Subscale Test Methods for Combustion Devices

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School of Aeronautics and Astronautics
Purdue University
Outline

• Motivation for Scaled Experiments
• Brief Scaling History
  – Steady-State Combustion
  – Combustion Stability
  – Life Prediction
• Scaling Approaches Presently Used at Purdue
Background

- Stated goals for long-life LRE’s have been between 100 and 500 cycles
  - Inherent technical difficulty of accurately defining the transient and steady state thermochemical environments and structural response (strain)
  - Limited statistical basis on failure mechanisms and effects of design and operational variability
  - Very high test costs and budget-driven need to protect test hardware (aversion to test-to-failure)

- Ambitious goals will require development of new databases
  - Advanced materials, e.g., tailored composites with virtually unlimited property variations
  - Innovative functional designs to exploit full capabilities of advanced materials
  - Different cycles/operations

- Subscale testing is one way to address technical and budget challenges
  - Prototype subscale combustors exposed to controlled simulated conditions
  - Complementary to conventional laboratory specimen database development
  - Instrumented with sensors to measure thermostructural response
  - Coupled with analysis
SSME Film Cooling Analysis

• Configuration
  – Propellant = LOX + LH2 with O/F = 6.02
  – M_dot_LOX = 64,000 liter/min
  – M_dot_LH2 = 178,000 liter/min
  – M_dot_coolant for regen cooling = 29.06 lb/sec

• Chamber condition
  – P_c = 3300 psi
  – T_c = 3500 K (5840 F)
  – D_throat = 10.88"
  – E = 77

• Cooling channel
  – Wall thickness = 0.03"
  – Width = 0.04 “
  – Height = 0.12 “
  – Pressure_throat = 3851 psi

• Thermal condition at throat
  – Heat flux = 80 Btu/in^2-s
  – h_g = 58000 W/m^2-K
  – Twg = 1100 F

• Wall adiabatic temperature
  – Taw = Tr - η(Tr-Tco)
    Where Tr = recovery temperature
    η = film cooling efficiency
    Tco = initial coolant temperature

• Current near wall O/F ratio
  – q_dot = h_g(Taw-Twg)
    Where q_dot = 80 Btu/in^2-s
    h_g = 58000 W/m^2-K
    Twg = 1100 F
  – Taw = 3125 K
  – η = 0.5
  – Tco = 2750 K
  – O/F_nw = 3.54 from Flame temperature vs O/F ratio chart

![Cooling Effectiveness](image-url)
SSME Film Cooling Analysis

- Current film cooling condition
  - O/F\textsubscript{nw} = 3.54

- Parametric study with fixed film flow rate (5 %)
  *Porowski et al. method (AIAA Journal Vol. 2 No. 2, 1985)
    - O/F\textsubscript{nw} change = 3.54 → 1.0
    - Life change = 61 → 107 (75.4\% increase)
    - Isp change = 465 → 457 (1.83 \% decrease)
Scaling Objectives and Approaches

• Combustor characterization is goal
  – Validation data for design analysis models
  – Assess innovative functional design, materials, operation
  – Investigations into specific physics
• Single element, multi-element, 40K, 250K
• Cold flow and hot fire
• Performance, heat transfer, life, stability
• Experimental objective needs to define scaling approach and measurement
  – Well-instrumented combustors linked to analysis
  – Thrust level and number of elements
  – Element scaling and configuration
Hierarchy of injector experiments

General trend: an increase in subscale efforts

- Single element atmospheric cold flow
- Single element high pressure cold flow
- Single element hot fire
- Subscale Multi-element hot fire
- Full scale testing
- Full scale testing

AFRL cold flow facility

degree of simulation

difficulty / cost
Brief History of Scaling in the US – Steady State Combustion

- JPL studies of mixing efficiencies of impinging jets
- Bell Aerospace/AFRL holographic and shadowgraphic studies of combusting flows
- Rocketdyne development of LISP methodology for SDER
- Aerometrics development of PDPA
- Rocketdyne studies of flameholding behind LOX post
- PSU measurements of chemical species in HO combustors
- AFRL studies of supercritical jets
Single Element Test Chamber
Stability Scaling

• Simulation of chamber dynamics in subscale configuration is very difficult
  – Acoustic frequencies scale as \( \sim 1/d \)
  – Pressure \( v \) velocity sensitivity

• Scaling approaches
  – Wedges, T-burners, 2-d chambers
  – \( 1T = 3T \) scaling

• Single element rarely used in US, but is more typical in Russia
This facility screened Injector elements for Liq/liq and gas/liq Injectors for over 20 Years (1965-85)

Typical $P_c = 750$ psi, Total flowrate of 5 lb/s

‘self-oscillation’ and response to pulsations measured

Fig. 8  Pneumatic and hydraulic scheme of fire stand
1-piston, 2-measuring vessel, 3-nozzle collector, 4-combustion chamber, 5-pulsator, 6-fuel tank, 7-time delay valve, 8-blow through valve, 9-main bi-propellant valve, 10,11-pressurising gas reducers, 12-oxidizer tank, 13-exhaust tubes, 14-water valve, 15-oxidizer return tank, 16-pressurised water tank, 17-ejector, 18-air compressor
Experimental Approach of NIICHIMMASH

- Use full-scale injector elements
- Experiment designed to simulate controlling process - mixing
- Match equivalence ratio and volumetric flowrates using diluted gaseous propellants
- Combustor acoustics matched by using appropriately sized low-pressure chamber
- Stability boundaries determined by varying flowrates
- Relative boundaries indicate stability ranking

Figure 6. Schematic of Single Element Model Set-up and Instrumentation
Propellant Distribution Effects

Figure 7.2.5a.—Injection radial profile comparison.

Table 7.2.5a.—Gas Rocket Test History With Various Injection Profiles

[Instabilities initiated spontaneously and linearly; mean chamber pressure, 150 psia; combustion chamber diameter, 7 in.; combustion chamber length, 6 in.]

<table>
<thead>
<tr>
<th>Profile</th>
<th>Amplitude, psi</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>7</td>
<td>1st tangential</td>
</tr>
<tr>
<td>II</td>
<td>0</td>
<td>Stable</td>
</tr>
<tr>
<td>III</td>
<td>11</td>
<td>1st tangential</td>
</tr>
<tr>
<td>IV</td>
<td>13</td>
<td>1st radial</td>
</tr>
<tr>
<td>V</td>
<td>0</td>
<td>Stable</td>
</tr>
<tr>
<td>VI</td>
<td>40</td>
<td>1st tangential</td>
</tr>
</tbody>
</table>
Single Element ‘Instability’

Impinging jets driven by piezoelectric actuator

Combustor oscillations at driven atomization frequency
Subscale Test Activities at Purdue - Maurice Zucrow Laboratory
Advanced Propellants and Combustion Lab

- Two cells w/ 1 Klbf thrust stands
- Propellant supply of 1800 psia
- 2 - 4 gallon oxidizer tanks
- 1 & 4 gallon fuel tanks
- National Instruments hardware & LabView software
  - 32 channels pressure
  - 32 channels temperature
- All valves computer controlled
- Rapid test article installation
- Design/Build/Test course
High Pressure Lab

Renovation funded thru Indiana 21st Century R & T Fund – Propulsion and Power Center of Excellence
Facility activated in May ‘03
6,000 psi Nitrogen System

- Pressurization, Actuation and Purge Gas
- 2,400 gallon Liquid Nitrogen Tank w/ 6,000 psi Pump
- 253 ft³ 6,000 psi Nitrogen Tube Trailer
- Computer Controlled Pressurization Systems
Propellant/Coolant Tanks

- 22 gal 5,000 psi LOx
- 16 gal 5,000 psi Fuel
- 220 gal 5,000 psi H₂O
- 400 gal 800 psi H₂O₂
- Hydraulic Control Valves
10,000 lbf Thrust Test Cell

- LabView 6.1-based DACS
- 10,000 lbf thrust measurement
- 64 channels pressure
- 96 channels thermocouples
- 18 channels analog control
- 32 channels on/off control
Control System Operation

- Data System Located Adjacent to Test Cell
- Operation Remoted to Control Room (KVM Extender) for Testing
- Video Recorded Directly to DVD
Test Cells

- 18" Thick Reinforced Concrete Test Cell Walls
- High Flow Capacity Test Cell Exhaust Fans
- Heated High Pressure Air Plumbed to Both Cells
- Walled Containment Area
Injector Characterization Scaling Approach

• Study Objectives
  – Steady state and dynamic characterization of ORSC MC injector elements

• Approach
  – Investigate full-scale elements at realistic operating conditions
  – No film cooling (if possible)
  – Evaluate different injector design configurations
  – Couple with analysis

• Measurements
  – Energy release profile from axial pressure gradient
  – Injector face and chamber wall thermal environments
  – Plume signature with IR tomography
  – Manifold, injector and chamber p’
ORSC Main Combustor Components

271 elements, 1722 lbf each, d = 0.5 in
Principle Design Features

- Gasflow inlet lip to affect acoustic admittance
- Ox tube length set to tune injector acoustics
- Swirl injectors isolated from gas path
- Two rows of inlets provides wave cancellations
- Beveled recess to provide injector face cooling
- Atomization due to Kelvin-Helmholtz instability
- Two-phase region enhances impedance
- Liquid submergence to enhance mixing, control face heating & promote stability
Single Element Sizing Exercise

Approach

- use full scale F/element (1722 lb_{f_{vac}})
  - mox = 3.6 lb/s, mf = 1.2 lb/s
- test at ‘full’ Pc (2250 psia)
  - At = 0.39 in^2, dt = 0.70 in
- match injection pressure drops (10%)
  - dinj, ox = 0.43 in, dinj = 0.57 in

Possible scaling methods:
- Contraction ratio (1.61) \( dc = 0.89 \) in
- Element to chamber area ratio (0.30) \( dc = 1.04 \) in
- Element-element spacing (0.60d) \( dc = 0.91 \) in
- Element-wall spacing (0.60d ?) \( dc = 0.91 \) in
- Element area (0.65 in^2) \( dc = 0.91 \) in
- Chamber length based on \( L^* \sim 30 \) in (?)
Baseline Injector Design

- Mating Flange
- Sensor Ring
- Insert
- Ox Rich Gas
- Fuel Manifold
- Inlet
- P' Measurement
- Injector Face
- RP-I Inlet
High-Pressure Chamber

- Mating Flange
- Igniter Section
- Gun-Drilled Chamber Sections
- Dump-Cooled Throat Section
- Injector Assembly
- Calorimeter Sections
- Nozzle Jacket
- Nozzle Liner
- Igniter Assembly
- Gun-Drilled Chamber Sections
- Calorimeter Sections
- Flanges
- Igniter Section
- Nozzle Jacket
- Igniter Liner
- Igniter
- Gun-Drilled Chamber Sections

Dimensions:
- Ø 0.81
- Ø 1.60
- Ø 1.00
- 16.13
- 6.00
Life Prediction - Background

- Rocket combustor liner such as SSME operated at high temperature (6000°F) and pressure (3000 psi) ranges as well as extreme heat flux (80 Btu/in²-s) requires active cooling devices to prevent material failure.
- Combustor liner experiences high thermal structural stress (~100 MPa) during mission profile (SSME 8 min)
- Experiments by Quentmeyer and Jankovsky showed bulging and thinning of liner due to cyclic loading
- Kasper and Porowski developed analytical life prediction methods using simple fatigue and creep model
- Robinson, Arnold and Freed developed visco-plastic model for fatigue-creep interaction phenomena which is believed to be a main failure mechanism

Typical failure mode of combustor liner at throat so called “dog house effect” per Quentmeyer
Full Scale – Subscale Life Comparison
– \( P_c = 3300 \) psi, \( T_c = 3500 \) K

<table>
<thead>
<tr>
<th>Scale</th>
<th>Strain_max</th>
<th>Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full scale engine</td>
<td>2.4</td>
<td>120</td>
</tr>
<tr>
<td>1/10 scale model</td>
<td>3.94</td>
<td>48</td>
</tr>
</tbody>
</table>
Approach

- Develop DBT course with life prediction as part of AAE curriculum
- Develop design requirements
  - Controlled hot-gas environments – use ‘pre-combustor’
  - Creep-fatigue interaction failure of cooled liner
  - Failure within reasonable number of cycles
- Life prediction analysis using conventional methods
  - Chemical equilibrium in pre-combustor
  - One-dimensional heat transfer analysis for initial design
    - critical heat flux and cooling requirements, duty cycle
  - FEM for stress and plastic strain
  - Strain-life curves for cycle life
  - More advanced life modeling by graduate student following project
- Cyclic testing of test article
  - Ten cycles per test
  - Validation of cooling analysis
  - Regular inspection
- Test-to-failure
Combustor Design Parameters

• Top level requirements
  – Less than 200 life cycle
  – Test should produce verifiable results
  – Liner has no melting prior to the LCF failure
  – All parts had to be manufactured in ASL at Purdue

• Under these requirements, the coolant pressure, flow rate and cooling channel aspect ratio (0.5) were determined.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>90% H₂O₂ + JP-8</td>
</tr>
<tr>
<td>Propellant mixture ratio (O/F)</td>
<td>4.0</td>
</tr>
<tr>
<td>Propellant flow rate</td>
<td>1.25 lb/s</td>
</tr>
<tr>
<td>Chamber pressure (Pₖ)</td>
<td>200 psia</td>
</tr>
<tr>
<td>Chamber temperature (Tₑ)</td>
<td>3440 °F</td>
</tr>
<tr>
<td>Characteristic velocity (C*)</td>
<td>4961 ft/s</td>
</tr>
<tr>
<td>Throat area (Aₜ)</td>
<td>0.915 in²</td>
</tr>
<tr>
<td>Characteristic length (L*)</td>
<td>70</td>
</tr>
<tr>
<td>Test liner diameter</td>
<td>2.0 in</td>
</tr>
<tr>
<td>Test liner length</td>
<td>5.0 in</td>
</tr>
<tr>
<td>No. of cooling channel</td>
<td>30</td>
</tr>
<tr>
<td>P_{coolant}</td>
<td>110 psi</td>
</tr>
<tr>
<td>M_{dot_{coolant}}</td>
<td>0.8 lb/s</td>
</tr>
</tbody>
</table>

Table 1: Combustor design parameters
Thermal Structural Prediction

Thermal analysis
- Burn out heat flux --- 6.54 Btu/in²
- Max wall temp --- 670 K

Total strain predicted by ANSYS around rectangular cooling channel.
- Total strain --- 2.0 %
- Life expected --- 115 cycles

Strain-life curve for OFHC at 810 K from NASA CR-134806, 1975
Test Article

- Catalyst bed for decomposing H$_2$O$_2$
- Heat sink dump combustor for hot gas generation
- Chamber liner --- water cooling
- Center body --- water cooling with TBC (0.01” thick)
Testing

- Tests were conducted in the APCL at Purdue University
- Propellant flow timing sequence was automatically controlled by pneumatically actuated valve with LABVIEW system

Test article assembly on test stand

Cyclic test
Test Results

- Chamber pressure, C* efficiency, propellant mass flow rate, coolant temperature and pressure were measured and calculated.
- Data reduction was performed using in-house code written by students using MATLAB.
- Validation procedure:
  - Measure coolant ΔT, wall thinning rate
    - 2.15E-5 in/cycle (0.032”→0.029”)
  - Verify 1D thermal model
  - Compute updated thermo-structural environment
  - Make life prediction

Predicted and measured coolant temperature
ΔT = 4.0K at throat

Discoloration and deformation at 90 cycles (1.5”×0.6”)

![Tw_pred & Tw_corr](chart.png)
Updated Structural Analysis

- Simulation of temperature, strain and deformation (bulging, thinning) using ABAQUS explicit module
- Maximum strain: 1.2% at middle of ligament
- Only bulging of ligament was simulated

Plastic strain distribution

Deformation after 60 cycle

Deformation after 80 cycle

Deformation after 100 cycle
Summary and Conclusions

- Small-scale rocket combustor was designed and tested to verify life prediction models for low cycle fatigue and fatigue-creep interaction.
- Several life prediction methods were applied to predict combustor life and were compared with test results.
- Correlation data used to improve predictions.
- Improvements would include fixing the liner lands to the structural jacket, and testing at more severe conditions.

<table>
<thead>
<tr>
<th>Prediction method</th>
<th>Estimated life cycle</th>
<th>Determined life cycle by experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective stress-strain</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>ANSYS</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>Porowski</td>
<td>51</td>
<td>270</td>
</tr>
<tr>
<td>Dai and Ray with Freed model</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>ABAQUS</td>
<td>320</td>
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</tr>
</tbody>
</table>

Comparison of life prediction with test
Summary and Conclusions

• 100’s of cycle goal is very challenging and verification would be very expensive
  – Question of economic feasibility

• Improved life prediction methodology for expanding range of design and operational scenarios is needed
  – Probabilistic life prediction design analysis
  – Testing methodologies with *in situ* thermostructural response measurements
  – Environments definition
  – Improved material database and understanding of damage mechanisms
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