Impact of secondary air on emissions

A Technical Deep Dive: Quantifying the Impact of Secondary Air on DLE Combustor Emissions

Introduction: The Overlooked Variable in Emissions Control

The central challenge in modern Dry Low Emissions (DLE) combustion systems is the continuous drive to reduce Nitric Oxide (NOx) emissions while simultaneously managing critical operational constraints, such as the hardware cooling required for system durability. A key component of this balance is the use of "secondary air"—the portion of the total combustor airflow used for cooling, dilution, and managing leakage, which is distinct from the primary air that flows through the fuel-air premixer.

While common engineering practice relates emissions performance to the theoretical mixer flame temperature (Tflame), the direct influence of this secondary air is not well-quantified in published literature. This represents a significant knowledge gap for designers aiming for single-digit NOx levels.

This article presents a detailed analysis of a study that experimentally quantifies the impact of varying secondary air percentage on emissions, flame interaction, and thermo-acoustic stability. The experiments were conducted under the high-pressure, high-temperature conditions representative of an H class gas turbine, providing a practical and data-driven perspective on this critical design variable.

1. Experimental Methodology and Boundary Conditions

Test Rig and Configuration

The study was conducted using a DLE combustion system configured with two independently controlled premixers mounted side-by-side. This dual-mixer setup allowed for the investigation of local flame interactions and the effects of non-uniform flame temperatures.

The key feature of the test rig was its secondary air circuit. The rig featured a fixed secondary air component of ~8% for dome cooling and leakage, supplemented by a variable circuit that could add an additional 0% to 6% of the total airflow. This allowed the total secondary air fraction to be precisely adjusted from a baseline of 14% down to 8%. This variable secondary air stream was injected into the combustor at an axial position approximately 25% of the combustor's total length downstream from the dome.

Operating Conditions

The experiments were performed at conditions representative of H class gas turbine operation to ensure the findings are relevant to modern engine design. Key parameters were held constant to isolate the effect of the secondary air variation. Critically, to confirm that the observed emissions impact was driven by fluid dynamic quenching rather than a simple thermal effect, the study repeated key tests using a heated secondary air stream (588.7 K), which confirmed the quenching mechanism was dominant.

Parameter	Value
Combustor Pressure (P3)	~22.1 atm
Air Preheat Temperature (T3)	785 K
Combustor Residence Time	~13.5 ms
Pressure Drop (ΔP/P)	3.5%
Variable Secondary Air Temperature	~310 K (unheated)

Instrumentation and Data Acquisition

To ensure high-fidelity data, the combustor was extensively instrumented. Key measurements included:

- **Static and dynamic pressure ports** to monitor operating pressure and detect thermo-acoustic instabilities.
- **Four strategically placed thermocouples** (TKHSA1, TKHSA2, TKHSB1, TKHSB2) brazed onto the dome heat shield to measure metal temperatures. These provided critical insight into the upstream flow interactions between the secondary air and the main flame zones.
- **Four emissions rakes at the combustor exit**, equipped with a total of 20 sampling ports. The system was configured to measure emissions from individual rakes (for local profiles) or to combine the samples (ganged) for a bulk-averaged measurement.

All data points presented in the study represent an average of 60 instantaneous measurements taken at steady-state conditions, ensuring a high degree of accuracy and minimizing measurement deviation.

2. Primary Finding: The Effect of Secondary Air Reduction on NOx and CO

NOx Emissions: TFlame vs. TExit Perspective

A preliminary analysis of the data reveals an apparent contradiction. When NOx emissions are plotted against the mixer flame temperature (Tflame), reducing secondary air appears to *increase* NOx. However, when the same data is plotted against the combustor exit temperature (TExit), the opposite is true.

For a real gas turbine engine operating at a specific load, the combustor's function is to deliver hot gas at a prescribed exit temperature to the turbine. Therefore, analyzing emissions against a fixed TExit is the proper engineering approach for evaluating design changes. From this perspective, the primary result of the study is unambiguous: **At a fixed combustor exit temperature (TExit), reducing the percentage of secondary air significantly reduces NOx emissions.**

The table below, derived from the study's data at a constant TExit of 1850 K, illustrates this effect. To maintain the same exit temperature with less cool secondary air, the flame temperature must be reduced, which in turn lowers NOx production.

Secondary Air %	TFlame [K] (Approx.)	NOx15 [ppmvd] (Approx.)
14.08%	2000	22
11.08%	1960	18
8.08%	1920	14

Limitations of the NOx Design Curve

A standard NOx design curve, which plots NOx versus Tflame for a fixed system configuration (e.g., at 14% secondary air), is often used to predict the benefit of design changes. An engineer might use this curve to estimate the NOx reduction from lowering Tflame, which is the direct result of redirecting secondary air to the premixer.

However, the study revealed a critical finding: **The study revealed that the NOx reduction predicted by the standard design curve is approximately two times higher than the benefit actually measured.** This significant discrepancy is attributed to the strong quenching interaction between the cooler secondary air and the main flame—an effect that a simple design curve model fails to capture. The secondary air was already providing some NOx reduction via quenching, so reducing it yields a diminished return compared to theoretical predictions.

Impact on CO Emissions

The study also found that reducing secondary air reduces Carbon Monoxide (CO) emissions, particularly at lower operating temperatures where CO is most problematic. This improvement occurs because a primary source of CO at these conditions is flame quenching. By reducing the amount of cool secondary air interacting with the flame, quenching is lessened, allowing for more complete combustion and lower CO.

3. Visualizing Flow Interaction and Acoustic Impact

Evidence of Flame Interaction

Data from the heat shield thermocouples revealed the significant extent of the physical interaction between the secondary air and the main flames. Even though the variable secondary air was injected 25% downstream of the dome, increasing its flow (at a constant Tflame) caused a measurable drop in the dome's metal temperature. This indicates **upstream recirculation of the cooler secondary air**, which is carried back to the front end of the combustor by the main flow's recirculation zones.

Furthermore, local emissions profiles measured by the exit rakes confirmed that this interaction is not a localized phenomenon. The interaction continues and grows along the entire length of the combustor, influencing the final emissions profile at the exit.

Thermo-Acoustic Stability

Given the strong fluidic interaction, the study assessed the impact on thermo-acoustic instabilities, a critical concern for DLE systems. The results were encouraging:

- High-frequency dynamics (1000-6000 Hz) were not impacted by the change in secondary air percentage.
- Low-frequency dynamics showed a slight change, but the overall oscillation levels remained small and were not detrimental to combustor operability.

This suggests that, for this system, varying the secondary air fraction within the tested range does not introduce a significant risk to acoustic stability.

4. Advanced Strategy: Exploiting Secondary Air for Ultra-Low NOx

Many advanced DLE systems operate with a "mixer flame temperature bias," where adjacent mixers are intentionally run at different flame temperatures. This non-uniformity is a common and effective strategy for suppressing thermo-acoustic instabilities. However, because NOx production increases exponentially with temperature, this technique typically incurs a NOx penalty from the hotter flame zones, even when the overall combustor exit temperature is held constant.

The study's most novel finding demonstrates how this trade-off can be transformed into a synergistic win. Data from the baseline case with no *variable* secondary air (8% total) confirms the expected penalty: the biased flame case produced ~13.4 ppm NOx, significantly higher than the ~11.8 ppm from the uniform flame case.

The key insight is that **when operating with a flame temperature bias, the NOx penalty can be mitigated or even reversed by strategically injecting the secondary air.**

In a breakthrough experiment, the 6% variable secondary air stream was injected near the mixer operating with the *hotter* flame. This targeted quenching completely reversed the outcome. The biased-flame case now produced only **8.25 ppm** NOx—substantially *better* than the **9.25 ppm** produced by the uniform-flame case under the same secondary air conditions. This change, achieved without any hardware modifications, effectively transitioned the system from a "low NOx" to an "ultra-low NOx" (< 9 ppm) performer.

The mechanism behind this improvement is targeted quenching. By directing the cooler secondary air to the hottest part of the flame—the region where NOx production is exponentially highest—the chemical reactions are selectively slowed, leading to a net decrease in the total NOx generated by the combustor. This turns a common operational trade-off (acoustics vs. NOx) into a combined benefit.

5. Conclusion: Key Takeaways for Combustor Design

This detailed experimental study provides several crucial insights for the design and optimization of advanced DLE combustion systems.

1. **Reducing secondary air is an effective method for lowering both NOx and CO emissions.** However, the benefit predicted by standard NOx design curves is approximately 2x higher than what is actually measured, due to complex flame quenching effects that these models do not account for.
2. **The physical interaction between secondary air and the main flame is significant**, involving upstream recirculation that influences the entire combustor length. In the system tested, this interaction had a minimal detrimental impact on acoustic operability.
3. **Secondary air can be used as an active tool for emissions control.** The typical NOx penalty associated with flame temperature biasing (used for acoustic control) can be eliminated and even reversed. By intelligently directing secondary air injection towards hotter flame zones, designers can achieve additional NOx reductions and push combustion systems toward ultra-low emissions targets.