Experimental and Modeling Studies of Liquid Hydrocarbon Rocket Injectors: Status and Future Research Directions

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OUTLINE

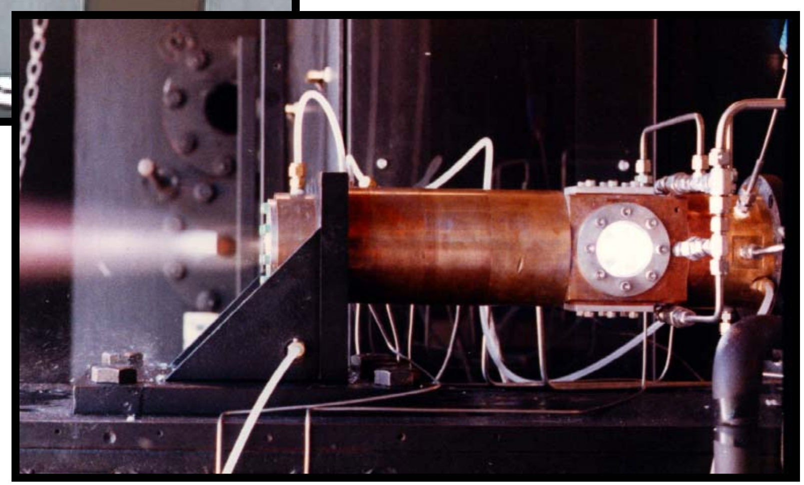
- **Cryogenic Combustion Laboratory (CCL)**
- **Uni-element bi-propellant rocket experiments**
  - **Liquid hydrocarbon (LHC; *methanol, ethanol, RP-1, JP-7*)/ oxygen (GO_2, LO_2) injector designs**
    - ***impinging***
    - ***bi-centrifugal swirl***
    - ***pintle***
  - **Operating conditions**
    - ***near-stoichiometric, fuel-rich, oxidizer-rich***
    - ***sub-critical, super-critical pressures (for LHC)***
  - **Diagnostics**
    - ***performance (c*)***
    - ***shadowgraph imaging, laser light scattering***
    - ***phase Doppler interferometry (PDI), CH emission***

OUTLINE (*continued*)

- **Uni-element tri-propellant rocket experiments**
  - **GO_2/RP-1/GH_2 injector designs (coaxial-type, effervescent)**
  - **near-stoichiometric, super-critical conditions (RP-1)**
  - **performance (c*), laser light scattering, phase Doppler interferometry**
- **Sub-/super-critical LHC jet experiments**
  - **detailed jet breakup at sub- and super-critical pressure and temperature conditions**
  - **shadowgraph imaging**
- **Experimental challenges**
  - **experimental complexities**
  - **diagnostic limitations**
- **Modeling studies**
  - **CFD model development for gas/gas propellants based on extensive data base**
  - **limited studies to date for liquid hydrocarbons**
- **Current/future work**

CRYOGENIC COMBUSTION LABORATORY (CCL)

ROCKET TESTBED



CCL FLOWRATE CAPABILITIES

Propellant	Maximum Flowrate (lbm/s)
Liquid Oxygen (LO_2)	1.0
Gaseous Oxygen (GO_2)	1.0
Gaseous Hydrogen (GH_2)	0.25
Liquid Hydrocarbon (Methanol, RP-1, etc.)	0.5
Air	5 (can be upgraded to 16)

MAXIMUM CHAMBER PRESSURE OF 1400 psia

DIAGNOSTICS EMPLOYED AT CCL

System	Measurement	Demonstrated For
2 component PDPA system	drop size and velocity	measuring LO_2, methanol and RP-1 drops under hot-fire conditions.
2-component LDV system	2 -component velocity	characterizing velocity field for GO_2/GH_2 combusting flowfield for shear coaxial element.
Raman system (Nd:Yag laser/Flash pumped dye laser + ICCD camera)	species measurements	measuring H_2, O_2 and H_2O species for various injectors (GO_2/GH_2 propellants) at pressures up to 1000 psia.
Planar Laser Induced Fluorescence System (Nd: Yag laser + Dye laser + frequency doubler + ICCD camera)	OH- radical measurements	marking combustion zone for shear layers.
Laser Induced Incandescence	soot	soot concentration measurements in hydrocarbon fuel flames at pressures up to 150 psia.
High speed cinematography	dynamic event capture @ 8000 fps	atomization and combustion phenomena.
Schlieren photography	density gradient visualization	reacting shear layer, two-phase flow injection, super-critical injection.

ROCKET INJECTOR DESIGN

Application Defines Propellants/Injector Design

PROPELLANTS
- LO_2/GH_2
- GO_2/GH_2
- LO_2/Ethanol
- GO_2/RP-1
- LO_2/RP-1
- LO_2/H_2O_2

LO_2/GH_2
- SSME
- X-33
- LO_2 Rich Preburner

LO_2/H_2O_2
- Upper Stage Engine

LO_2/RP-1
- X-34
- RS-84

GO_2/RP-1
- RS-84

GO_2/GH_2
- Full Flow Engine Cycle
- RBCC Rocket

LO_2/Ethanol
- OMS
- RCS

UNI-ELEMENT BI-PROPELLANT EXPERIMENTS

Near Stoichiometric Uni-Element Operation

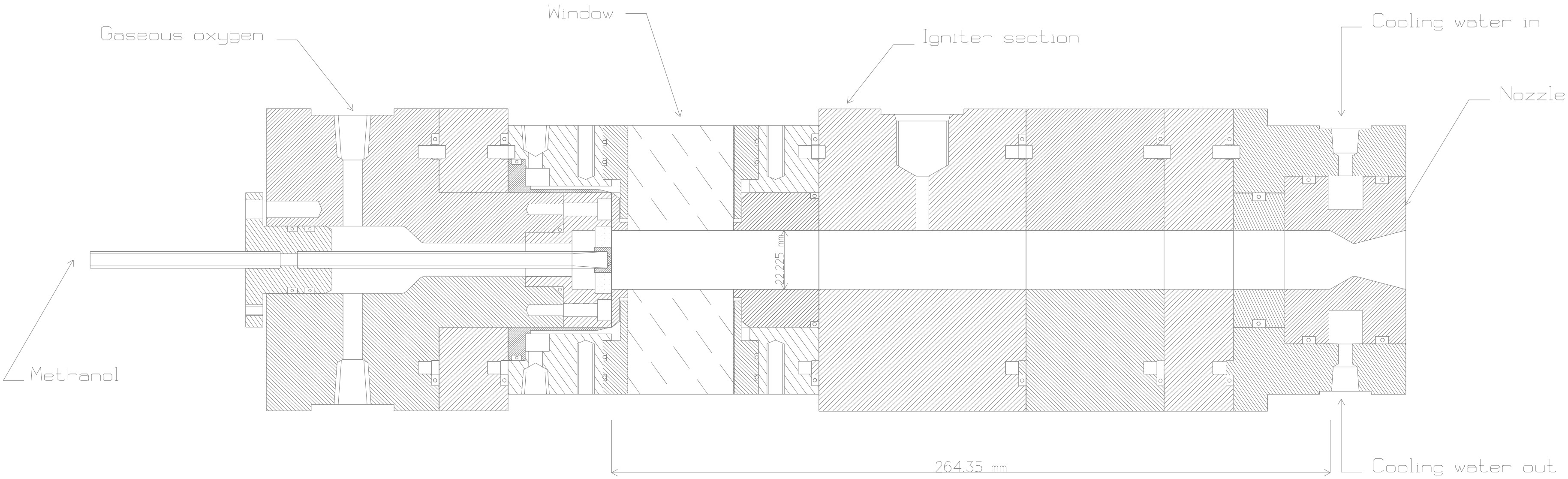
- ►**Flowfield characterization for impinging injector element**
  - **GO_2/methanol propellants**
  - **drop size velocity measurements (PDI)**
- ►**Injector dynamics study of impinging injector element**
  - **GO_2/ethanol propellants**
  - **high frequency electro-mechanical control of fuel jets**
  - **instability analysis**
- ► **Injector studies for OMS upgrade**
  - **LO_2/ethanol propellants**
  - **pintle, bi-centrifugal swirl elements**
  - **performance analysis, shadowgraph imaging**

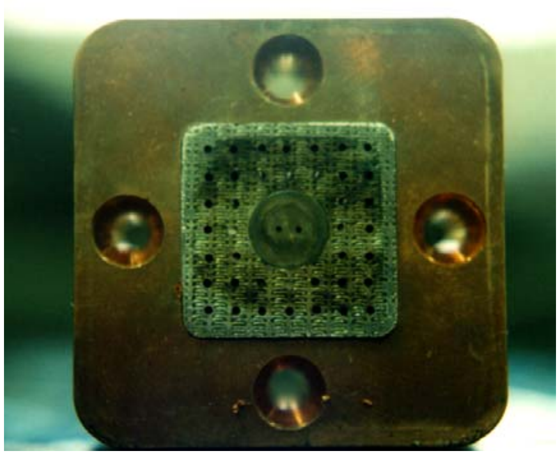
IMPINGING INJECTOR FLOWFIELD STUDIES

Motivation

- **Provide data base for validation of computational fluid dynamic (CFD) models for combustion in rocket chambers**
  - **Impinging jet injector element**
  - **GO_2/methanol propellants**
- **Apply laser-based diagnostic techniques to characterize flowfield in a uni-element optically-accessible rocket chamber**
  - **Phase Doppler interferometry (PDPA) for drop size and velocity measurements**

IMPINGING INJECTOR FLOWFIELD STUDIES

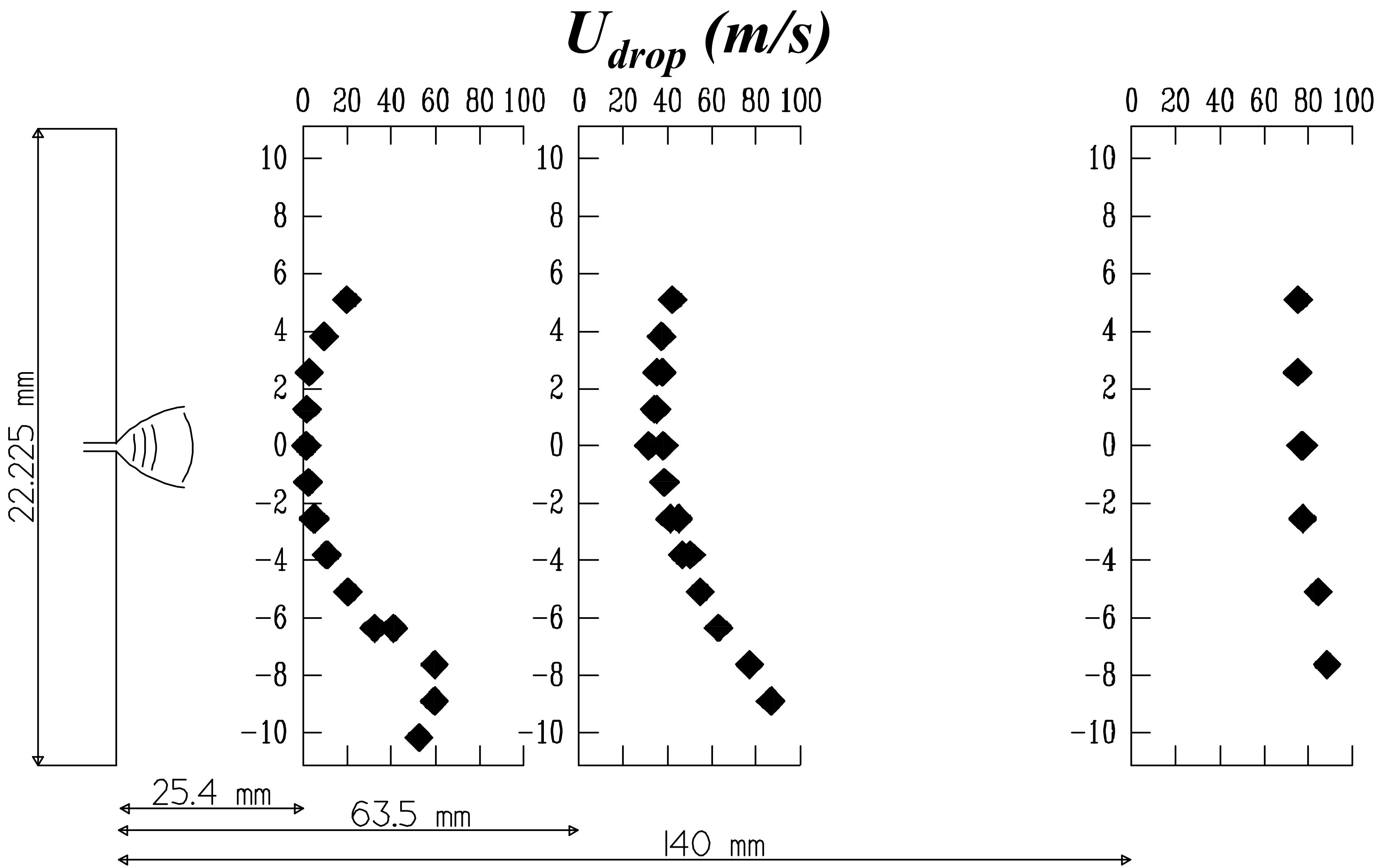




Methanol flowrate = 0.0183 lbm/s
GO_2 flowrate = 0.0942 lbm/s
O/F = 5.15
c* efficiency = 0.96

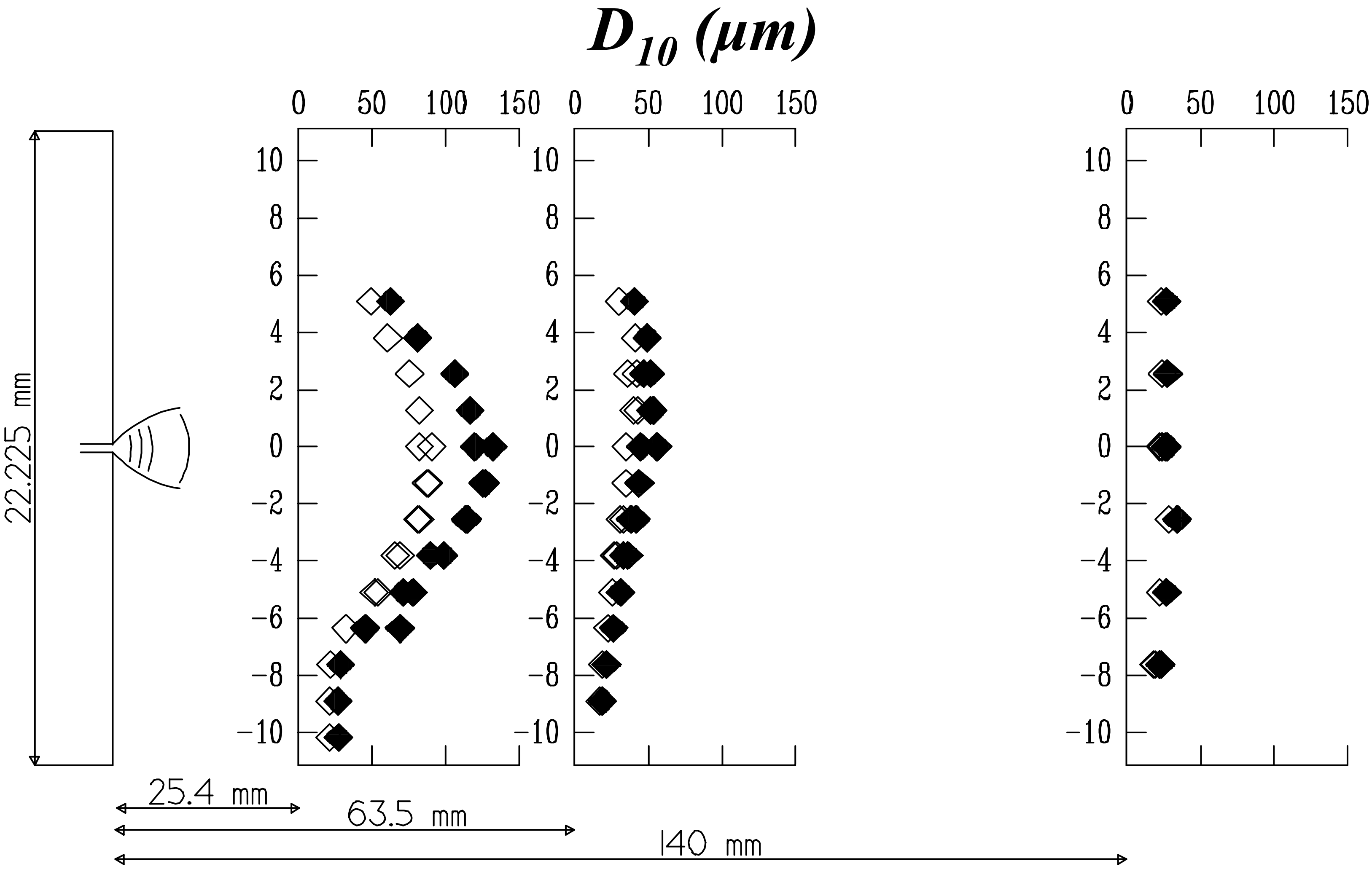
IMPINGING INJECTOR FLOWFIELD STUDIES

DROP MEAN VELOCITY PROFILES AT 3 AXIAL LOCATIONS



IMPINGING INJECTOR FLOWFIELD STUDIES

DROP SIZE PROFILES AT 3 AXIAL LOCATIONS



IMPINGING INJECTOR FLOWFIELD STUDIES

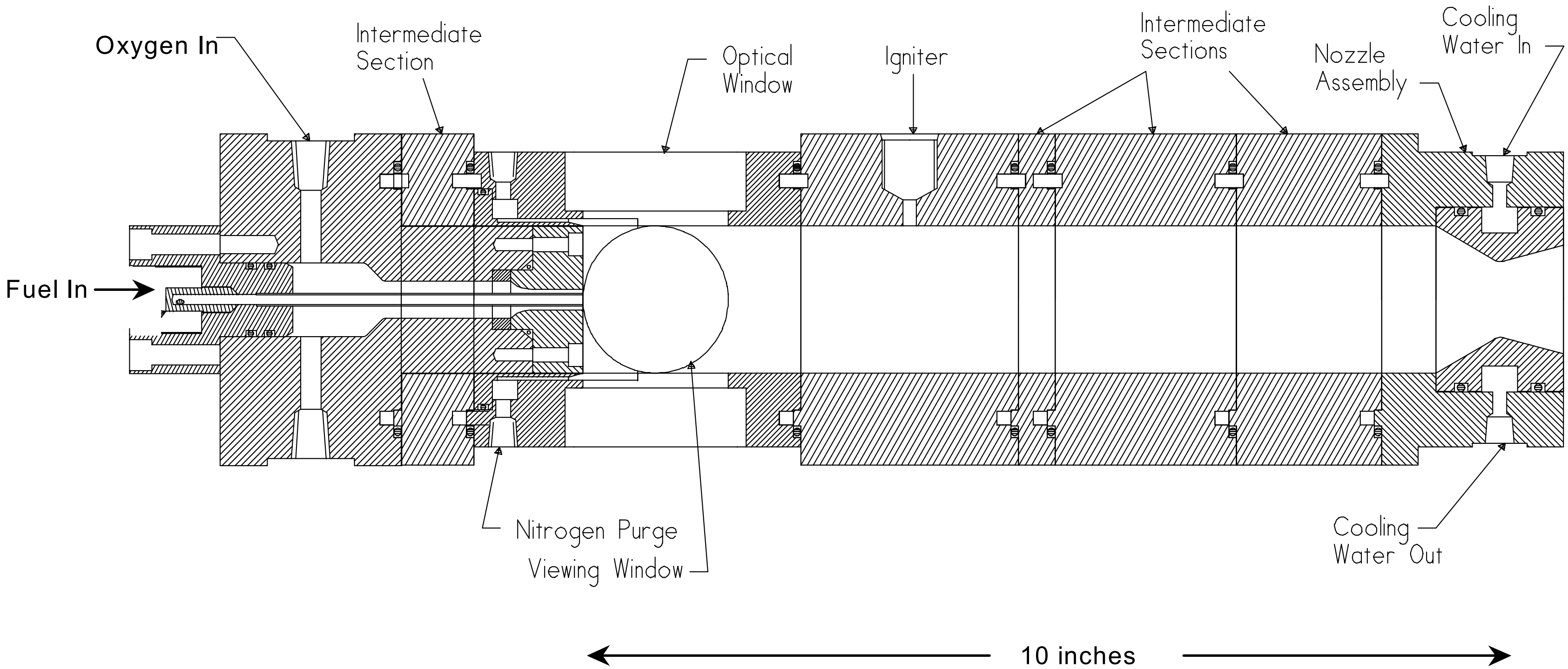
Summary

- Methanol Drop Size and Velocity Measurements Made in a Optically-Accessible Uni-Element Rocket Environment
  - Mean Drop Size Decreases with Axial Distance
  - Mean Drop Size Largest along Centerline and Decreases with Radial Distance
  - Mean Drop Velocity Indicates Presence of Strong Recirculation Zone near Injector Face
  - Estimate of Integrated Mass Flux About 10% of Injected Mass at Closest Measurement Location (Z = 25.4 mm)
  - Measurements Indicate Near Complete Combustion at Furthest Measurement Location (Z = 140 mm)

Motivation

- **Determine conditions under which impinging jet injector periodic atomization can cause combustion instabilities**
  - **Longitudinal mode excitation for GO_2/ethanol propellants in model rocket chamber**
  - **Electromechanical drivers controlling individual ethanol jets (*of impinging jet injector*)**

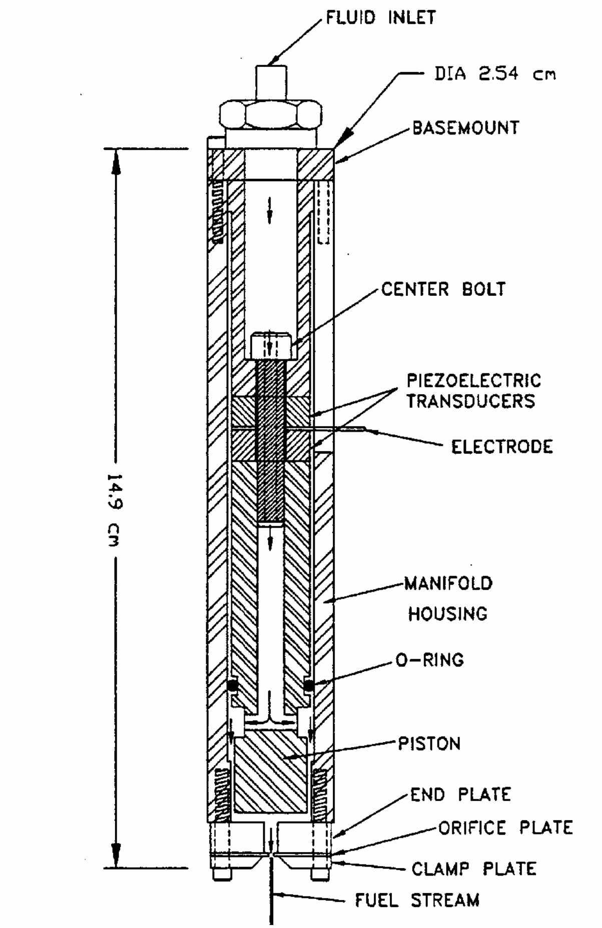
DYNAMICS OF IMPINGING JET INJECTORS



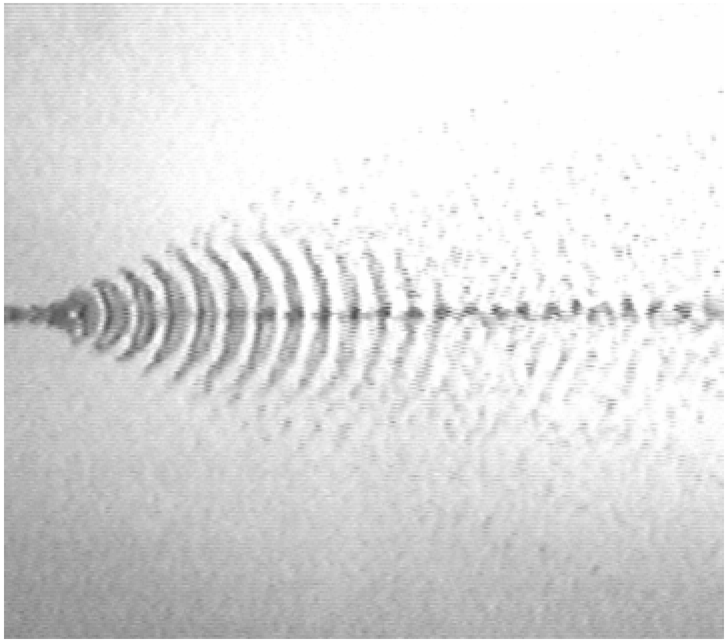
- **Ethanol Impinging Jet Injector (Individual Electromechanical Drivers)**
- **Annular Flow of GO_2**

DYNAMICS OF IMPINGING JET INJECTORS

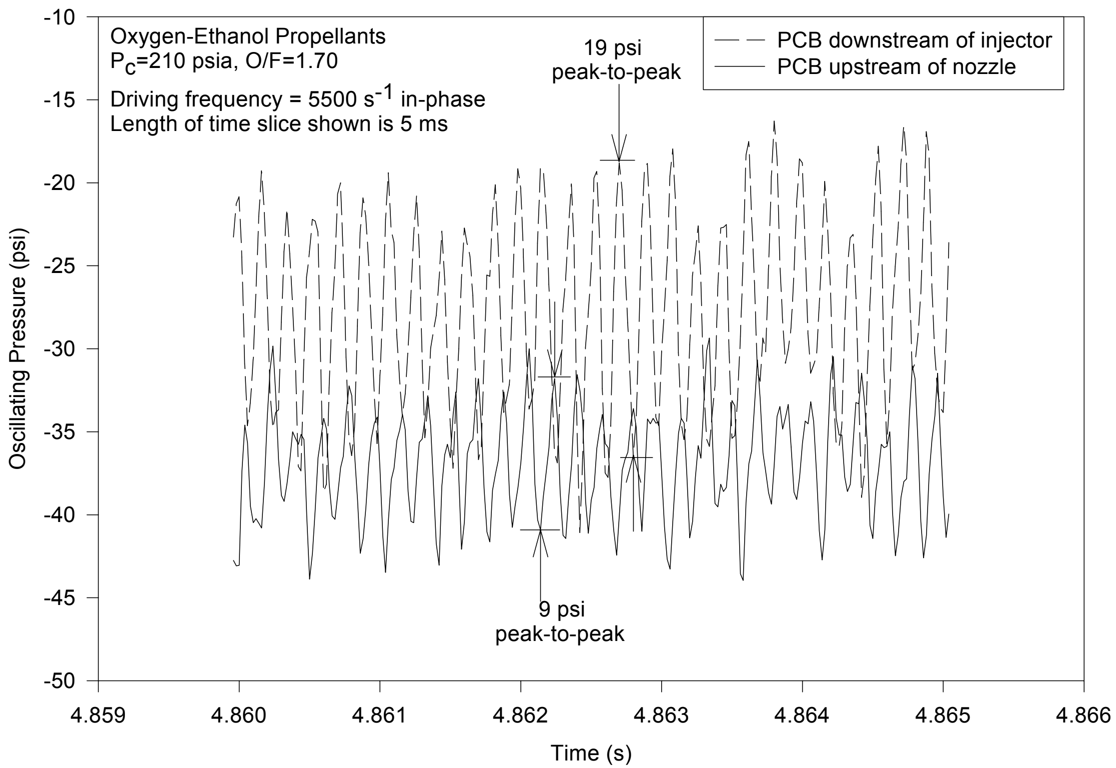
ELECTROMECHANICALLY DRIVEN INJECTOR ASSEMBLY

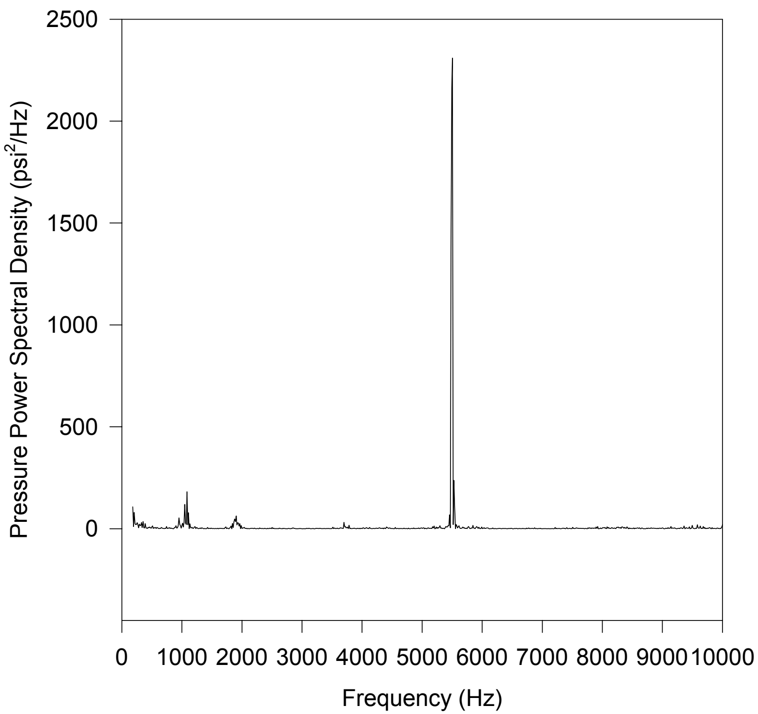


IMPINGING INJECTOR JETS PERTURBED OUT-OF-PHASE AT 2500 Hz



DYNAMICS OF IMPINGING JET INJECTORS





DYNAMICS OF IMPINGING JET INJECTORS

Summary

- ► **Successful demonstration of combustion instability by periodic**
- ► **Atomization for impinging jet injector**
- ► **Technique has potential as active control of combustion instability**

INJECTOR STUDIES FOR OMS UPGRADE

Motivation

- NASA was investigating the feasibility of a non-toxic OMS/RCS upgrade for the space shuttle to eliminate the safety and cost issues associated with hypergolic propellants

Broad objectives

- To provide NASA and contractors with an objective base from which future injector design decisions could be made for OMS and future HEDS applications

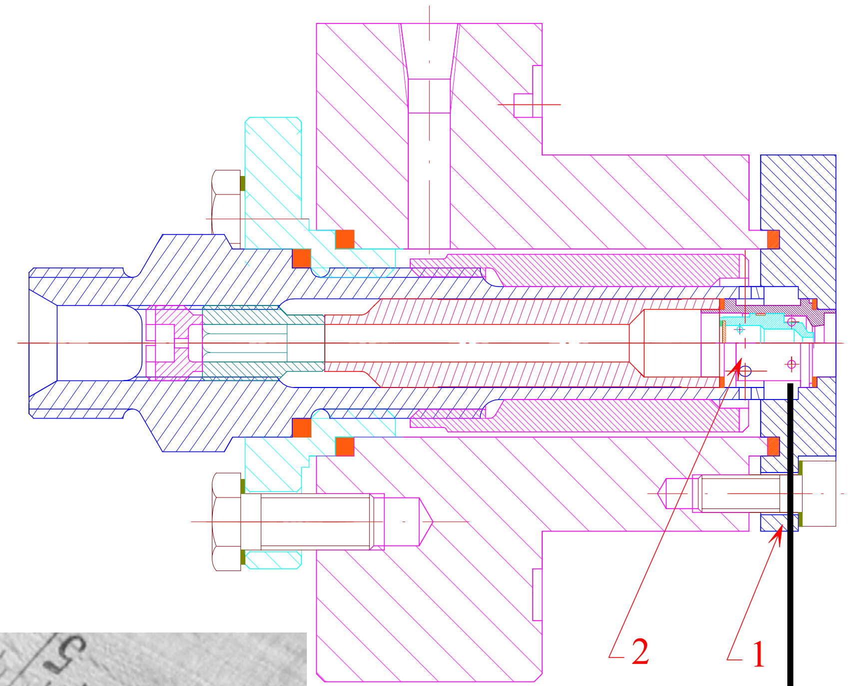
Specific objectives

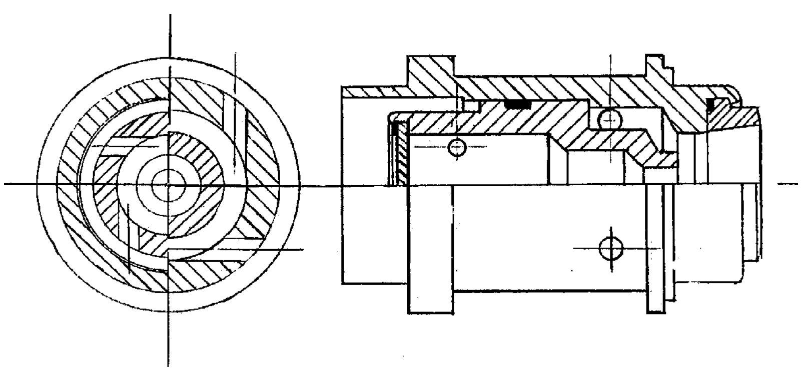
- To measure and analyze detailed combustion characteristics of LO_2/ethanol propellant combinations at representative thrust chamber conditions for various candidate injectors

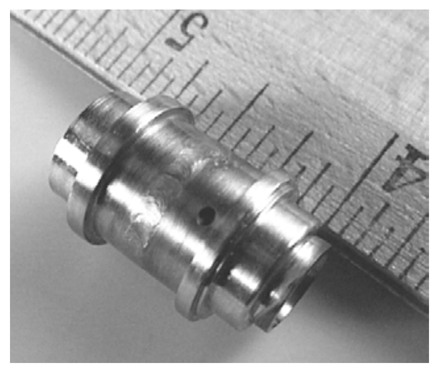
INJECTOR STUDIES FOR OMS UPGRADE

PINTLE INJECTOR TIP

BI-CENTRIFUGAL SWIRLER







INJECTOR STUDIES FOR OMS UPGRADE

OMS Engine Design
Thrust: 27 kN (6000 lbf)
Isp: 326 sec
Mixture Ratio: 1.7
Propellant Flowrate: 8.3 kg/s (18.4 lbm/s)
-Oxygen: 5.26 kg/s (11.6 lbm/s)
-Ethanol: 3.08 kg/s (6.8 lbm/s)

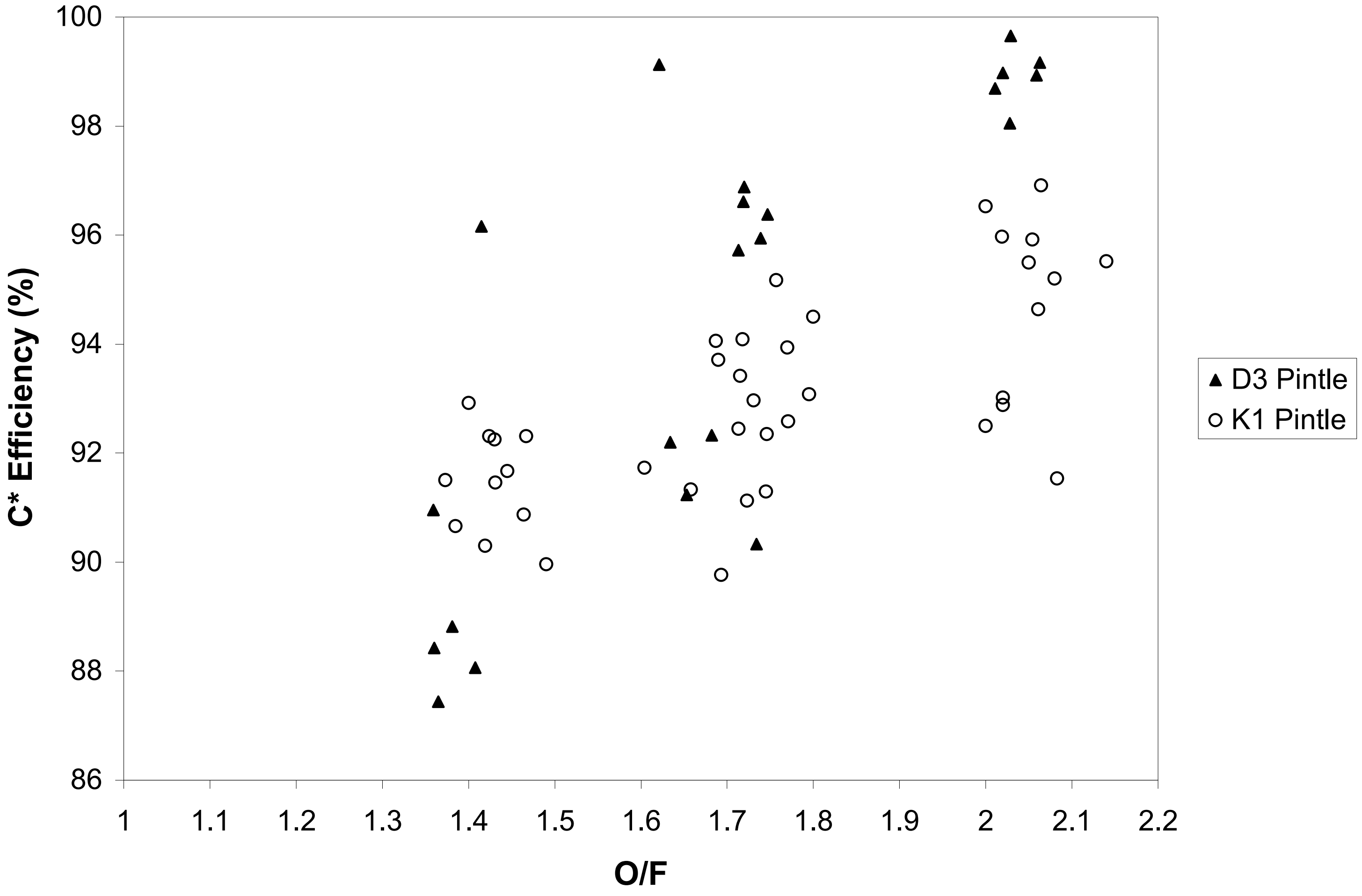
Sub-Scale Engine Design
1/60 of Full Scale-mass flowrate
Mixture Ratio: 1.7

Propellant Flowrate: 0.14 kg/s (0.307 lbm/s)
-Oxygen: 0.088 kg/s (0.193 lbm/s)
-Ethanol: 0.052 kg/s (0.114 lbm/s)

Case #	1	2	3	4	5	6
P_c (MPa)	1.10	1.10	1.10	2.07	2.07	2.07
O/F	2.0	1.7	1.4	2.0	1.7	1.4
LOX flowrate (kg/s)	0.095	0.088	0.082	0.177	0.163	0.155
ethanol flowrate (kg/s)	0.048	0.052	0.059	0.088	0.096	0.111
GN2 flowrate (kg/s)	0.014	0.014	0.014	0.014	0.014	0.014
Nozzle Diameter (mm)	16.51	16.51	16.51	16.51	16.51	16.51

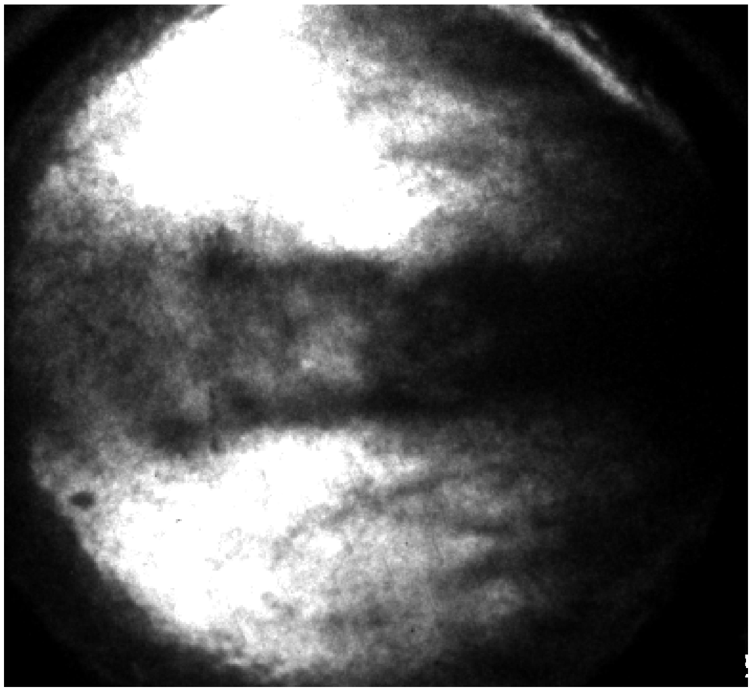
INJECTOR STUDIES FOR OMS UPGRADE

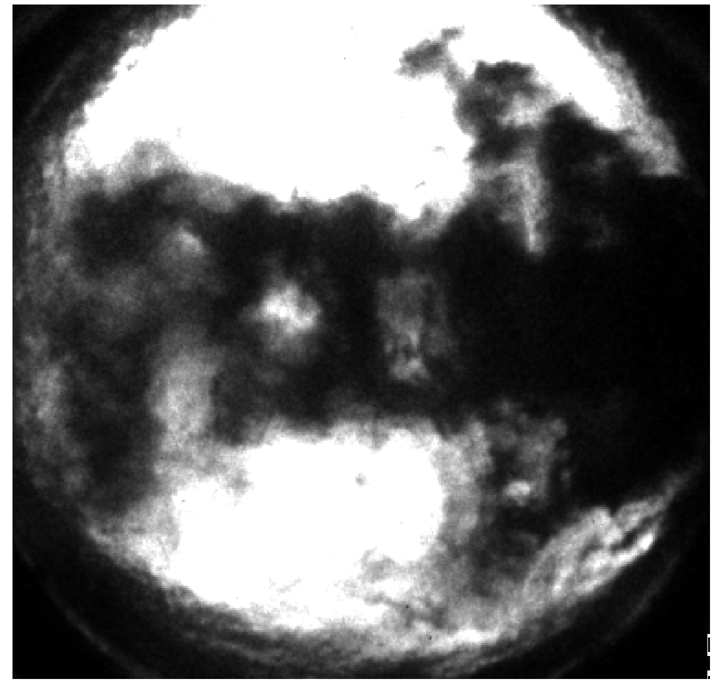
- Over 100 LO_2/Ethanol Tests Were Conducted on Pintle Injectors



INJECTOR STUDIES FOR OMS UPGRADE

BI-CENTRIFUGAL NEAR INJECTOR FLOWFIELD





2M injector, Case 2

← Flow

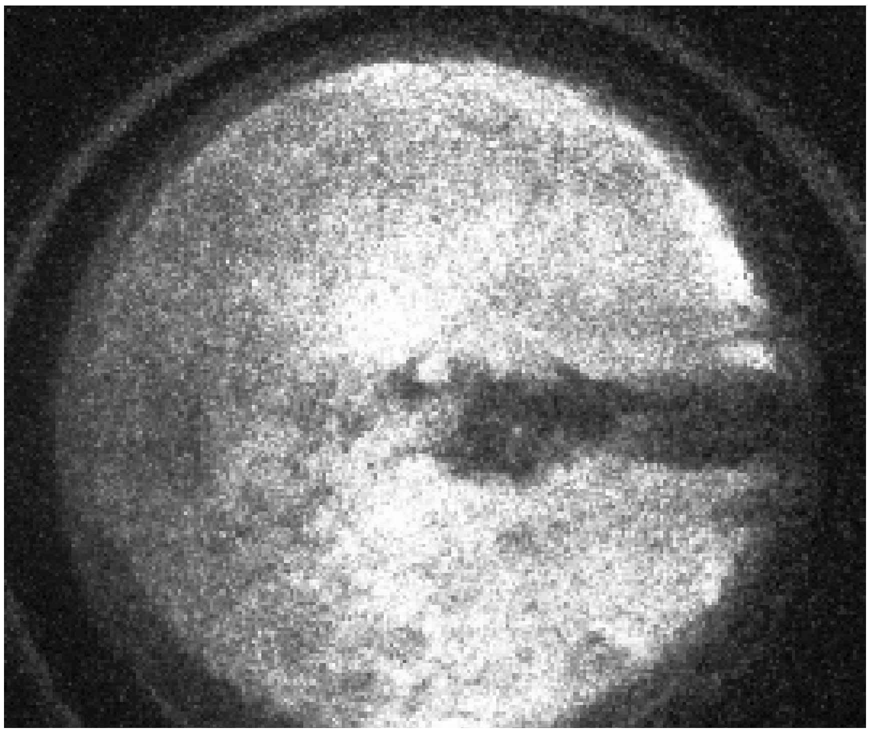
2M injector, Case 6

Outer LOX flow is separated from inner ethanol cone by layer of vaporized oxygen

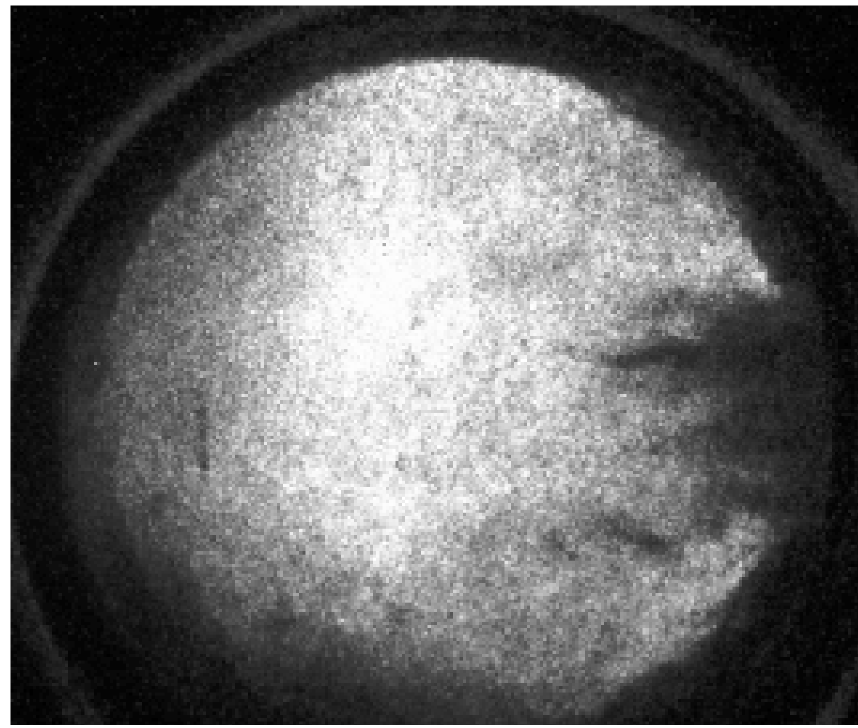
INJECTOR STUDIES FOR OMS UPGRADE

MODIFIED BI-CENTRIFUGAL INJECTOR WITH LARGE RECESS

- 2M w/large recess face plate exhibits good mixing and combustion over wide range of operating conditions and is insensitive to LOX quality



Case 3

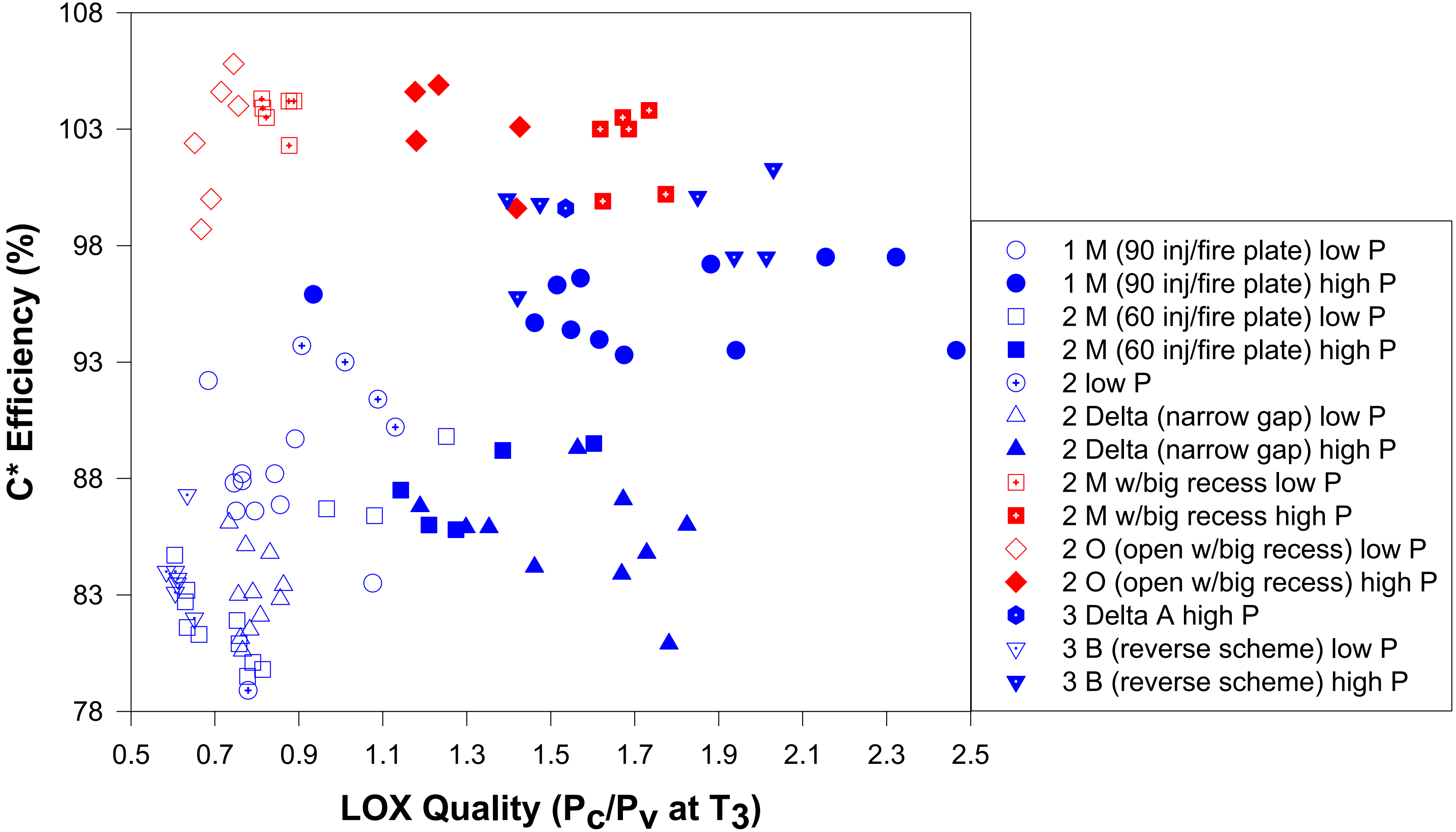


Case 4

← Flow

INJECTOR STUDIES FOR OMS UPGRADE

PERFORMANCE OF BI-CENTRIFUGAL INJECTOR



INJECTOR STUDIES FOR OMS UPGRADE

Summary

PINTLE INJECTOR

- **Pintle Injector Designed for OMS Conditions Operated in a Stable Manner**
- **For Pintle Injector, c* Efficiency Increase With O/F**

BI-CENTRIFUGAL SWIRLER

- **Marginal LO_2 Quality Influenced Combustion Efficiency for All Injector Configurations**
- **Shadowgraph Imaging Was Instrumental in Assessing Flow Phenomena Which Caused Lower Than Expected Performance**
- **Use of Recess Is Reasonable Solution to Spray Cone Separation Problem:**
- **Recess Insensitive to LO_2 Quality (of Significance to OMS Upgrade), Stable Under All Conditions Tested, LO_2 Cooling of Injector Face Effective Here**

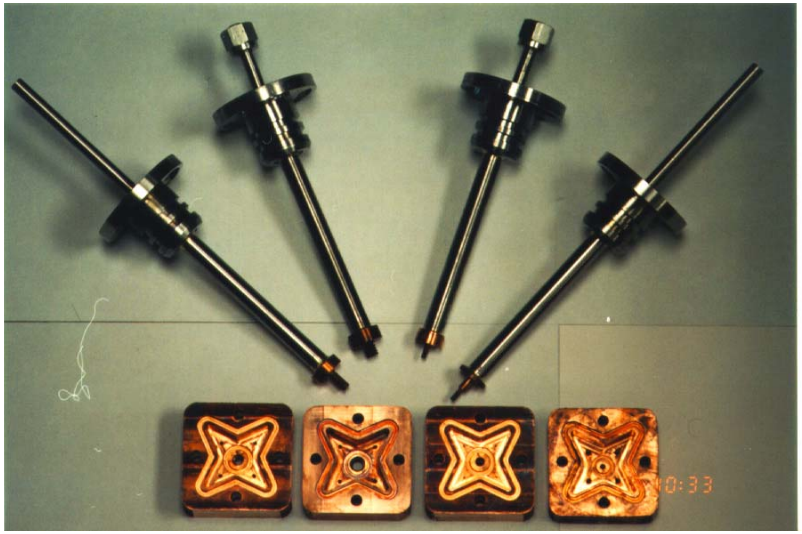
UNI-ELEMENT BI-PROPELLANT EXPERIMENTS

Fuel-Rich, Oxidizer-Rich Operation

- ►Fuel-rich LO_2/RP-1 pentad injector
  - LO_2 flow in center
  - 4 angled holes for RP-1 impingement on central LO_2 jet
  - design for O/F = 0.5
- ►Oxidizer-rich LO_2/RP-1 pentad injector
  - RP-1 flow in center
  - 4 angled holes for LO_2 impingement on central RP-1 jet
  - design for O/F = 50
- ► Oxidizer-rich LO2/RP-1 pintle injector
  - RP-1 centered design
  - maximum O/F of 14

UNI-ELEMENT BI-PROPELLANT EXPERIMENTS

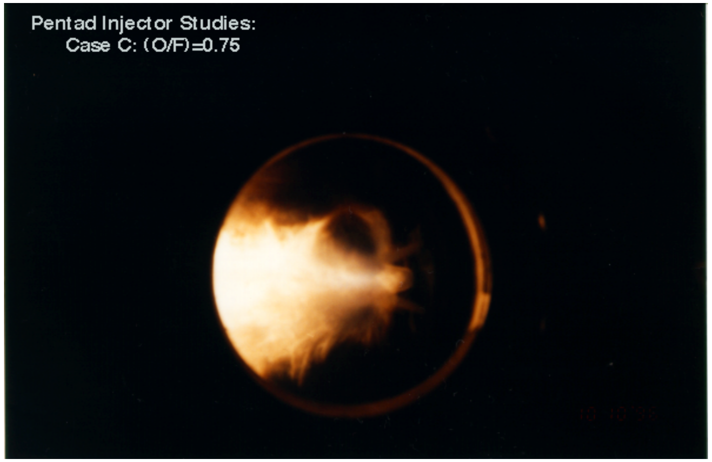
Fuel-Rich, Oxidizer-Rich Operation (Summary)



- **Fuel-rich LO_2/RP-1 pentad injector**
  - **high performance**
  - **'sooty' environment challenges use of diagnostics**
- **Oxidizer-rich LO_2/RP-1 pentad**
  - **failure due to improper start sequence**

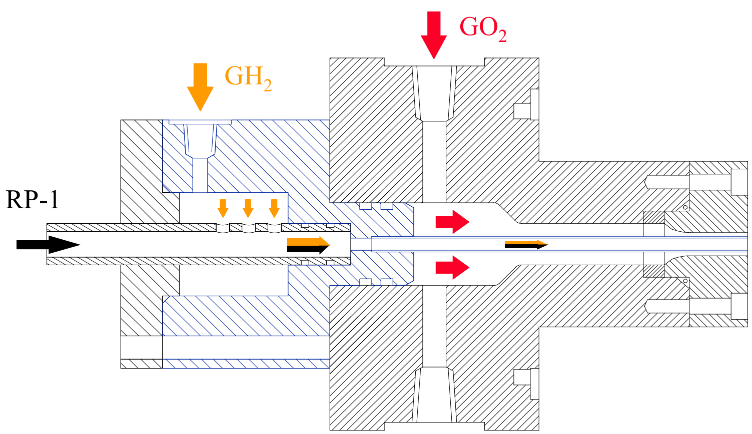
PENTAD DESIGNS

FUEL-RICH OPERATION

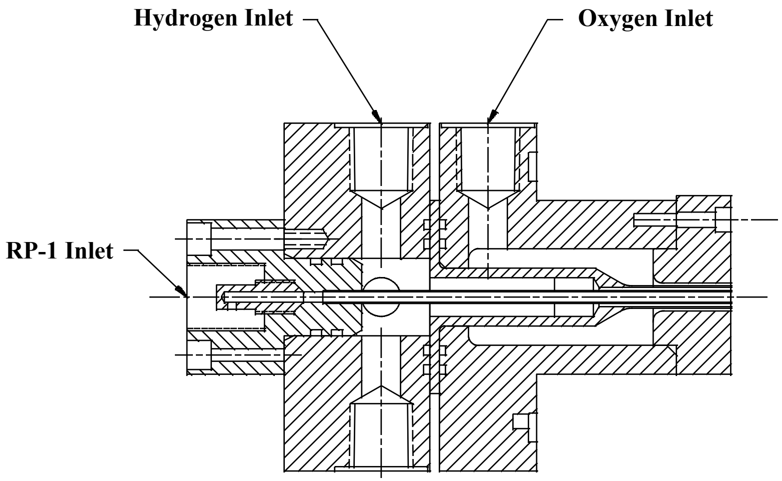


UNI-ELEMENT TRI-PROPELLANT EXPERIMENTS

- **Injector designs for GO_2/RP-/GH_2 propellants**
  - **Effervescent**
  - **Coaxial-type**
- **Flowfield characterization for**
  - **GH_2 mass flowrate up to 10% of RP-1 flowrate at overall stoichiometric conditions for pressures up to 550 psia**



EFFERVESCENT INJECTOR

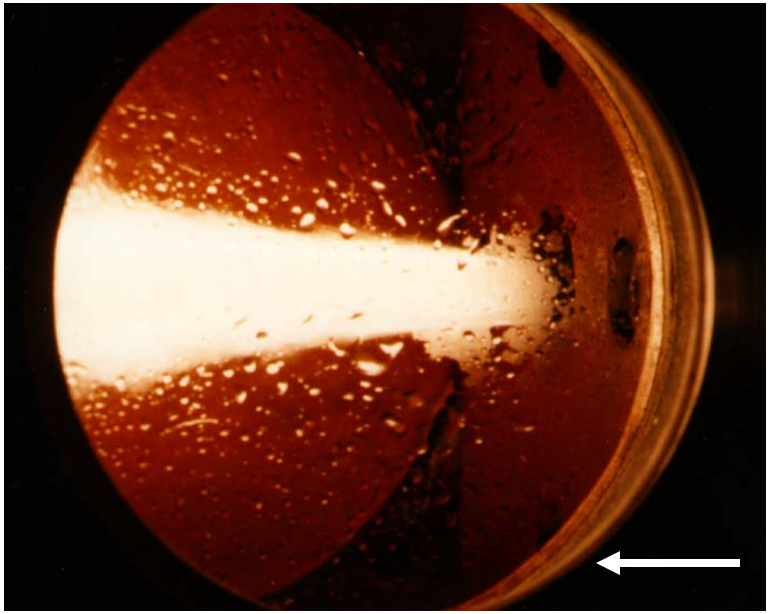


COAXIAL-TYPE INJECTOR

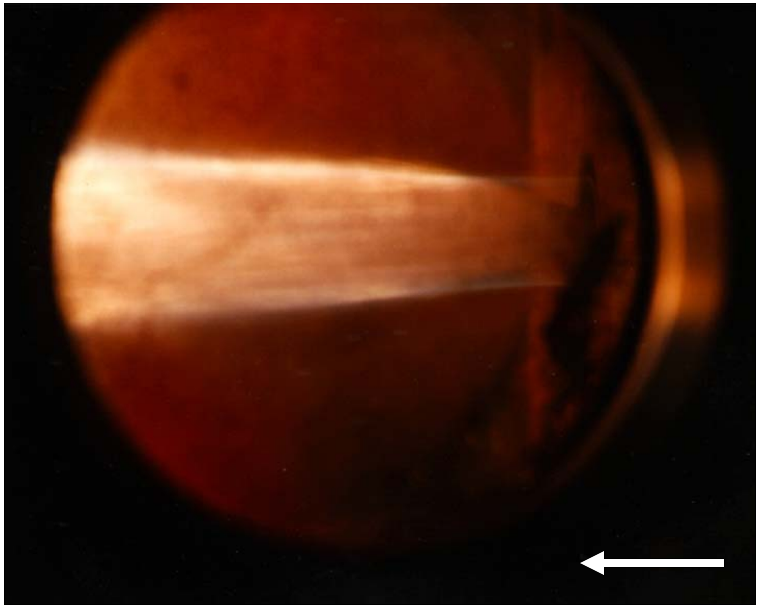
UNI-ELEMENT TRI-PROPELLANT EXPERIMENTS

Summary

- ►Integrated GO_2/RP-/GH_2 injector designs
  - Improved RP-1 atomization yields high performance
  - Performance increases with GH_2 addition
- ► First tri-propellant experimental rocket studies in US



EFFERVESCENT INJECTOR

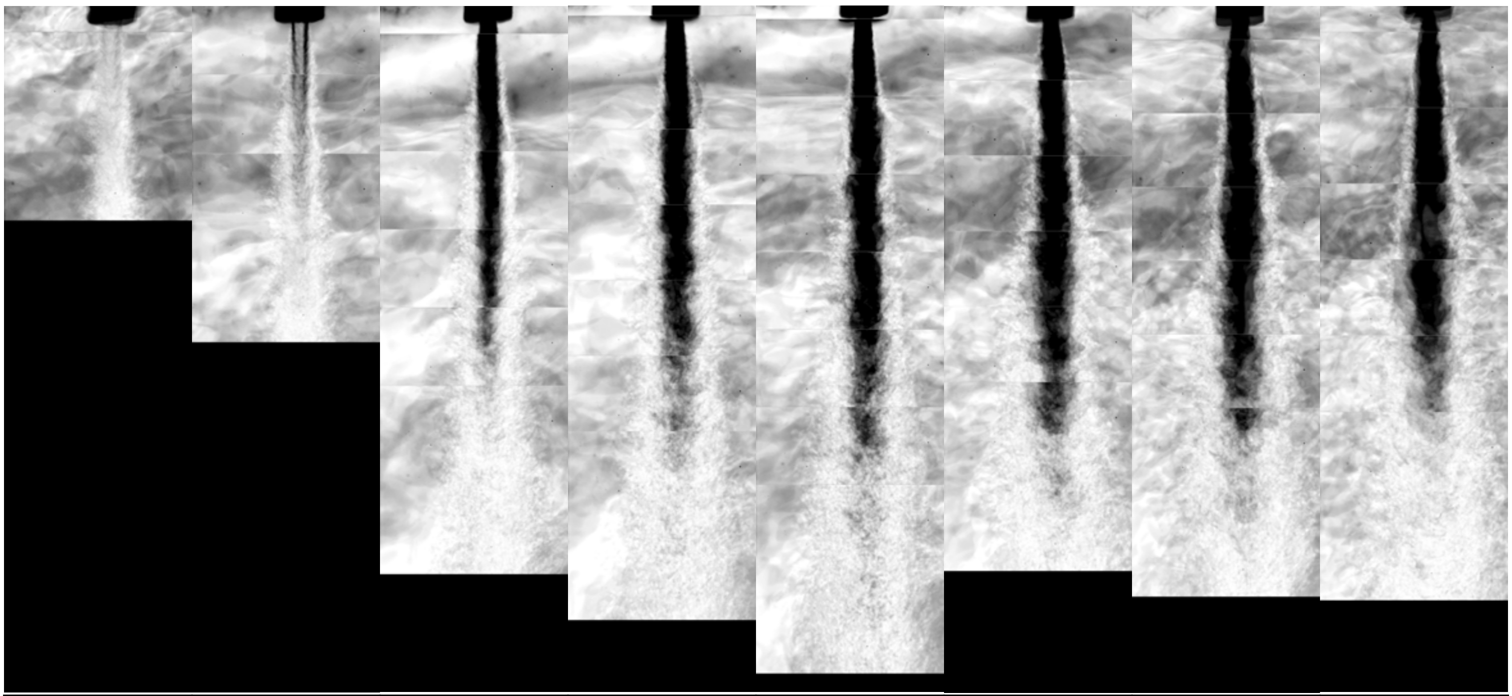


COAXIAL-TYPE INJECTOR

SUB-/SUPER-CRITICAL LHC JET EXPERIMENTS

Summary

- ►n-heptane jets studied for sub-/super-critical temperature and pressure conditions



21.9 bar 70 kg/m³	28.6 bar 107 kg/m³	35.6 bar 222 kg/m³	42.6 bar 288 kg/m³	49.3 bar 325 kg/m³	56.4 bar 347 kg/m³	63.5 bar 365 kg/m³	70.7 bar 371 kg/m³

NEAR- OR SUPER-CRITICAL TEMPERATURE INJECTION OF N-HEPTANE INTO SUPER-CRITICAL TEMPERATURE NITROGEN CHAMBER

EXPERIMENTAL CHALLENGES

Experimental Complexities

- ►**Super-critical pressure operation**
  - ▪ **maximum chamber pressure of 1400 psia limits experimental conditions to maximum 2× LO_2 critical pressure**
  - ▪ **“liquid-like” structures still evident at high pressures (1400 psia)**
- ► **Optical access requires curtain flow (GN_2 or GHe) that complicates measurement analyses**

EXPERIMENTAL CHALLENGES

Diagnostics Challenges

- **Gaseous propellant (GO_2/GH_2) flowfields are the least complex**
  - **LDV, PLIF and Raman spectroscopy for velocity, OH and major species concentration measurements have been demonstrated**
  - **Challenges lie in improving measurement accuracies**
- **Liquid/gas propellants (LO_2/GH_2) flowfields are challenging**
  - **PDI for LO_2 drop measurements, shadowgraph, schlieren and laser sheet imaging for LO_2 region identification have been demonstrated**
  - **Challenges lie in improving fidelity of demonstrated diagnostics (PDI) and in implementing other diagnostics (PLIF, Raman spectroscopy) to liquid drop laden flowfield**
- **Liquid/liquid propellants (LO_2/RP-1) flowfields are the most challenging**
  - **Issues here are same as above (liquid/gas propellants)**
  - **'Sooty' flowfield adds additional challenges for flowfield measurements**

MODELING STUDIES

- Overall model (CFD) development philosophy is to progress from simple flowfields to complex flowfields. Complexity includes:
  - chemistry (hydrogen versus hydrocarbons)
  - propellant phase (gas/gas, liquid/gas, liquid/liquid)
  - propellant state (sub-critical, super-critical)
  - injector complexities (shear, swirl, impinging)

GO_2/GH_2 shear and swirl coaxial injectors

LO_2/GH_2 shear and swirl coaxial injectors at sub- and super-critical pressures

GO_2/RP-1 coaxial and impinging injectors

LO_2/RP-1 injectors at sub- and super-critical pressures

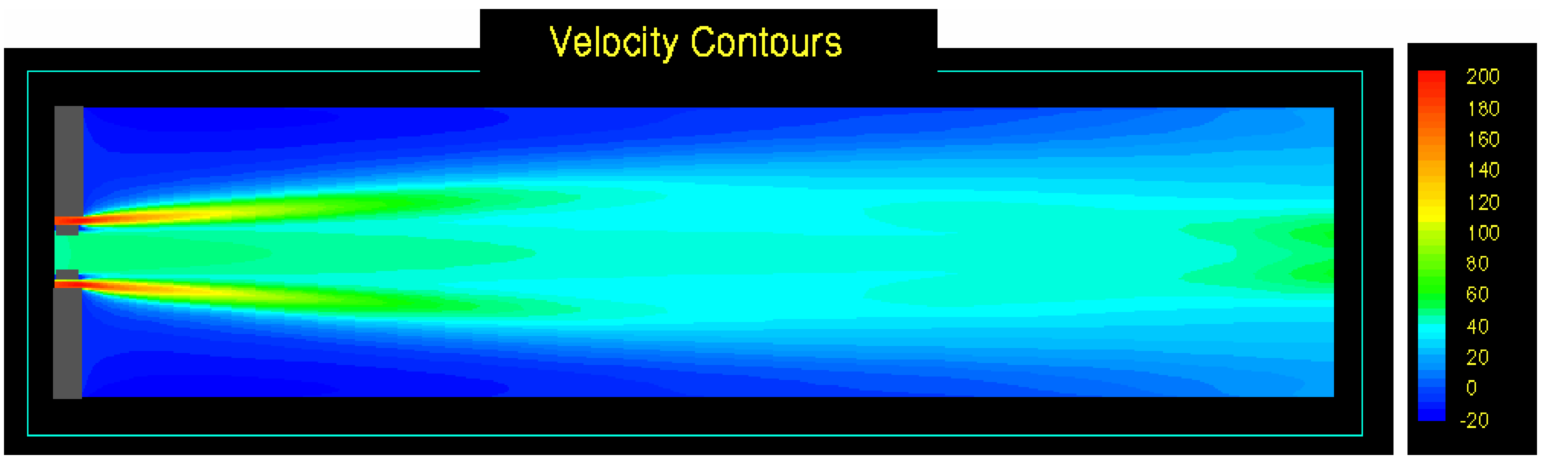
■ *MODELING TO DATE HAS FOCUSED ON FIRST TWO ITEMS*

MODELING STUDIES

► CFD modeling efforts with Penn State data base has and is been conducted by government, industry and universities

- NASA MSFC, AFRL
- Boeing Rocketdyne
- Penn State, UTSI, UAB

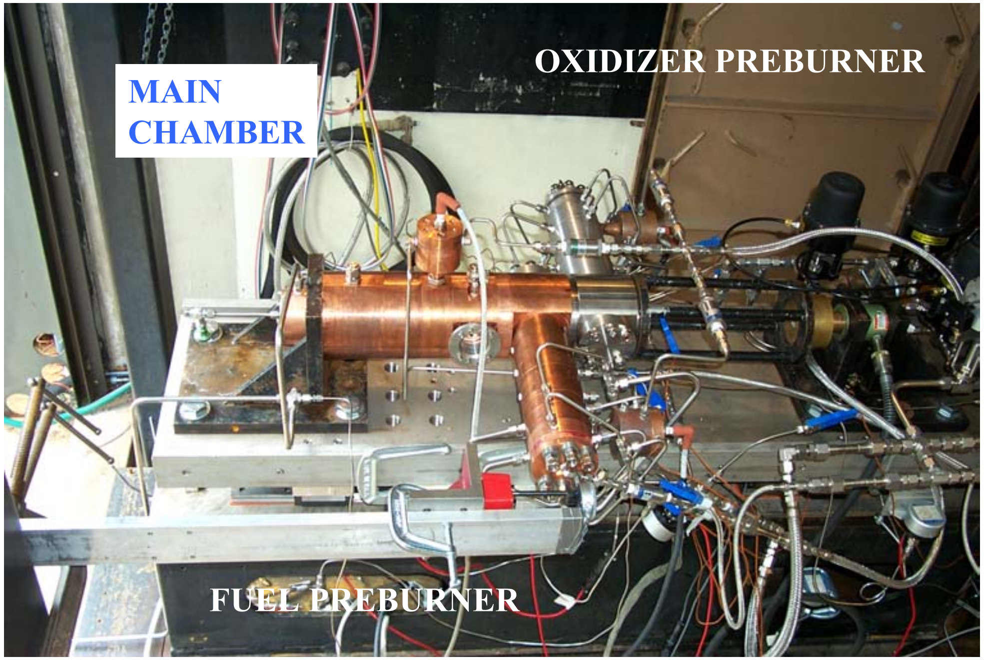
► Most complete data base is for a GO_2/GH_2 shear injector



PROF. C. L. MERKLE'S CALCULATIONS FOR PENN STATE EXPERIMENT

CURRENT/FUTURE WORK

► Detailed gas/gas injector flowfield characterization using preburner oxidizer-rich and fuel-rich propellants



► Experiments to study combustion instability for hot GO_2/RP-1 injector concepts

Future Modeling/Experiments for Liquid Rocket Injectors

- **Lessons Learned**
  - Continuous interactions between experimentalists and modelers critical to success.
  - Despite concerted efforts, definition and characterization of initial and boundary conditions remain a significant challenge.
  - The development of steady-state and transient codes needs to be a balanced effort between experiment design and computation resources, that is do the right problem with the best tools.

Future Modeling/Experiments for Liquid Rocket Injectors

- **Observations on approach to future work**
  - Initial work on liquid hydrocarbon injectors should be an extension of gas/gas work.
    - Focus on supercritical conditions to eliminate atomization and drop combustion.
  - Experiments needed to develop more extensive data base for supercritical conditions, particularly for velocity and temperature.
  - Extension to liquid propellant cases, that is subcritical hydrocarbon fuels and liquid oxygen in general, requires significant increase in modeling and experimental complexity

Future Modeling/Experiments for Liquid Rocket Injectors

- **Needed Experimental Measurement Capabilities**
  - Species and temperature measurements in two phase environments.
  - Measurements of liquid mass fraction.
  - Drop and gas velocities measurements.
- **Needed Modeling Capabilities**
  - Atomization/vaporization models
  - Validated transport and mixing models for supercritical conditions

Conclusions and Summary

- Current experimental data base is relatively broad for liquid hydrocarbon systems, but lacks needed detailed measurements.
- Extending data base will require experiments involving novel application of existing diagnostics or development of new techniques.
- More care must be given to initial and boundary condition specification and characterization.
- Initial modeling for hydrocarbon systems should extend gas/gas capabilities by focusing on supercritical conditions.

Conclusions and Summary

- **New capabilities will be needed for both the experimental and modeling challenges that liquid hydrocarbon systems present.**
- **The state-of-the-art experimental and modeling work accomplished for gas/gas injectors provides a firm basis from which to extend work to liquid hydrocarbon system.**

Acknowledgements

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