Space Launch System Base Heating Test: Sub-Scale Rocket Engine/Motor Design, Development & Performance Analysis

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Outline

♦ Test Program Background & Motivation

♦ ATA-002 Core-Stage Rocket Engine Module (CS-REM)
  • Design, Development & Performance Analysis

♦ ATA-002 Booster Stage Solid Rocket Motor (BSRM)
  • Design, Development & Performance Analysis

♦ CS-REM & BSRM Integrated Test

♦ Conclusions
ATA-002 Technical Team

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Space Launch System (SLS) Architecture

**RS-25 Engines**: LOX/LH2
**SRB**: ACP/16% Al loading
Total Vac Thrust ~8 million lbf

- **Launch Abort System**
- **Orion**
- **Interim Cryogenic Propulsion Stage (ICPS)**
- **Interstage**
- **Core Stage**
- **Cargo Fairing**
- **Upper Stage With J-2X Engines**
- **2 Solid or Liquid Rocket Boosters**
- **2 Solid Rocket Boosters (SRBs)**
- **4 RS-25 Engines**

**2017 EM-1**
Motivation for Ground Tests

♦ Six hot rocket plumes expanding and interacting near the vehicle base
  • Potential to generate high thermal environments within base and nozzles

♦ Base flows demonstrate complex flow physics
  • No pure analytical methods have been developed for adequate prediction

♦ New base geometry and performance requirements for SLS
  • Cannot blindly use heritage data

♦ CFD and semi-empirical methodologies show poor comparisons
  • Significant deviations in magnitude and trends

♦ Accurate base flow environment prediction needed to efficiently size TPS
  • Decreases vehicle cost and improves crew safety
Limited numerical and analytical studies have been conducted to fully characterize multi-plume base heating.

For the following reasons:
1. Complex
2. Unsteady
3. Many interacting flow features
4. Leads to many different trends, distributions and deltas

Base Flow Regimes:

**Aspirating** – Freestream air is entrained by the non-interacting rocket plumes (cooling)

**Transitional** – slight interactions by adjacent plumes leads to updraft plume component and downward aspirating jet

**Recirculating** – large interactions by highly expansive plumes leads to predominantly an updraft plume (heating)
ATA-002 SLS Pathfinder Test Program

♦ ATA-002 Base Heating Test Program is broken down into two sub-test programs: (1) Pathfinder and (2) Main Base Heating Test

♦ Goal is to develop sub-scale SLS propulsion systems similar to full-scale flight system to be used for short-duration (~100 msec) base heating tests.

♦ The Pathfinder Program has many difficult challenges:
  • Highly complex test program (simulate solid & liquid propulsion systems)
  • Short-duration testing
  • Different configuration/performance than Shuttle Base Heating Models
  • Not attempted in 40 years
  • Limited heritage technical resources (engineers/technicians/components)
  • Limited funding & short schedule as compared to heritage test programs

♦ Pathfinder Test Program is the main focus of this paper
Main Goal: To measure base flow and heating characteristics for the SLS1000x vehicle and to scale these measurements for flight predictions

Test Requirements
- 2% SLS-1000x Model
- Test in short-duration test facility – CUBRC LENS II
- Simulated altitude: 45 kft to 200 kft, Mach 2.5 to 5.5
- Configuration: full-stack and core-only stage space flight conditions
- Test Duration: ~100 msec steady-state time window
- No gimbaling of engines/motors
- No Angle of Attack
- Test Engine-Out Case
- 200 measurements within base and external nozzles
CUBRC LENS Shock Tunnels

LENS I $M=7-24$

LENS II $M=2.5-10$
(including Ludwieg Mode)

48-inch Tunnel $M=8-20$
[Low Density]

LENS XX
Velocity
2,500-12,000 km/sec

LENS II test run times:
200 msec – 30 msec
Rocket Combustion Chamber Failure During Ignition Start

Rocket Combustion Chamber Failure During Ignition Start

ROCKET SCIENCE IS HARD

H2-F2 5000 lbf Engine Injector Failure
ATA-002 Core-Stage (CS) Rocket Engine Module (REM) Design

- Initial design based on in-house engineering codes and assessment:
  - QICE – engine component sizing/design & performance
  - IBFF – state parameter time history prediction code of the model performance
  - Valve-venturi design & performance code
  - Heritage design comparisons

- Final design based on in-house CFD internal flow modeling of propulsion system:
  - Combustion Instability Assessment
  - CUBRC developed CAD geometry
  - Loci-CHEM – CFD Code with finite-rate chemistry
  - Led to re-design of GO2 manifold system and combustor
  - Provided performance curves

- Final design based on thermal modeling
  - Patran/Sinda G – Led to nozzle material and coating selection

- Developed nozzle specific enthalpy flow code
  - Determines the nozzle exit specific enthalpy profile, the required test duration and material selection

- Loads FEA

- Extensive design & analysis efforts were done to minimize cost and schedule risks.

Internal engine instrumentation installed by CUBRC to determine performance and validation of design methodology
♦ All performance parameters:
  • Have met design requirements
  • Show good agreement with EV33 prediction and design tools
  • Show similarity to full-scale RS-25D engine system

♦ All engine pressure measurements obtained by PCB-111 quartz gauge
CS-REM Plume

- MSFC camera provided high-resolution (1280 px x 800 px) and high frame-rate (16000 Hz) visible (VIS) video of CS-REM hot-fire tests
- MSFC infra-red (IR) camera provided long-wave IR video of CS-REM hot-fire tests
- Able to adequately determine the shock structure and flow physics

SSME VIS video taken during static sea-level testing at NASA Stennis Space Center
CS-REM Plume Analysis

♦ CS-REM plumes:
  - Are over-expanded at sea-level conditions
  - Free-jet boundary converge toward the centerline
  - Develops a characteristic Mach disc
  - No plume-plume interactions observed

♦ CS-REM shock structure and flow physics show good similarity with full-scale RS-25D (SSME) systems.
  - Important to obtain high-fidelity base heating data

♦ Zone of silence normalized distance increases linearly with chamber pressure.
ATA-002 Booster Solid Rocket Motor (BSRM) Design

- Initial design based on in-house engineering codes:
  - Conservation of mass sizing/design & performance code
  - Heritage design comparisons

- Final design based on thermal modeling
  - Patran/Sinda G – Led to nozzle material and coating selection

- Developed nozzle specific enthalpy flow code
  - Determines the nozzle exit specific enthalpy profile, the required test duration and material selection

- Initial design did not meet performance requirements due to significant ignition delay
  - Required trial-and-error igniter options to obtain desired ignition response time

- CUBRC with NASA MSFC collaboration developed an innovative igniter to meet design requirements

Internal engine instrumentation installed by CUBRC to determine performance and validation of design methodology
ATA-002 BSRM Performance Analysis

Model Results

CERAMIC COATED NOZZLE

Model Solution

Test Data

SRM Run 006

PROPELLANT X

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Integrated Core/Booster Stage Propulsion
Integrated Core/Booster Stage Hot-Fire Test
Integrated Core/Booster Stage Rocket Plumes

- CUBRC VIS camera 4700 fps at 800 px x 600 px resolution
- VIS and LW-IR videos show CS-REM and BSRM plumes all-firing together as designed.
- All CS-REM plume Mach discs are within the same location and have the same diameter
- Plumes are fully-developed and steady in less than 35 msec
- Plume diameters are similar between the left and right BSRMs
- No flow asymmetry observed
- Showed propulsion designs are successful.
Conclusions

♦ ATA-002 Technical Team has successfully designed, developed, tested and assessed the SLS Pathfinder propulsion systems for the Main Base Heating Test Program.

♦ Major Outcomes of the Pathfinder Test Program:
  • Reach 90% of full-scale chamber pressure
  • Achieved all engine/motor design parameter requirements
  • Reach steady plume flow behavior in less than 35 msec
  • Steady chamber pressure for 60 to 100 msec during engine/motor operation
  • Similar model engine/motor performance to full-scale SLS system
  • Mitigated nozzle throat and combustor thermal erosion
  • Test data shows good agreement with numerical prediction codes

♦ Next phase of the ATA-002 Test Program
  • Design & development of the SLS OML for the Main Base Heating Test
  • Tweak BSRM design to optimize performance
  • Tweak CS-REM design to increase robustness

♦ MSFC Aerosciences and CUBRC have the capability to develop sub-scale propulsion systems to meet desired performance requirements for short-duration testing.
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Detail information on propulsion design, fabrication, test and performance analysis will be published as a NASA Technical Memorandum.
Thank You

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