The Effects of Pressure and an Acoustic Field on a Cryogenic Coaxial Jet

Dustin Davis
Bruce Chehroudi
Doug Talley
1. REPORT DATE 22 JUN 2004
2. REPORT TYPE N/A
3. DATES COVERED -

4. TITLE AND SUBTITLE
The Effects of Pressure and an Acoustic Field on a Cryogenic Coaxial Jet

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER
5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

6. AUTHOR(S)
ERC Inc.; The Pennsylvania State University University Park, Pennsylvania 16802, U.S.A.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
ERC Inc.; The Pennsylvania State University University Park, Pennsylvania 16802, U.S.A.

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

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

<table>
<thead>
<tr>
<th>a. REPORT</th>
<th>b. ABSTRACT</th>
<th>c. THIS PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>unclassified</td>
<td>unclassified</td>
<td>unclassified</td>
</tr>
</tbody>
</table>

17. LIMITATION OF ABSTRACT
UU

18. NUMBER OF PAGES
22

19a. NAME OF RESPONSIBLE PERSON

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18
Effect of Pressure and Acoustic Field on a Cryogenic Coaxial Jet

• **Objectives:**
  – Document the nature of the acoustic wave/coaxial-jet injector interaction
  – Map a range of input variables
  – Explore application of the data and the findings for rocket combustion instability

• **Motivation:**
  – Combustion instability has always been one of the most complex phenomena in liquid rocket engines
  – High amplitude and high frequency acoustic instabilities (screaming), can lead to local burnout of the combustion chamber walls and injector plates

• **Approach:**
  – Using the AFRL supercritical facility
    • Span sub and supercritical pressures
    • Cryogenic temperatures
    • Acoustic Field
  – A coaxial injector design based on the single-jet cryogenic injector used in all previous studies (well characterized)
  – A specially-designed acoustic driver
  – Single-shot shadowgraph
High-Pressure Test Rig

Housing for the PiezoSiren and the Waveguide flanged to the high-pressure chamber

LN2 Cooling Tower

Pressure transducer traversing micrometer
Available Data

• Fluids:
  – Warm Gas-Like N\textsubscript{2} flow in the annulus of coaxial injector
  – Cold Liquid-Like N\textsubscript{2} flow in the center post of coaxial injector
  – Ambient temperature Gas-Like N\textsubscript{2} pressurizing the chamber

• Operational Conditions:
  – 4 Chamber Pressure 1.4, 2.4, 3.5, 4.8 MPa
  – 3 Central jet (“oxidizer”) flow rates ~275, 450, 625 mg/s
  – 5 Annular jet (“fuel”) flow rates 0, 480, 1300, 2200, 2800 mg/s
  – Acoustic field off and on at 2700 Hz

• Data:
  – 10 Backlit images at each flow rate and pressure
  – More than 1400 images total
  – Exit plane temperature measurements
SUBcritical Chamber Pressure

Acoustic OFF

Acoustic ON

Increasing Annular Flow Rate

Center flow ~ 275mg/s; Chamber Pressure 1.4 MPa
NEAR-Critical Chamber Pressure

Acoustic OFF

Acoustic ON

Increasing Annular Flow Rate

Center flow ~ 275mg/s; Chamber Pressure 3.5 MPa
SUPERcritical Chamber Pressure

Acoustic OFF

Acoustic ON

Increasing Annular Flow Rate

Center flow ~ 275mg/s; Chamber Pressure 4.8 MPa
Acoustic Effect Rating

Acoustic Rating “0”
- Pch ~ 3.5MPa
- $\dot{m}_{fuel} = 2255 \text{ mg/s}$

Acoustic Rating “1”
- Pch ~ 4.8MPa
- $\dot{m}_{fuel} = 486 \text{ mg/s}$

Acoustic Rating “2”
- Pch ~ 1.4MPa
- $\dot{m}_{fuel} = 1355 \text{ mg/s}$
Acoustic Effect

N₂ Pᵉ = 3.4MPa

Mass Flow Ratio
"Fuel" / "Oxidizer"
Rocket Combustion Stability Data

Stable

Unstable

Center Jet Exit Temperature

"Oxidizer" mass flow rate ~ 275mg/s

"Fuel" mass flow rate / max("Fuel" mass flow rate)
Annular Flow Temperature

"Oxidizer" mass flow rate ~ 275 mg/s

"Fuel" mass flow rate / max("Fuel" mass flow rate)

P = 1.4 MPa
P = 2.4 MPa
P = 3.5 MPa
P = 4.8 MPa
• The size of the thermocouple bead is about the same size as the gap width and center jet diameter

• Thermocouple probably touching the wall of the injector tube
Center Jet
Temperature Corrections

• Corrections to the subcritical pressures necessary to make the results physical
  – Given mass flow rates of fuel and oxidizer and chamber pressure the predicted center jet “oxidizer” temperature produced a vapor pressure that was greater than chamber pressure.
  – Implied a vapor phase condition of the center jet, image data showed liquid phase to be present.

• Attempted corrections using a commercial CFD code
  – Limited by equation of state and transport properties

• Turbulent Pipe Flow
  – Assumed TC measured bulk mix mean temperature and computed centerline temperature
  – Average correction about 7K lower
  – Gave physically meaningful densities to most subcritical conditions
Velocity Ratio

- Velocity Ratio
- Chamber Pressure (MPa)

- Uncorrected "Oxidizer" Temperature
- Corrected "Oxidizer" Temperature
- N2 Critical Pressure

"Fuel" to "Oxidizer" Velocity Ratio

Chamber Pressure (MPa)
Velocity Ratio

- Uncorrected "Oxidizer" Temperature
- Corrected "Oxidizer" Temperature
- N2 Critical Pressure

Chamber Pressure (MPa)

"Fuel" to "Oxidizer" Velocity Ratio
Comparison to Rocket Combustion Stability Data

Momentum Ratio vs. Acoustic Impedance Ratio

1.4MPa
4.8MPa
3.5MPa
2.4MPa

Acoustic Effect "0"
Acoustic Effect "1"
Acoustic Effect "2"
Future and Ongoing Work

• Make improvements to the temperature measurements
  – Improved Correction
  – Different technique to make measurement
  – CFD

• Further analyze the available image data
  – Complete measurements
  – Further inspection of the images for effect of acoustic field interaction

• Conduct experiments using He as the fuel simulant
• Implicate findings to rocket combustion instability
• Collect data different frequencies of the acoustic field
• Make measurements with Laser Induced Thermo Acoustic (LITA)
Summary and Conclusions

• Unique setup enables conditions as close to the real rocket engine without combustion as possible

• Preliminary analysis of the data show global effects of acoustic field more noticeable at subcritical pressures compared to supercritical pressures
  — With exceptions
• Absolute magnitude of temperature measurements at the exit of the injector are not known with great accuracy yet, but the trends can be considered valid

• Possibly a better way to separate the stability of real rocket engines is to plot the data with a fluid mechanics parameter and an acoustic parameter, which remains to be verified
Acknowledgements

• Mike Griggs, Technician

• Work supported by Air Force Office of Scientific Research, Mitant Birkan Program Manager