AFOSR – THEORETICAL, NUMERICAL, AND EXPERIMENTAL INVESTIGATIONS OF THE FUNDAMENTAL PROCESSES THAT DRIVE COMBUSTION INSTABILITIES IN LIQUID ROCKET ENGINES

Program Update

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September 13th, 2012
Report Documentation Page

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE
   13 SEP 2012

2. REPORT TYPE

3. DATES COVERED
   00-00-2012 to 00-00-2012

4. TITLE AND SUBTITLE
   Program Update

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
   Georgia Institute of Technology, Guggenheim School of Aerospace Engineering, Atlanta, GA, 30332

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
   Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
   Presented at the 2012 AFOSR Space Propulsion and Power Program Review held 10-13 September in Arlington, VA. U.S. Government or Federal Rights License

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:
   a. REPORT
      unclassified
   b. ABSTRACT
      unclassified
   c. THIS PAGE
      unclassified

17. LIMITATION OF ABSTRACT
   Same as Report (SAR)

18. NUMBER OF PAGES
   11

19a. NAME OF RESPONSIBLE PERSON

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18
The Actively Controlled LRE Simulator (ACLRES) Concept

- Testing full scale cylindrical or two dimensional LRE is very costly
- The acoustic environment within any section of a full scale LRE is controlled by the acoustic impedances on its boundaries
- For simplicity, the proposed small scale rig concept is being demonstrated on a 2-D rig that can also experience transverse instabilities
- The boundary impedances in the small scale rig are actively controlled by speakers
Actively controlled LRE Simulator (ACLRES)

- Active control of boundary impedance capabilities
- Excites transverse acoustics (instabilities)
- Has access for optical diagnostics
- Injector plate may be interchanged to allow investigation of the driving by different injection systems
Development of the ACLRES Active Control System

• The ACLRES system

• Acoustic model

\[ u_D(t) = \frac{i [p_2(t) - p_1(t + \tau)] \sin(\omega \tau) e^{ikx_1}}{\rho c [1 - \cos(2\omega \tau)]} \left[ e^{-ikx_d} - e^{ik(x_d - 2L_2)} \frac{Z_{L_2} - 1}{Z_{L_2} + 1} \right] \]

• Speaker model (transfer function)

\[ I(t) = u_d(t) \left[ \frac{i \omega m + \frac{\kappa}{i \omega} + \nu + \frac{(N \pi dB)^2}{Z_{el}} + Z_{Md}}{G_{amp} N \pi dB} \right] \]
Preliminary Results

• The “Full scale” LRE tested to identify its instabilities (~170 Hz)
• Investigated the acoustics of the ACLRES rig (~250 Hz)
• The ACLRES (using one injector and combustion) was actively controlled to excite full scale LRE instabilities in the rig
• The “full scale” engine instabilities and the ACLRES natural acoustic modes were excited in the first test
  – Need to “remove” the ACLRES natural modes in future tests
• Modeling efforts show the mean flow controls the spinning instability
Interest and Governing Physics

Explore role of stability of nozzle-generated triple flame on LRE combustion instability

- **Stabilization through premixed flame segment =>**
  - Chemistry inherently important
  - Prone to exhibit flamefront instability

- **Bulk flame is still diffusion controlled**
  - Source of heat release
  - Also prone to flamefront instability
  - Couples to chamber acoustics

9/13/2012
Various Intrinsic and Acoustic Flamefront Instability Modes

<table>
<thead>
<tr>
<th>Instability Mode</th>
<th>Premixed Flame</th>
<th>Diffusion Flame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh-Taylor (RT)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Diffusional-thermal (DT)</td>
<td>Pervasive, ↓ as p ↑</td>
<td>Near-limit situations</td>
</tr>
<tr>
<td>Darrieus-Landau (DL)</td>
<td>↑ as p ↑ and δ ↓</td>
<td>No</td>
</tr>
<tr>
<td>Kelvin-Helmholtz (KH)</td>
<td>?</td>
<td>Yes</td>
</tr>
<tr>
<td>Acoustical / Parametric</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Instability Modes Analyzed

- Nonpremixed flame segment
  - Rayleigh-Taylor, Kelvin-Helmholtz

- Acoustic-flame interaction
  - Resonantly stabilizing but parametrically destabilizing

- Stability domains
  - Landau limit
  - Finite flame thickness
High-Fidelity Modeling and Simulation of Liquid-Propellant Combustion at Supercritical Conditions

• **Objective of Research:** To develop an integrated theoretical and computational framework for treating combustion dynamics of cryogenic and hydrocarbon propellants under conditions representative of contemporary liquid rocket engines.

• **State of the Art of Research:** Limited research on high-fidelity modeling and simulation of (1). turbulence-chemistry interactions at supercritical conditions; (2). supercritical combustion of hydrocarbon propellants (some progress made for cryogenic propellants); (3). swirl injector flow dynamics (only classic theories available); (4). liquid-liquid injector flame dynamics; (5). injector flow response to external forcing.

• **Advancements of Current Research:** (1). Establishment of a unified theoretical-numerical framework for treating supercritical combustion over entire fluid thermodynamic states; (2). study of swirl injector flow dynamics at supercritical conditions; (3). study of swirl injector combustion of hydrocarbons; (4). study of swirl injector flow response to acoustic excitations.
Research is currently undergoing to establish this correction.

**ACCOMPLISHMENT 1**

(1) high-fidelity, quantitative knowledge of liquid propellant combustion dynamics at practical engine operating conditions; (2) identification of key design attributes and flow conditions dictating injector behaviors; (3) reduced-base modeling for data presentation and knowledge synthesis.
ACCOMPLISHMENT 2

Identification of key injector design attributes and flow conditions for engine performance improvement and combustion instability mitigation

Snapshots of temperature, and mass fractions of H2 and OH of GO2/GH2 shear co-axial injector flames

LES techniques developed to address critical development issues of liquid rocket combustion devices

- injector dynamics
- chamber cooling
- wall compatibility
- combustion instability

Instantaneous temperature and density contours of LOX/kerosene double swirl injector flame