Dynamic Instability Limits in the Testing of an Advanced Premixed Combustor

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Background
Personal Background

- Grew up in New Orleans, LA

- Undergraduate education at the University of Virginia
  - Aerospace Engineering major

- Graduate studies at Princeton University
  - Department of Mechanical and Aerospace Engineering
  - Prof. Yiguang Ju’s Combustion Lab
For gas turbines, premixed combustion offers reduced emissions (particularly NO\textsubscript{x}) compared to nonpremixed techniques:
  - Using lean premixtures can allow for lower maximum flame temperatures

However, lean premixed combustion is more susceptible to combustion instabilities as a result of interactions between heat release, pressure, and mixing.

New premixed combustors must be able to control these instabilities to operate safely and effectively.
Siemens Combustor Development

- Many paths exist to improve gas turbines: new combustion techniques, material advances, more effective cooling methods
- Siemens has recently been investigating several concepts to improve mixing characteristics in premixed combustors
  - Better mixing results in fewer temperature gradients and therefore less NO\textsubscript{x}
  - However, the trade-off is a higher susceptibility to combustion instabilities
- Multi-step technology development process
  - Initial design, laboratory tests, detailed design, rig tests, etc.
- After rig testing, two designs (Design #1 and Design #2) were chosen for full-scale engine tests this past summer
Siemens Combustor Testing

- Full-scale engine set-up in Berlin Test Facility
  - Extensive diagnostics: thermocouples, pressure transducers, gas analyzers
- Expensive test due to its scale but extremely valuable in advancing the understanding of a design
- Some goals of the testing period (June-August 2015):
  - Confirm the emissions benefits of the new designs
  - Evaluate combustor behavior at engine operating conditions and off-design conditions
- Data was analyzed by engineers in both Germany and the United States
My Tasks

• Data processing:
  – (1) Convert raw data to useable form
  – (2) Compile analyzed data once testing period was complete

• Data analysis:
  – (3) Examine correlations between measurements (CO emissions vs load, NO\textsubscript{x} emissions vs various tuning parameters, etc.) to better understand how the engine performs under various conditions
  – (4) Check quality of steady-state data measurements
  – (5) Examine various points of interest during testing (engine trip, unstable pressure spikes, flame blow-off, etc.) to find possible causes behind events
Test Results
Design #1 Test: NO$_x$

- Full-scale engine test showed a NO$_x$ decrease for Design #1 compared to the current technology (a different premixed combustor design).

- Trend agreed with results from smaller rig tests.

- At these points, Design #1 could reach a higher turbine inlet temperature (higher efficiency) for the same NO$_x$ limit.
Design #1 Test: NO_x

- Design #1 also appeared less susceptible to outside conditions such as fuel or air temperature than the current technology.

- Fuel gas temperature showed little effect on NO_x emissions.

- Potential for Design #1’s ease of use in a wide variety of markets (hot climates, cold climates, etc.)
Design #1 Test: Tuning

• In order to optimize engine performance at a given load, various tuning parameters are utilized.

• Several parameters can be shown to correlate with NO$_x$ emissions (through linear regression or other types of analysis), but one specific tuning parameter was most strongly correlated with NO$_x$ in Design #1.

• However, thorough tuning of this parameter was limited during testing…
Design #1 Test: Tuning

- Tuning in Design #1 was often limited by combustion instabilities
- In several instances, reduction in a tuning parameter led to large pressure spikes caused by the dominant instability mode
  - Importance of this mode was somewhat suspected from thermoacoustic calculations
- These instability events often resulted in an engine trip a few seconds later
- As a result, the operational range of the Design #1 engine was restricted by these inherent instabilities throughout the testing period
Design #2

• Design #2 followed the same overall mixing concept as Design #1 but possessed a different fuel nozzle design
  – Potential for improved combustion dynamics due to reduction of the dominant instability mode
  – Small NO\textsubscript{x} penalty compared to Design #1 in rig tests

• Test results showed that for a drop in the same tuning parameter, no pressure spike was observed

• Larger degree of tuning possible for Design #2
like Design #1, Design #2 showed substantially lower NO\textsubscript{x} emissions than the current premixed technology.

- NO\textsubscript{x} penalty compared to Design #1 proved to be insignificant (possibly due to more extensive tuning).

- Design #2’s greater operational envelope allowed it to reach a wider range of conditions than Design #1 (both lower NO\textsubscript{x} regions and higher temperature regions).
Conclusions

• Combustion instabilities are not only important for their effects on engine lifetime but also in how they can affect combustion tuning and the overall operating envelope
  – Easy to underestimate importance of instabilities in smaller or unconfined experiments

• In the testing of Design #1, a reduction in NO$_x$ was achieved, but combustion instabilities limited engine operation

• Design #2’s modified fuel nozzles helped to control the problematic combustion instabilities, allowing the full potential of the new premixed system to be displayed
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