Thermoacoustic Oscillations in Aeronautical Gas Turbine Combustors

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Gas Turbine Combustor R&D Landscape

- Turbulent Reactive Flows
  - High Ka combustion
  - Rare events
    - Ignition, extinction, flashback
  - Chemistry of real fuels
  - ...

- Evolutionary Brayton Cycle
  - Engineering improvements to combustor architectures
    - Reduced design/development costs
  - ...

- Novel Brayton Cycle
  - New combustor architectures for Brayton cycle
    - TAPS
    - Multi-point LDI
    - Reduced design/development costs
  - ...

- Non-Brayton Cycle
  - Pressure gain combustion
    - Rotating detonation combustors
  - ...

- Digitalization
  - Digital twins
  - Real-time monitoring
    - Sensor networks
    - ANN
  - ...

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Measurement is Key

Wake-wake interactions in highly-loaded transonic turbomachines

www.vital-temp.com

Steinberg et al. PCI (2011)


Stopper et al. CnF (2013)

Coriton et al. Exp. Fluids (2014)

www.cedars-sinai.edu

Image from J. Gore (Purdue)

www.cedars-sinai.edu

An et al. CnF (2016)

2D distribution of minor species
Indicators of thermo-chemistry

2D number density
Temperature and mixing

3D major species and temperature
Detailed chemical state

Velocity fields by tracking particles
2D, 3D, 4D

Temperature, pressure, density
Highly accurate

Heat release rate
Fuel air ratio

Wake-wake interactions in highly-loaded transonic turbomachines

Laser induced fluorescence

Temperature and mixing

Laser Rayleigh scattering

Temperature, pressure, density
Highly accurate

Four wave mixing

Heat release rate
Fuel air ratio

Chemiluminescence


Steinberg et al. PCI (2011)

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Thermoacoustic Instabilities

Calpine: Equipment Failures From Siemens Turbines
February 24, 2005: 15:43 p.m. EST

SAN FRANCISCO -(Dow Jones)- Calpine Corp.'s (CPN) unexpected costs due to equipment failure in the fourth quarter were related almost entirely to turbines purchased from Siemens AG (SI), a Calpine executive said Thursday in a conference call with Wall Street analysts.

Calpine reported a fourth-quarter net loss of $172.8 million, compared with net income of $119.6 million in the final quarter of 2003. The company, which has built its huge fleet of natural gas-fired power plants in the U.S. over the past several years, said equipment-failure costs of $45.3 million were a significant part of the downturn in results. The fourth-quarter loss of 39 cents a share surprised Wall Street analysts, who had been expecting a loss of 14 cents on average, according to First Call.
Thermoacoustic Instabilities

- All combustors can exhibit thermoacoustic instabilities

\[
\frac{\partial e(\vec{x}, t)}{\partial t} + \nabla \cdot \left[ p'(\vec{x}, t) \vec{u}'(\vec{x}, t) \right] = \frac{1}{\rho_p} \int p'(\vec{x}, t) \dot{q}'(\vec{x}, t) \, dt \, d\vec{x} + \nabla \cdot \left[ \frac{1}{\mu} \int \dot{F}(\vec{x}, t) \, dt \, d\vec{x} \right]
\]

- Combustion methods that reduce emissions ($\text{NO}_x$, particulates) increase the chance of thermoacoustic instabilities

\[
\psi_s > 0: \text{Positive forcing} \\
\psi_s < 0: \text{Negative forcing}
\]
Thermoacoustic Instabilities

- All combustors can exhibit thermoacoustic instabilities

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Our Approach to Thermoacoustics

- Measure this...
  - With as much fidelity as possible
  - As close to in situ as possible

- Optical measurement techniques

- High-pressure optically accessible combustor facilities
Outline for Next ~15 Minutes

- Experiment
- Diagnostics
- Intermittent thermoacoustic oscillations
- Predictability
Experimental Setup

- Experiments at GE Global Research Center (Niskayuna, NY)
- Model injector for N+1/N+2 hardware
- $p \sim 10$ atm
- $P_{th} \sim 700$ kW
- Jet-A fuel
- Many different cases

Thermoacoustic Behaviors
Diagnostic Configuration

- S-PIV cameras
  - 5 kHz stereoscopic particle image velocimetry
- Intensified OH* CL camera
- S-PIV Laser (in separate room)
  - 5 kHz stereoscopic droplet image velocimetry
- 10 kHz OH* chemiluminescence
Aside: Managing Noise and Uncertainty

- Measurement with many data points rejected due to noise
- Velocity field deduced using data-driven reconstruction
Thermoacoustic Behaviors

Frequency

Time

Frequency

Time

Frequency

Time

Frequency

Time

Frequency

Time
Non-Stationary Dynamics

\[ \psi_s(\vec{x}, t) = \tilde{p}(t) \tilde{q}(\vec{x}, t) \cos[\Delta \varphi_p(\vec{x}, t)] \]

Positive forcing

Negative forcing
Intermittent Behavior

Oscillation attenuation associated with negative downstream forcing (main flame)

Condition on
Repeat for many ‘events’
Condition on
\(\text{sign}(d\tilde{p}/dt)\)

Oscillation growth associated with positive downstream forcing (main flame)

Sudden 180° shift in phase between pressure and heat release rate

\[\psi_s(\vec{x}, t) = \tilde{p}(t)\tilde{q}(\vec{x}, t) \cos[\Delta \phi_{pq}(\vec{x}, t)]\]
Intermittent Behavior

- Thermoacoustic driving cycles during intermittent oscillations follows a fairly repeatable behavior
- Different axial regions of driving and damping with some transitions
What Wobbles First?

- No detectable oscillations in gas phase velocity at low oscillation amplitudes
- Droplet velocity oscillations shortly after dump plane
  - Same spectral signature as pressure oscillations
- Total droplet scattering oscillations persist downstream
- Amplitude and phase of fuel oscillations linked with pressure oscillations
Prediction of Oscillation Amplitudes

\[ \Theta = \int_{0}^{2\pi} p' q' d\phi_p \]

Air/Velocities

- \( \tilde{u}_0 \)
- \( \tilde{u}_{u0} \)
- \( \tilde{u}_{p0} \)

Fuel

- \( \tilde{s}_0 \)
- \( \tilde{s}_{u0} \)
- \( \tilde{s}_{p0} \)

\( \Delta \phi_{pu0} \)

\( \Delta \phi_{ps0} \)

\( \tau_{c,uq} \)

\( \tau_{c,sq} \)

(\( \text{Rayleigh Gain} \))

\( \tilde{p} \)

\( \tilde{q} \)
Prediction of Oscillation Amplitudes

- Relatively simple model using algebraic equations for time lags, amplitude responses, etc.
- Predicts saturation thermoacoustic amplitudes as a function of design parameters
- Allows sensitivity studies, design guidance, etc.
- Needs to be retuned for each combustor configuration

Experimental results from all other cases

We think we know why these are off

Phase shift between fuel droplet oscillations at dome face and...
Conclusions

- Laser (and other optical) diagnostics allow for high-fidelity data to be obtained regarding complex dynamic processes in practical hardware at realistic conditions
  - Treatment of uncertain data requires careful consideration

- Provides mechanistic understanding that can be used to
  - Directly aid design and operation
  - Develop best practices for simulations