section, water injection provides a significant "homogenization" effect, reducing exit profile variability by 60%. This protects downstream turbine stages from uneven thermal loading.

Bifurcated Carbon Monoxide Response Water injection impacts CO through two distinct thermal mechanisms:

1. **Quenching (<2600°F):** At lower exit temperatures, water increases CO by quenching the reaction near the cooler walls.
2. **Dissociation (>2650°F):** At high temperatures, water reduces CO by suppressing the dissociation reactions occurring in the high-temperature center stream.

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5. Key Insight 3: Acoustic Operability and Pressure Oscillations

Combustor operability is fundamentally limited by thermo-acoustic instabilities. Managing pressure oscillations (dynamics) is vital, as high-amplitude coupling between heat release and chamber acoustics can lead to rapid hardware deterioration.

Acoustic Signatures by Fuel Type

- **Natural Gas:** Exhibits the lowest amplitudes (1–2 psi pk-pk) due to marginal CRZ involvement in the flame stabilization process.
- **Liquid Fuels:** Dry liquid fuel operation results in significantly higher amplitudes (5–7 psi pk-pk).

Sensitivity to Pressure Drop While water injection generally provides an average 2 psi reduction in amplitude, it is not a universal mitigation strategy. The study demonstrated that under high pressure-drop conditions (\Delta P/P), water injection can interact with turbulence structures in the recirculation zones to cause a **5X increase** in acoustic levels. Designers must treat water injection as a potential dynamic amplifier depending on the specific combustor pressure-drop environment.

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6. Engineering Takeaways: Strategic Guidance for Designers and Operators

The SNR data transforms operational variables into a mandate for precise thermal and acoustic management. Designers must look beyond "average" conditions to the zone-specific realities of high-power operation.

- **Zone-Specific Load Accounting:** Designers must mandate different safety margins for load transitions. When moving from part load to full load, the **Primary Zone** maximum metal temperature increases by **280°F to 360°F**, whereas the **Liner Zone** increases by only **80°F to 150°F**. Average-based calculations will fundamentally underestimate Primary Zone stress.
- **The Gradient Penalty of Wet Operation:** While water injection offers a 300°F cooling benefit in the head-end, it increases localized temperature variability by 70%. Hardware life models must account for these increased gradients, which can accelerate fatigue despite the lower average temperatures.
- **Pressure Sensitivity Mandates:** Because the pressure exponent for NOx (0.9–1.05) is nearly double the industrial standard (0.5), emissions compliance strategies for high-pressure F-class systems must be significantly more aggressive than those for lower-pressure assets.
- **Pattern Factor Optimization:** Beyond NOx reduction, water injection should be prioritized as a tool for improving the thermal uniformity (pattern factor) at the combustor exit, thereby extending the life of the first-stage turbine nozzle.

In modern thermal fluid systems, the "mode of operation" is not an auxiliary variable—it is a primary design constraint that dictates the thermal, chemical, and acoustic boundaries of the machine.