Small Engine / Low Emissions Combustor Design Considerations

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13th Annual Israeli Jet Engine Symposium (AIJES)
Agenda

- Honeywell aero gas turbine product lines
- Environmental regulations
- Small engine challenges for low emissions combustors
- Honeywell’s design approach and development process
- Enablers for developing combustor technology
- Honeywell SABER-1 combustor technologies
- Analytical and Experimental Results
- Go-forward plans
- Summary
Honeywell Turbine Engine Products

**APU**
- 660
- 131 Series
- 36 Series
- 331 Series
- 700 Series
- RE220
- RE100
- APU
  - 100 to 1400 hp for commercial and military aircraft

**Turbofan**
- HTF7000
- 731 Series
- CFE738
- LF507
- F124
- ATF3
- Turbofan Engines
  - 3,000 to 10,000 lb thrust for commercial and military aircraft

**Turboprop**
- TPE331-14
- TPE331-12
- TPE331-10/11
- TPE331-5
- Turboprop Engines
  - 575 to 1,600 shp for commercial and military aircraft

**Turboshaft**
- T55
- T53
- AGT1500
- CTS800
- LTS101
- HTS900
- Turboshaft Engines
  - 500 to 5,000 shp for tanks, commercial and military rotorcraft

**More Than 135,000 Engines Delivered**
Drivers for Low Emissions

• Situation:
  – Pollutants: NOx, CO, UHC and Smoke / nvPM
  – Local air quality and global climate change

• Regulations & Other Drivers:
  – ICAO regulation (LTO cycle)
  – Economic measures (Airport landing charges)
  – Market expectations
More on Emissions Regulations

- **ICAO***
  - Sets standards for aviation emissions
  - Works through CAEP** which meets every 3 years to update standards
  - CAEP has representation from government agencies & industry

- **ICAO regulations**
  - DP/Foo for NOx, CO, UHC
  - Smoke – Filter stain
  - nvPM - Most likely will be decided during CAEP/10 in 2016

\[
\frac{D_p}{F_{\infty}} = \sum_{LTO} t_m \times W_f \times EI
\]

* International Civil Aviation Organization
** Committee on Aviation Environmental Protection

**Emissions Index g /Kg (Pollutant/Fuel)**

**DP/Foo** – Mass of pollutant during LTO cycle / Rated thrust of engine

**LTO Thrust & Time in Mode**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Time</th>
<th>% Rated Thrust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off</td>
<td>0.7</td>
<td>100</td>
</tr>
<tr>
<td>Climb</td>
<td>2.2</td>
<td>85</td>
</tr>
<tr>
<td>Approach</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>Taxi/idle</td>
<td>26</td>
<td>7</td>
</tr>
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Engine Cycle Effects on LTO cycle

- Landing/Take-off (LTO) Emissions Cycle*:

\[ \frac{D_p}{F_\infty} = \sum_{LTO} t_m \times W_f \times EI \]

- Cycle effect focuses only on performance parameters:

\[ \frac{\tilde{W}_f}{F_\infty} = \sum_{LTO} t_m \times W_f \]

**Engine Performance has significant impact on LTO emissions**
**Small Engines have 30% emissions challenge**

The low emissions combustor must satisfy emissions regulations along with the other combustor design requirements.
Requirements & Challenges in Advanced Combustor Development for Small Engines

• High surface area/volume ratio
  – Proportionally more cooling required

• Centrifugal compressor Effects
  – Packaging diffuser discharge with combustor to minimize pressure distribution effects

• Cyclic content
  – More than 1 cycle per hour induces more fatigue and interactions with other modes (creep, oxidation, spallation)
Challenge to Emissions Reduction

- Aero engines have wide range of firing temperatures at the emissions measurement points
- Both NOx and CO are criteria pollutants
  - Inversely correlated with flame temperature
- Implications:
  - Need to reduce coupling between combustor flame temperature from engine firing temperature (staging)
  - Combustor optimization dependent upon engine operating conditions

State-of-the-art combustor technology at 7%, 30%, 85%, 100% rated thrust
Plotted from Engine Emissions Databank
The low emissions primary zone design is realized through some often conflicting design choices.

Trade Challenges with Low NOx Combustor

Trade Considerations
- Reduced PZ aero loading improves ignition & starting
- Reduced PZ airflow reduces PZ aero loading but it may require reduced cooling which reduces combustor life & excessive smoke can result if PZ F/A is too rich
- Increased volume reduces PZ aero loading but also increases NOx

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\[
\phi_{load} = \frac{\text{Wa}_{\text{comb}}}{(\delta_{3.0})^{1.75} \cdot VOL_C \cdot e^{\left(\frac{T_{3.0}+459.67}{540}\right)}}
\]
RQL Technology Focus Areas

1. Improved Mixing for primary zone fuel to air ratio uniformity

2. Lower cooling flux for higher primary zone fuel to air ratio & less CO generation at low power

3. Residence time optimization

4. Quench Zone mixing optimization
Technology Maturation Process

Flight Testing
Method: B757 Flying Test Bed
Purpose: Operability, Handling

Engine Testing
Method: Ground Engine Testing
Purpose: Durability, Emissions, Noise

Annular Rig Test
Method: Testing with Scaled Conditions
Purpose: Test Assessment All Parameters

Sector Rig Test
Method: Sub-element Testing
Purpose: Test Evaluation of Concepts

Analysis
Method: CFD w/ Large-Eddy-Simulation
Purpose: Concept Screening & Evaluation

Technology Readiness Levels (NASA)

TRL 9
TRL 8
TRL 7
TRL 6
TRL 5
TRL 4
TRL 3
TRL 2
TRL 1

System Test & Operations
System/Subsystem Development
Technology Demonstration
Technology Development
Research to Prove Feasibility
Basic Technology Research

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Combustion Design and Analysis Enablers

**Combustor Analysis**

- **CFD Analysis focus:**
  - High-fidelity mesh generation
  - Large Eddy Simulation
  - High-Fidelity Reduced Mechanisms for Jet-A
  - Soot Modeling & Radiation
  - Spray Modeling
  - Conjugate Heat Transfer
  - High Performance Computing

- **Thermo-mechanical Analysis focus:**
  - Combustor materials & coatings Properties & Lifing

**Enablers**

- LES Analysis
- Conformal Mesh w/ BL
- High Performance Compute Cluster
- Partnership with Academia

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Combustion Testing Enablers

**Combustor Testing**

**Leverage Existing facilities:**
- Sector & Annular Rig Testing
- Tech7000 Engine
- B757 Flight testing

**Continue to Develop:**
- Configured Specimen Testing
- Optical access to primary zone
- Fuel Spray Diagnostics
Combustor Technology: Well Coordinated Combustor Development Shop and Production Shop

**Combustor Development Shop**
- Rapid hardware turnaround
- Full manufacturing & repair capability
- Production quality
- Process knowledge transitioned to & from Production Facility

**Production Facility**
- High volume
- Low cost
- Full manufacturing capability
- Process knowledge transitioned to & from Development Shop

Enablers

Combustor performance remains unchanged between facilities
Optical Capability Provides Enhanced Understanding

Atomizer spray @ 25,000 fps

Full power on full annular rig @ 20fps

Post ignition on full annular rig @ 20 fps

LBO on sector rig @ 20fps

Conditions:
~10 Atmospheres
>3000°F
HTF7000 Turbofan Engine Family

**Overall Description:**
- 30.6 kN (6,900 lbs) SL takeoff thrust
- PR@Sea level = 22, BPR = 4.2
- Architecture: 2 spool, 2 fan, 4 axial + centrifugal compressor, 2-stage HP turbine, 3-stage LP turbine

**Aircraft Applications:**
- **HTF7000:** Bombardier Challenger 300, Certified in 2002 with 600 engines w/ 2,000,000 hours; Recertified with SABER-1 combustor in 2010
- **HTF7250G:** Gulfstream G280, Certified in 2013
- **HTF7500E:** Embraer Legacy 450/500, Certified in 2014
- **HTF7350:** Bombardier Challenger 350 - 2014

*Low-Emissions Combustor Technology Initially Focused on HTF7000*
Design Features of SABER-1

- **SABER**
  - Single Annular combustor for Emissions Reduction

- **CLOSE-COUPLED DIFFUSER DESWIRL TO COMBUSTOR HEAD END**

- **FUEL INJECTOR**

- **RICH BURN PRIMARY ZONE (PZ)**

- **QUENCH ZONE (QZ)**

- **LEAN-BURN SECONDARY & DILUTION ZONE**

- **QUENCH JETS**

- **MULTI-HOLE ANGLED (EFFUSION) COOLED LINERS**

- **Dome**
  - Streamwise path of the effusion cooling holes

- **Combustor Exit**

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Temperature Contours are Injector CL

CFD Modeling approach:
- **Geometry**: High-fidelity Annulus + Combustor Model
- **Turbulence**: Large Eddy Simulation
- **Chemistry**: Laminar Flamelet with reduced jet-A mechanism
- **Fuel Spray**: Lagrangian tracking, from experimental data
- **Soot**: Customized formation, coagulation, oxidation model
- **Radiation**: Discrete-Ordinates
Comparison of predicted/measured wall temperatures

- Liner Temperatures predicted using hot-side convective/radiation boundaries*
- Quantitative predictions match well to measured results

SABER-1 Validation & Certification

- Extensive development testing
  - 18 sector rig tests
  - 30 rig tests
  - 2 endurance tests
  - 2 emissions tests
  - 1 noise test
  - 3 flight tests

- Initial certification in 2010:
  - Compatibility, Operability, Durability and Emissions validated

**Significant Emissions Reduction Achieved**

![Emissions Reduction Graph](image)
ICAO LTO Emissions for Small Engines have sensitivity to scale effects

Low emissions combustors require careful balance to satisfy operability and hot section life requirements in addition to emissions regulations

Analytical design, test and fabrication tools enable successful delivery low emissions designs to market

Honeywell has developed SABER Rich-Quench-Lean technology for initial application to the HTF7000 turbofan engine family

Honeywell continues work to further reduce emissions on the SABER family of combustors