Literary Investigation of Fuel Type Viability for Scramjet Combustors

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OVERVIEW

INITIAL RESEARCH
- How a scramjet works
- Fuel injector design

FUEL TYPES
- Conventional (liquid and gas)
- Solid
- Gelled

CONVENTIONAL FUELS
- Methane
- Ethylene
- Heptane
- JP-10
- Hydrogen

SOLID FUELS
- Advantages/ Disadvantages
- Poly-methyl-meth-acrylate (PMMA) test

GELLED PROPELLANTS
- Overview
- Atomization

Initial Research

- Compression waves pile up in front of object[1]
  - Stack of compression produces shockwave
  - Air is slowed down drastically-> needs to be slower for combustion to occur
- Scramjet uses high speed to compress air[2]
  - Air is supersonic throughout engine (unlike ramjet)
  - Utilize geometry to create shocks & areas for flame holding
- Injector design produces rapid combustion and mixing (allowing for combustor length and weight to be minimized)[3]
  - Injector sticks out for better fuel mixing & creates space for flames to form, but requires cooling
  - Penetration of the fuel stream into the cross flow is governed by the jet-to-freestream momentum flux ratio
  - The fuel jet interacts with the cross flow to create shock

Types

Liquid

- Currently used
- Variable thrust
- Fuel is easily replaceable
- Requires pressurization and storage container
- Shutdown capability
- Greater specific impulse than solid fuels

Solid[4]

- Fuel consumption changes combustion chamber geometry
- Requires pre-determined mission profile
- Fuel regression rate heavily dependent on incoming air temperature (slightly on pressure)
- Denser
- Easier to store (stable)

Gelled Propellants[5]

- Fluids with additives that have aspects of solid and liquid fuels
- Has to be atomized before combustion
- Three major types
  - Pseudo plastic, Shear Thinning, Low-Yield
  - Viscoelastic Gel
  - Yield thixotropic
- Stored as solid, but liquified upon injection to combustion chamber

Conventional Fuels

- Methane[6]
  - CH_4
- Ethylene
  - C_2H_4
- Heptane[7]
  - $H_3C(CH_2)_5CH_3$
- JP-10
  - Mixture of (in decreasing order) endo-tetrahydrodicyclopentadiene, exo-tetrahydrodicyclopentadiene, and adamantane
- Hydrogen
  - H_2
- Hydrocarbon mixture
  - 30/60/10 molar ratios of methane, ethylene, heptane

- Looking at ignition delays
  - Defined as onset of emission from hydroxyl radicals (when does OH start being emitted)
  - Has to be rapid in order for efficient combustion in a practical length
- Fuel cracking decreases ignition time
  - Breaking fuel into mixture of small hydrocarbons and hydrogen prior to combustion
- Lack of research in hydrocarbon mixtures prior to 2001
  - Small addition of hydrocarbon contaminants in methane reduced ignition delay (1/3 -> 1/5)

Conventional Fuels (Ignition delays)[8]

Methane

- Strong inverse depe
  oxygen concentrati
- Weak direct depend
  methane concentrat

$\tau = 2.21\times10^{-14} \exp(45000$

Ethylene

Heptane

on Argon (but set
y within the paper)

xygen dependency

$50/RT)[C_7H_{16}]^{0.4}[O_2]^{-1.2}$

Table 2 Ignition delay correlations,
($\tau = A \exp(E/RT)\ [O_2]^a\ [\text{fuel}]^b$; 1100 K $\leq T \leq$ 1500 K)

Fuel	A	E	a	b
Methane[1]	2.21×10^{-14}	45,000	−1.05	0.33
Heptane	6.76×10^{-15}	40,160	−1.20	0.40
Ethylene	2.82×10^{-17}	35,000	−1.20	0.00
Hydrogen	1.60×10^{-14}	19,700	−1.00	0.00
JP-10	2.36×10^{-15}	43,855	−1.20	0.40

[ ] concentrations in mol/cc.

JP-10

- Used in volume lin
  applications due to
- Low vapor pressure
  nonvolatile) limits
  heated shock tube a
  system
- Tested JP-10 and o

erse
direct at low
res; very
atures

of HO_2 radical

cipate in chain

methane > JP-10 ≅ heptane > reformed endothermic fuel > ethylene > hydrogen

- Similar ignition delays to heptane

$\tau = 7.63 \times 10^{-16} \exp(46{,}834/RT)[\text{JP-10}]^{0.4}[O_2]^{-1.2}$

of components did not
drastically change ignition time

- Favored at low temps due to
  weak temperature dependence

$\tau = 1.6 \times 10^{-14} \exp(19{,}700/RT)[O_2]^{-1}$

Solid fuels

Advantages

- Denser
- Easier to store containers
- Operating conditions are closer to normal temperatures (does not have to be kept extremely cold)
- Simpler systems

Disadvantages

- Fuel consumption changes combustion chamber geometry
- Requires pre-determined mission profile
- Fuel regression rate heavily dependent on incoming air temperature (slightly on pressure)

Solid fuel Test[4]

- Previous research has shown:
  - Combustion of solid fuel at good combustion efficiencies
  - Evidence of spontaneous ignition and stable supersonic combustion with no external aid
- Combustor was poly-methyl-methacrylate (PMMA)
- Simulated conditions of Mach 5.5, 1500K, 50 atm
- Examined solid fuel inherent features:
  - Fuel regression rate
  - Fuel-air mixing
  - Reaction kinetics
  - Flame holding capacity

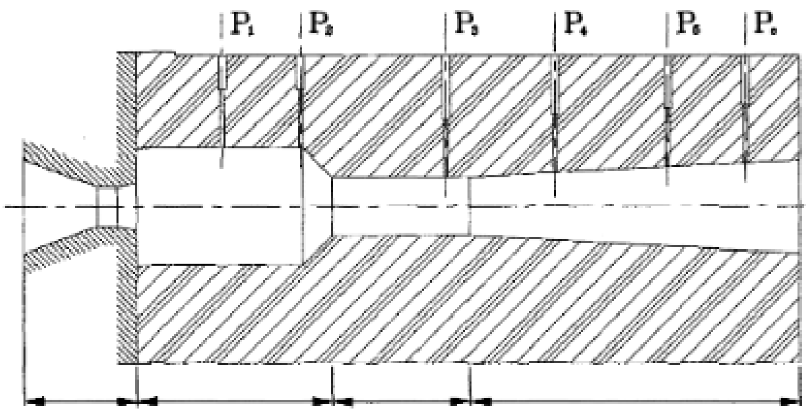


Fig. 5 Schematic of the solid fuel scramjet combustor.

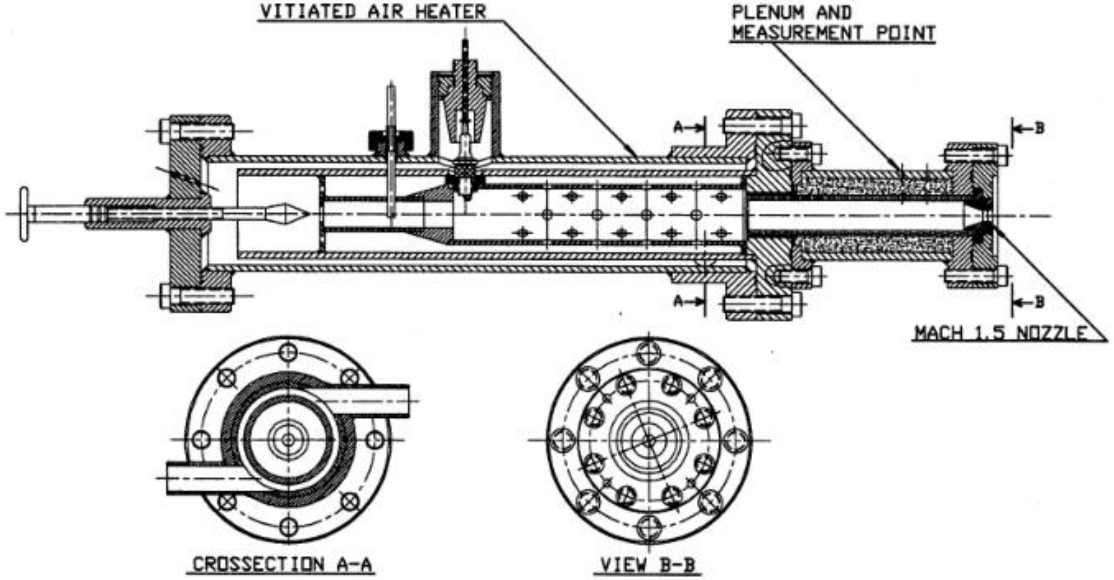


Fig. 6 Facility VAH, cutaway view.

Solid fuel Results[4]

- Initial stage of operation has very little of evaporating fuel being burned (thermal efficiency starts near zero)
- Shock boundary layer interaction develops surface roughness (increases mixing)
- Initial combustion outside the motor
- Fuel regression rate was calculated as the combination of inlet air mass flow rate, inlet air temperature, inlet air pressure
  - Increasing fuel regression rate increases fuel in combustor (increase fuel mass flow rate)
  - Incomplete mixing
  - More fuel, but limited change in burn rate so, decrease in efficiency
- Decrease in thermal efficiency with increase in each parameter
  - Can be remedied by having multiple bores (increase ratio between bore circumference and cross sectional area)
- Larger diversion angles have a decrease in fuel regression rate (best at 3 deg)

Solid fuel Viability[4]

- Transition period of inefficiency due to high velocities and insufficient mixing
  - Negligibly short in realistic propulsion systems
  - Has to be considered for short operating time systems
- Relatively high I_{sp} but lower than liquid fuels
- Fuel consumption also changes combustion chamber geometry
  - Requires pre-determined mission profile
  - Fuel regression rate primarily dependent on incoming air temperature and slightly on pressure
- Performance better at higher altitudes
- *"These assessments confirm the potential of solid fuel scramjets as worthy candidates for the types of propulsion systems discussed."*

Gelled Propellants Overview[5]

- Fluids with additives
- Aspects of both solid & liquid fuels
- Solid in storage tank
- Liquified upon injection
- Several types, classified on properties:
  - Pseudo plastic, Shear Thinning, Low-Yield (non-Newtonian)
    - Inorganic fuels and water gels such as carbopols fall under this category
  - Viscoelastic Gel (resist flow, elastic)
    - Organic Fuels
  - Yield thixotropic (stressed -> less viscous)
    - Organic fuels, H2O2 and corresponding acids
- Metallized gelled leaves solid aggregates with hollow, permeable configuration
- Non-metalized gels:
  - Lack of research work
  - Al/HC (aluminum/ hydrocarbon) is one that has been tested
    - Revealed that gelled propellants have lower combustion efficiency than non-gel
- Possible as green alternative:
  - High test hydrogen peroxide (HPE)/Boron carbide based - SiO2 induced gel propellant
  - Hydroxyl ammonium nitrate (HAN)

Atomization[5]

- Required for higher combustion efficiency
- Since more viscous than kerosene or water, harder to atomize
- High pressure generation in small angle of jet
- Research suggests gelled propellants were unable to produce adequate jet & have significant variation in atomization characteristics
- 1991 NASA study shows feasibility with a coaxial injector[9]
- Atomization improves with:
  - Liquid flow rate
  - Overall flow rate

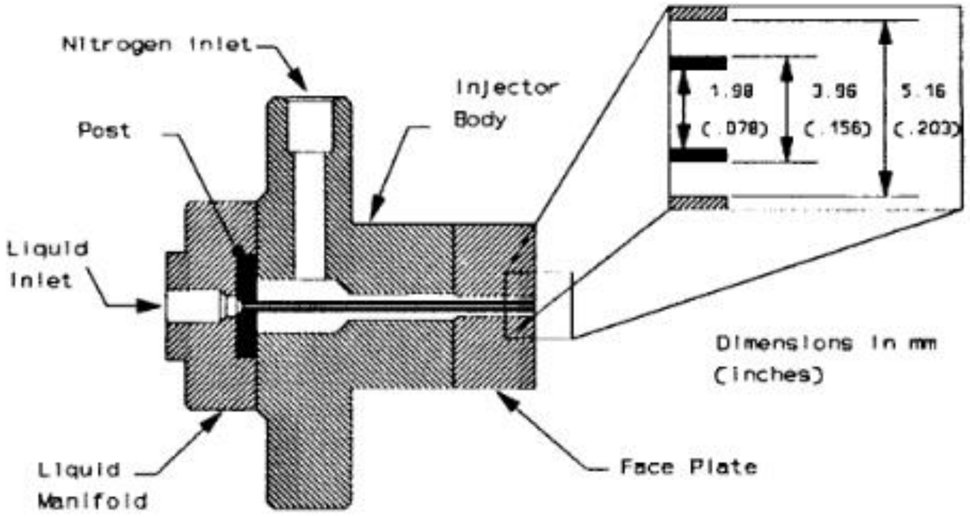
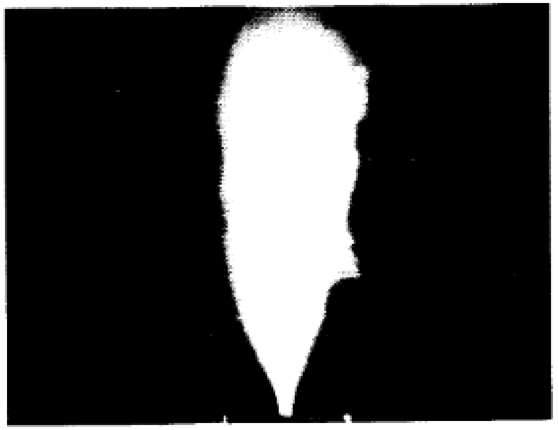
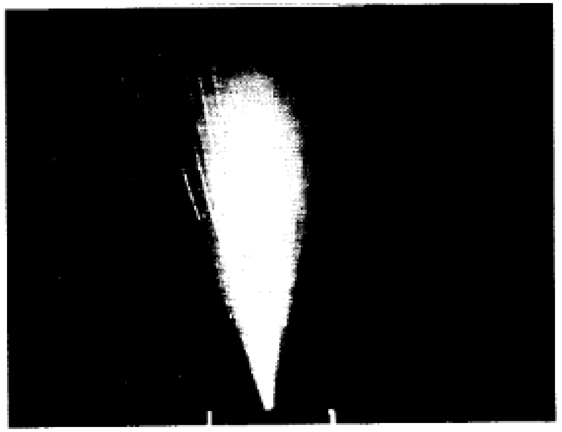


Figure 3: Schematic of Coaxial Injector



e) $\dot{m}_{N2}=9.07$ g/s(0.020 lb_m/s); $\dot{m}_{H2O}=9.07$ g/s(0.020 lb_m/s)



f) $\dot{m}_{N2}=9.07$ g/s(0.020 lb_m/s); $\dot{m}_{gel}=9.07$ g/s(0.020 lb_m/s)

Figure 10: Images of the coaxial injector at varying total mass flow rate for O/F=1.0.

Gelled Propellants Viability[5,9]

- Lower combustion efficiency than liquids
  - Negligibly short in realistic propulsion systems
  - Has to be considered for short operating time systems
- Increase in complexity
  - Atomizers
  - Delivery system
- Addition of certain additives could increase burning rates by increasing gel's vapor pressure
- Metalized gel propellants show most promise, but leave solid aggregates after combustion
- Needs to liquidity better under applied pressure or atomization
  - *"Increased fluid viscosity lead to decreased atomization quality, and that atomization improved as liquid flow rate increased"*
- Further research on changing parameters and their affect on droplet size distribution is needed

CONCLUDING REMARKS

FUEL/ PROPELLANT SELECTION

- Conventional (liquid and gas)
  - General use
  - Most research and testing
  - Easier to modify and control on the fly
- Solid
  - Possible, specialized use
  - Requires pre-determined flight profile and environmental parameters
  - Efficiency needs improvement
- Gelled
  - In development
  - Without improvements in atomization quality or injection scheme, it currently too inefficient when compared to liquid or solid fuels
  - Option for “green” propulsion

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