Fluid Thrust Chamber Design

Kevin Cavender, Den Donahou, Connor McBride, Mario Reillo, Marshall Crenshaw


9th Intercollegiate Rocket Engineering Competition
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GR
GREEN RIVER HIGH SCHOOL

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Fluid Thrust Chamber Design

Fuel Selection

Fuel	Mixture Ratio by mass w/O_2	Cost	Availability	Deposit Formation
Ethanol	2.1	Low	Good	Low
~~Kerosene(RP-1)~~	~~2.56~~	~~High~~	~~Fair~~	~~low~~
~~Gasoline~~	~~3.2~~	~~Low~~	~~Good~~	~~High~~

Oxidizers	Mixture Ratio by mass	Cost	Density(2MPa) (EES)	Storage Requirements
LOX	2.1	Medium	1156 kg/m^3	Pressure Relief
~~GOX~~	~~2.1~~	~~Low~~	~~28.73 kg/m^3~~	~~High Pressure~~
~~N_2O~~	~~6.08~~	~~Low~~	~~38.78 kg/m^3~~	~~High Pressure~~

Fluid Thrust Chamber Design

Performance Parameters

$$c = v_2 + (p_2 - p_3)A_2/\dot{m} \quad (2\text{–}16)$$

$$F = \dot{m}v_2 + p_2A_2 \quad (2\text{–}15)$$

$$c^* = p_1A_t/\dot{m} \quad (2\text{–}18)$$

$$c^* = \frac{\sqrt{kRT_1}}{k\sqrt{[2/(k+1)]^{(k+1)/(k-1)}}} \quad (3\text{–}32)$$

$$t_s = V_c/(\dot{m}\mathcal{V}_1) \quad (8\text{–}10)$$

$$L^* = V_c/A_t \quad (8\text{–}9)$$

Sutton, Rocket Propulsion Elements 7th edition

Characteristic Velocity
900 m/s to 2500 m/s

Stay time
0.001 to 0.040 sec

Characteristic Length
Typically 0.8 to 3.0 Meters for bipropellants (sutton)

Huzel, Dieter, and David Huang. "Introduction." *Modern Engineering for Design of Liquid-Propellant Rocket Engines*. Vol. 147. Washington D.C.: AIAA, 1992. 7-22. Print.

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Fluid Thrust Chamber Design

Outline

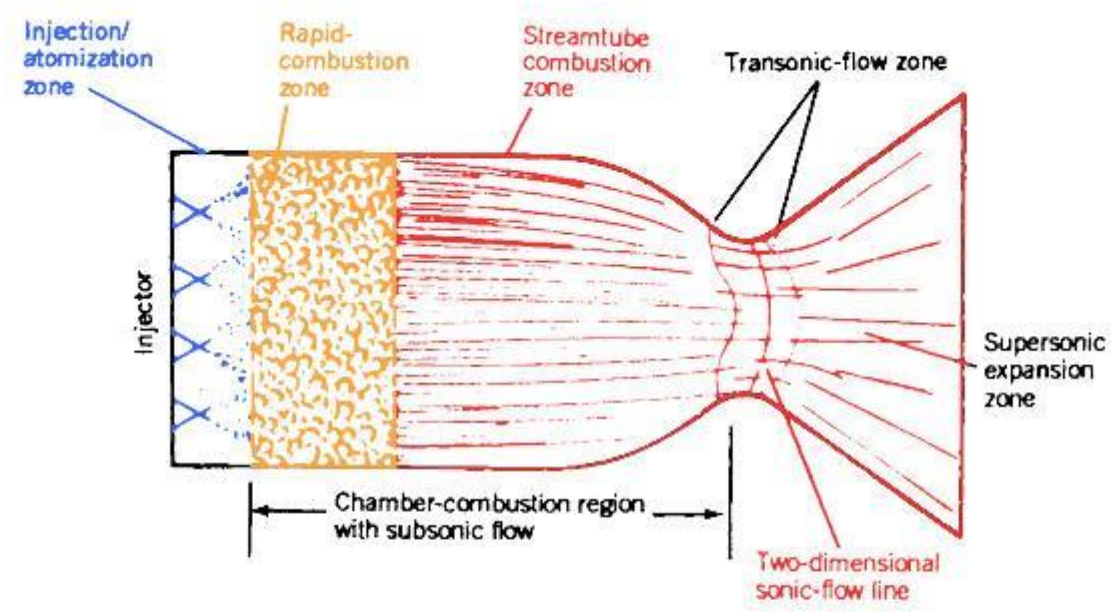


FIGURE 9–1. Division of combustion chamber into zones for analysis. (Reprinted with permission from Ref. 8–1, copyright by AIAA.)

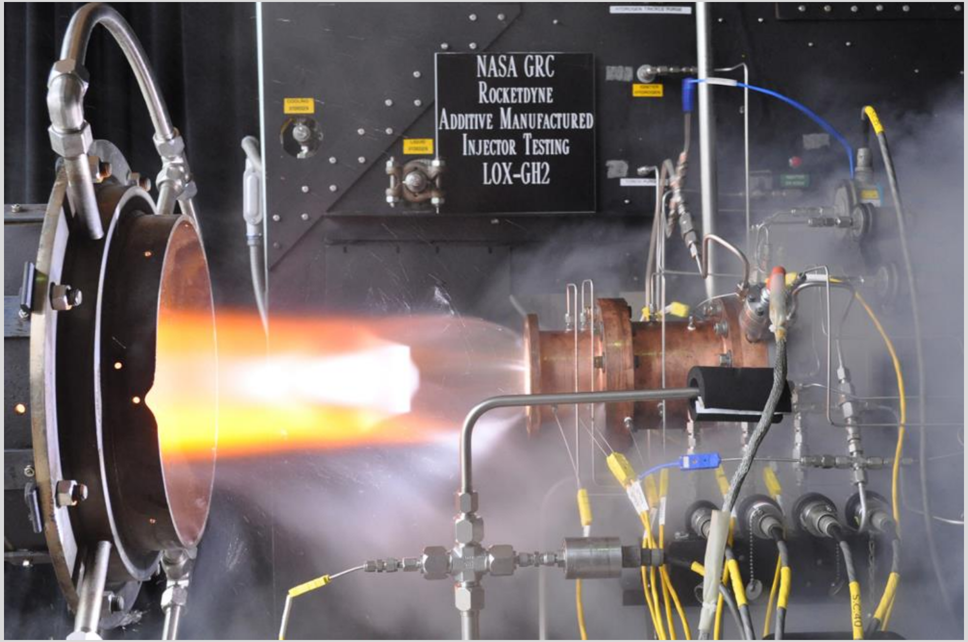
Sutton, Rocket Propulsion Elements 7th edition

Fluid Thrust Chamber Design

Fluid Injectors and Injector Heads

Selection Considerations

- Types of injector elements
- Number of elements/manifold design
- Selecting injector elements dependant on the the phase of the fluids being injected
- Manufacturing capabilities
- Heat transfer and combustion stability



http://www.dailytech.com/3D+Printed+Rocket+Engine+Injector+Designed+Tested/article31959.htm

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Fluid Injectors and Injector Heads

Liquid-Liquid Elements

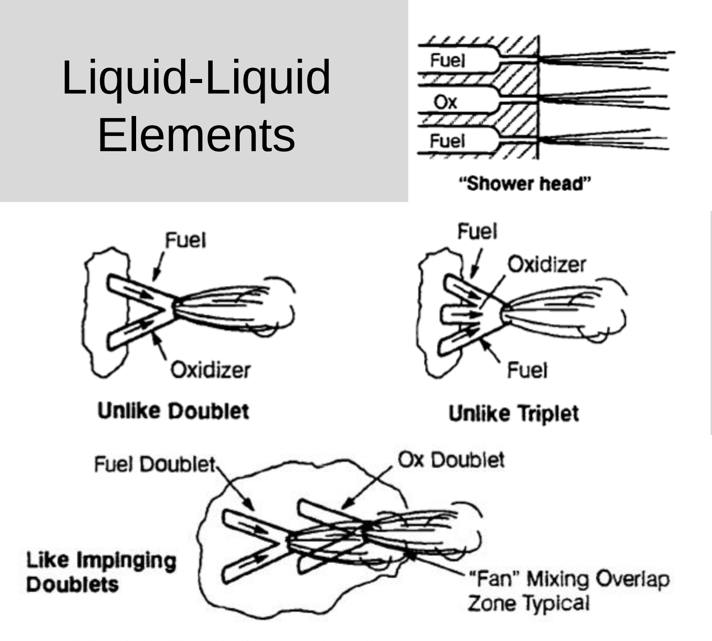


Fig. 4-57 Typical injector element types.

- Like and Unlike Elements
- Mixing Efficiency vs. Mass Distribution

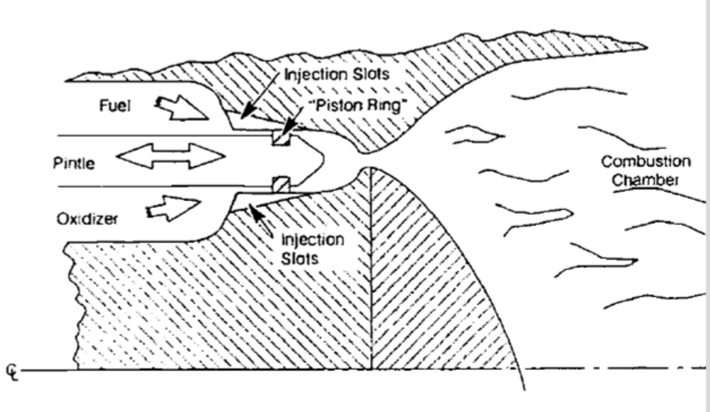


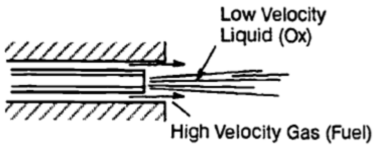
Fig. 4-60 Lance sustainer pintle injector.

Huzel, Dieter, and David Huang. "Introduction." *Modern Engineering for Design of Liquid-Propellant Rocket Engines*. Vol. 147. Washington D.C.: AIAA, 1992. 7-22. Print.

Fluid Thrust Chamber Design

Fluid Injectors and Injector Heads

Gas-Liquid Elements



Coax Element

- Requires Phase change of one of our propellants from liquid to gas

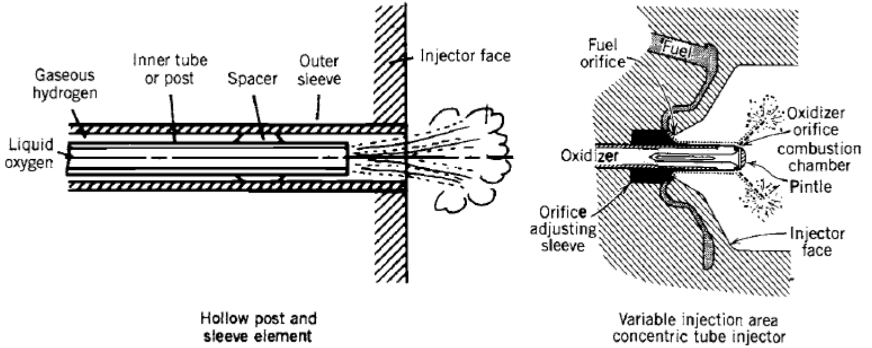


FIGURE 8–3. Schematic diagrams of several injector types. The movable sleeve type variable thrust injector is adapted from Ref. 8–1.

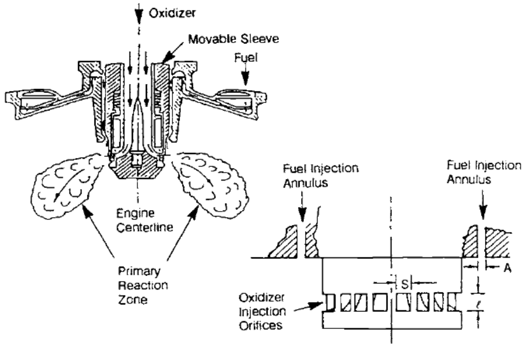


Fig. 4-59 Pintle injector.

Huzel, Dieter, and David Huang. "Introduction." *Modern Engineering for Design of Liquid-Propellant Rocket Engines*. Vol. 147. Washington D.C.: AIAA, 1992. 7-22. Print.

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Fluid Injector Impingement Patterns

- Conservation of Momentum
- Heat transfer to outer walls
- Reduce vortexing in the corner
- Account for different exit velocities

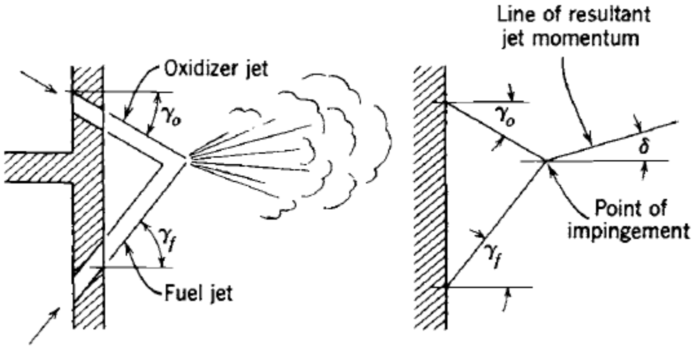

FIGURE 8–7. Angular relation of doublet impinging-stream injection pattern.

Sutton, George Paul, and Oscar Biblarz. "Thrust Chambers." Rocket Propulsion Elements. 7th ed. New York: John Wiley & Sons, 2001. Print.

For γ = 0 (axially aligned stream)

$$\dot{m}_o v_o \sin \gamma_o = \dot{m}_f v_f \sin \gamma_f$$

$$\tan \delta = \frac{\dot{m}_o v_o \sin \gamma_o - \dot{m}_f v_f \sin \gamma_f}{\dot{m}_o v_o \cos \gamma_o + \dot{m}_f v_f \cos \gamma_f}$$

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Fluid Thrust Chamber Design

Fluid Injector Manifolds

$$r = [(C_d)_o/(C_d)_f]A_o/A_f \qquad (8\text{--}4)$$

Corrected Mixture Ratio for injector testing

http://arstechnica.com/science/2013/04/how-nasa-brought-the-monstrous-f-1-moon-rocket-back-to-life/1/

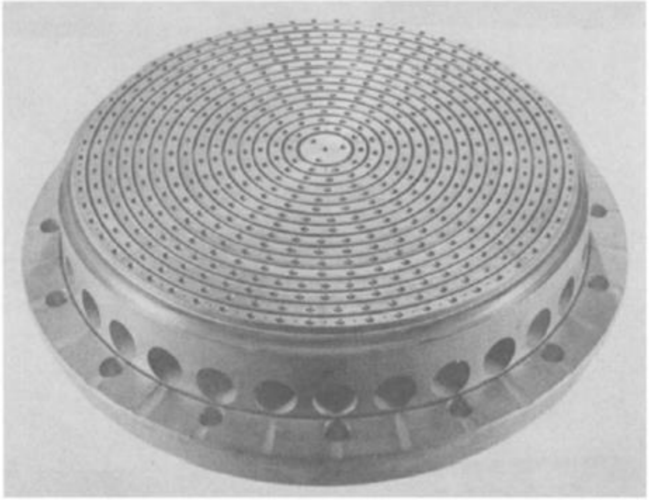

FIGURE 8–4. Injector with 90° self-impinging (fuel-against-fuel and oxidizer-against-oxidizer)-type countersunk doublet injection pattern. Large holes are inlets to fuel

Sutton, George Paul, and Oscar Biblarz. "Thrust Chambers." Rocket Propulsion Elements. 7th ed. New York: John Wiley & Sons, 2001. Print.

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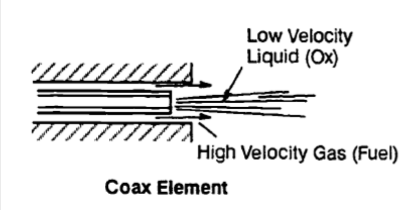
Fluid Thrust Chamber Design

Selection

Gas-Liquid Element



- 1st Choice
- Regenerative Cooling System

Liquid-Liquid Element

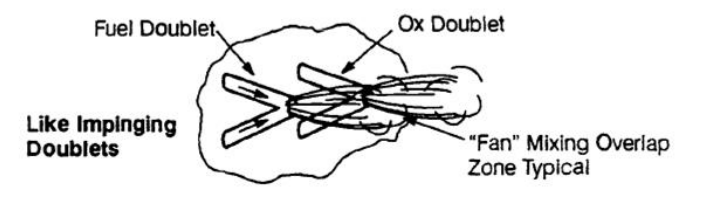


Fig. 4-57 Typical injector element types.

- 2nd Choice
- Ablative Cooling System

Fluid Thrust Chamber Design

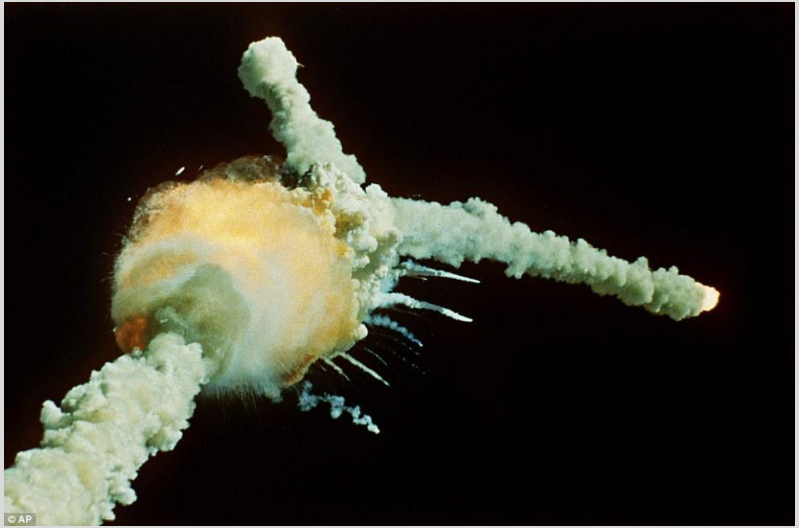
Heat Transfer - Introduction

Why is heat transfer important in rocket design?

- Guides the design, testing and failure investigations
- The thrust chamber must be cooled in order to withstand imposed loads and stresses

General idea of steady-state cooling methods

- Extreme temperatures are created in thrust chamber
- A liquid or solid is meant to absorb the heat being created before being expelled from the rocket



^boom

http://www.dailymail.co.uk/news/article-1341521/Boom-Indian-space-scientists-watch-horror-rocket-explodes-minutes-off.html

Fluid Thrust Chamber Design

Heat Transfer - Distribution

Heat Distribution

- Heat is transferred to the nozzle walls, injector face and thrust chamber
- Most heat transfer occurs due to convection and radiation
- Peak occurs at nozzle throat
- Minimum is at the nozzle exit

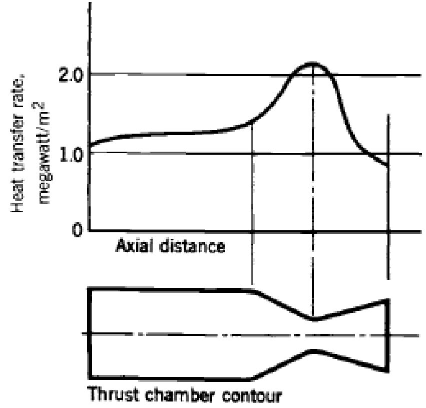


FIGURE 8–8. Typical axial heat transfer rate distribution for liquid propellant thrust chambers and solid propellant rocket motors. The peak is always at the nozzle throat and the lowest value is usually near the nozzle exit.

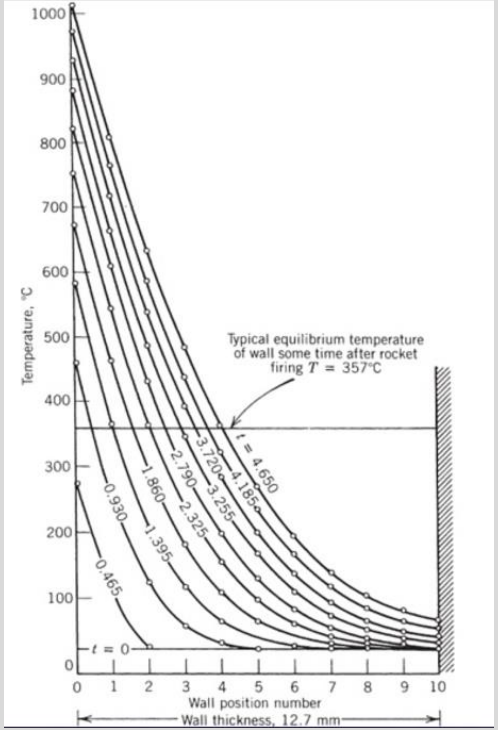
Sutton, Rocket Propulsion Elements 7th edition

Fluid Thrust Chamber Design

Heat Transfer - Method Overview

Methods

- Steady State Cooling
  - Heat transfer rate and temperature of the thrust chamber reach thermal equilibrium
- Transient Heat Transfer/Heat Sink Method
  - Temperature of thrust chamber does not reach equilibrium
  - Temperature continues to increase with duration of thrust
  - Design wall thickness and material to withstand max temperature
  - Simple to implement
  - Only works for very short burn times



Sutton, Rocket Propulsion Elements 7th edition

Fluid Thrust Chamber Design

Heat Transfer - Regenerative Cooling

- Regenerative Cooling
  - Summary
    - Regenerative because often times the coolant is one or both of the propellants before it is injected
    - Fuel, oxidizer or combination of the two is fed through a cooling jacket to absorb heat before ejection
  - Pros
    - Good for long durations
    - Requires less exotic materials than other alternatives
    - Preheating the fuel prior to injection raises it’s energy level
  - Cons
    - High manufacturing complexity

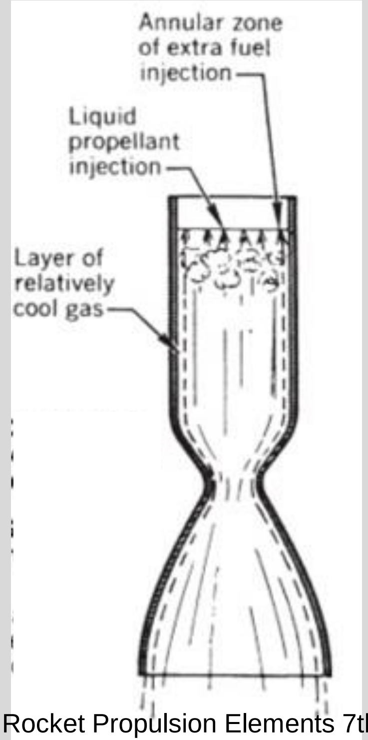
http://www.slideshare.net/srikanthlaxmanvinjam/cooling-in-liquid-rockets

Fluid Thrust Chamber Design

Heat Transfer - Supplementary Cooling Methods

Film cooling

- Summary
  - Auxiliary method to augment another technique of cooling
  - A relatively thin fluid film protects the walls from excessive heat
  - Can be applied by injecting small quantities of fuel or an inert fluid through at very low velocity through orifices in injector



Sutton, Rocket Propulsion Elements 7th edition

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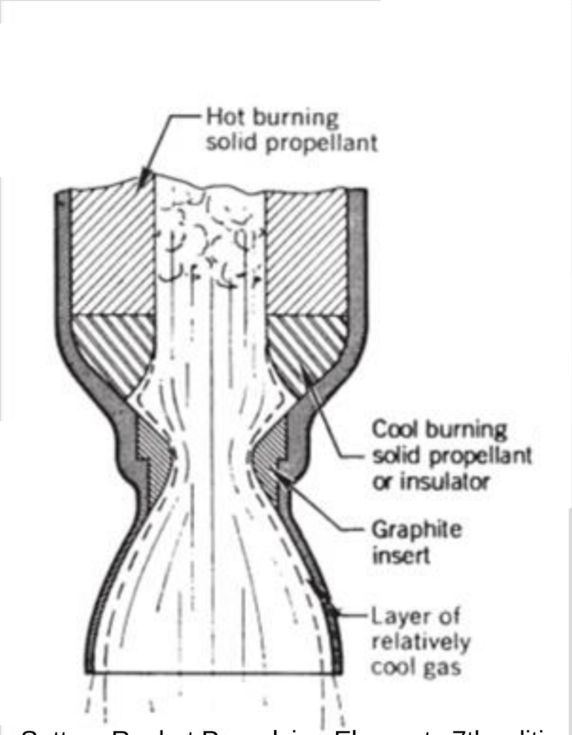
Heat Transfer - Supplementary Cooling Methods

Ablative cooling

- Summary
  - The inside of the chamber is coated with a solid ablative shield that slowly burns away in a controlled manner and carries the absorbed heat away from the rocket while the remaining material insulates the thrust chamber
- Pros
  - Operates for several minutes
- Cons
  - One time use
  - Low chamber pressure

Radiative Cooling

- Up to 35% of heat transfer is through radiation
- Nozzle and thrust chamber usually stick out of vehicle to accomodate



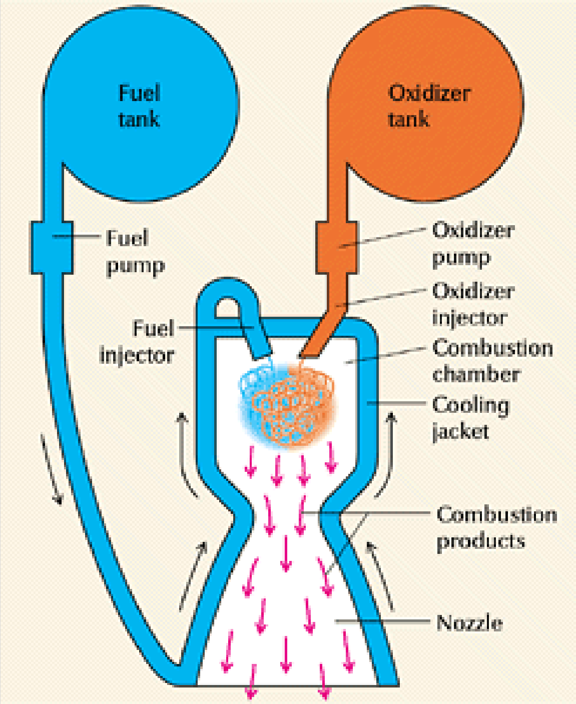
Sutton, Rocket Propulsion Elements 7th edition

Fluid Thrust Chamber Design

Heat Transfer - Design

Design Decisions

- Best option:
  - Regenerative cooling
  - pending whether or not we can 3D print
    - MTI
- Fallback options
  - Ablative cooling with graphite
  - Film cooling



http://darshan-earnmoney.blogspot.com/2010/02/rocket.html

Fluid Thrust Chamber Design

Combustion Instabilities

- Causes
  - Energy Flow
  - Coupling
- Consequences
  - Engine failure
- Three general types:
  - Low Frequency
    - Internal Damage
    - Non-acoustic
  - High Frequency
    - Large oscillations
    - Acoustic

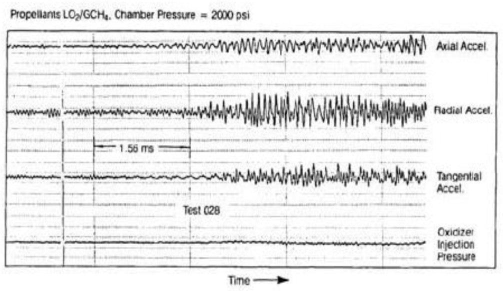


Fig. 4-77 Injection-coupled acoustic instability.

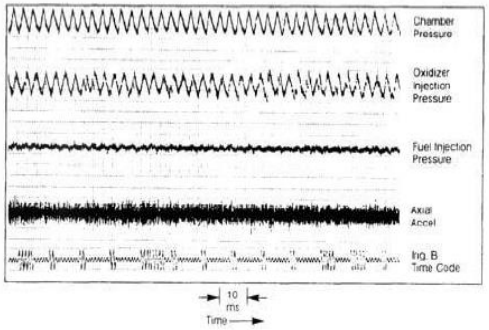


Fig. 4-78 Typical chug instability.

Arbit, Modern Engineering Design of Liquid Rocket Propellants

Fluid Thrust Chamber Design

General Frequency Equation

- Longitudinal Mode
  - Least severe form
- Tangential Mode
  - Most severe form
- Radial mode
- Optimize for Tangential

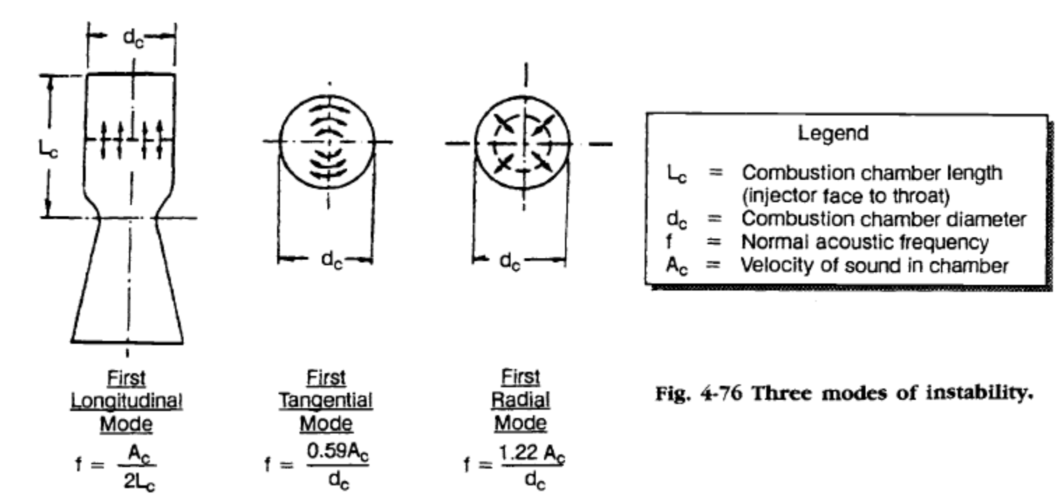


Fig. 4-76 Three modes of instability.

Arbit, Modern Engineering Design of Liquid Rocket Propellants

$$f_{ijk} = A_c[(a_{ij}/d_c)^2 + (k/2L_c)^2]^{0.5} \qquad (4\text{-}49)$$

Fluid Thrust Chamber Design

Acoustic Effects

- Intrinsic Acoustic
  - Dependencies
    - Chemical Kinetics
  - Coaxial injectors are best for preventing effects.

- Video
  - Geometry relates to acoustics
    - Affects coupling

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Fluid Thrust Chamber Design

Avoiding Instabilities/Practicality

- The steps to avoid instabilities require steady state pressure releases
  - Injectors must have constant heat release rate
- Testing for the oscillations require extensive studies.
  - Model procedures
- Stability Systems
  - Wall Gap
  - Cavities
  - Baffles

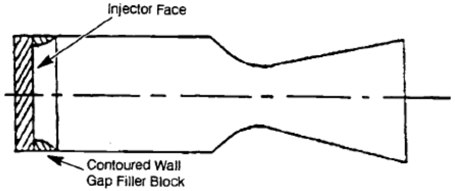
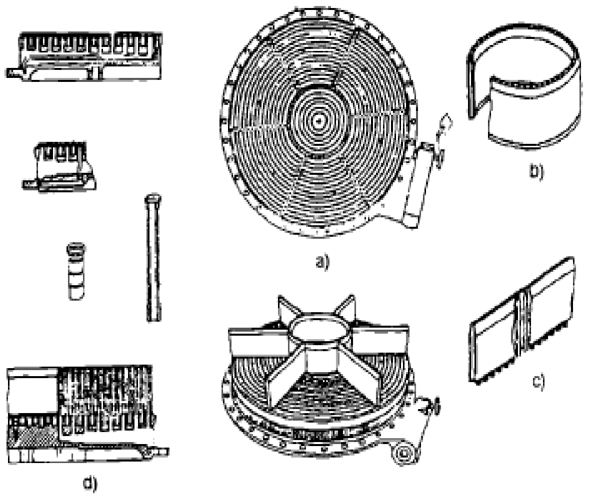


Fig. 4-79 Combustion chamber divergent wall gap.



a) Placement of baffles on injector face
b) Fuel-cooled baffle hub
c) Fuel-cooled baffle spoke
d) Baffle coolant feeds

Arbit, Modern Engineering Design of Liquid Rocket Propellants

Fluid Thrust Chamber Design

Application

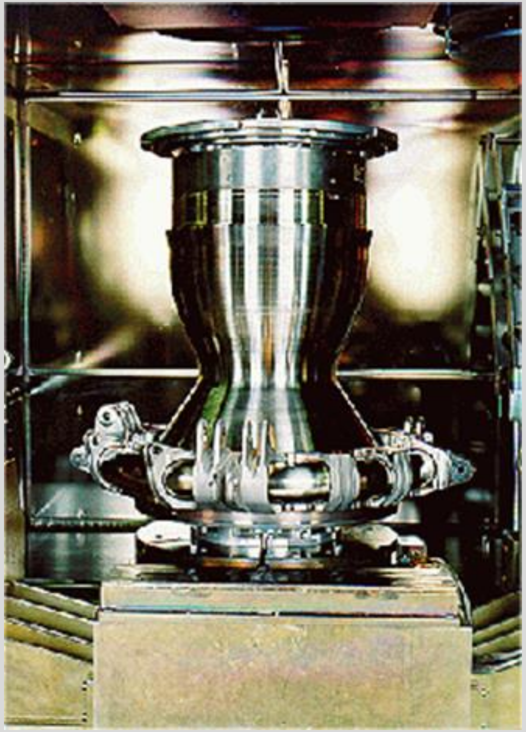
- Design of the combustion chamber to reduce oscillations
- Injectors should be regulated
- Rocket burn time
  - Experimental evaluation
  - Pressure transducers to check for this
- Account for tangential instabilities

Fluid Thrust Chamber Design

Combustion Chamber

Material Properties for the combustion chamber and nozzle:

- Working Temperature
- Strength at High Temperature
- Oxidation Resistance
- Machinability/Weldability
- Corrosion Resistance
- Thermal Conductivity



http://cs.astrium.eads.net/sp/launcher-propulsion/manufacturing/welding-technologies.html

Fluid Thrust Chamber Design

Combustion Chamber

Material of choice: Superalloy

Superalloy: Alloy that can withstand high temperature, high stresses, and highly oxidizing environments

Two Types of Superalloys:

- Nickel Based
- Cobalt Based

Nickel Based: More widely used, higher strength, ductility and fracture toughness

Cobalt Based: Higher oxidation, hot corrosion, and wear resistance

http://www.spacex.com/news/2014/07/31/spacex-launches-3d-printed-part-space-creates-printed-engine-chamber-crewed

Fluid Thrust Chamber Design

Combustion Chamber

Superalloy of choice: Haynes 230

Other Superalloys to consider:

- Haynes 25: Lower Working Temperature (WT) 980 °C
- Inconel 625: Hard to Machine, Lower WT (980 °C)
- Inconel 728: Lower WT than Inconel 625 (700 °C)
- Rene 41: Lower WT (980 °C), Harder to machine than Inconel

Other Material Considerations:

- 3D Printing C-103: Extremely expensive (MTI)
- Graphite: Would have to replace after every use
- Ceramic: Unknown distributor, low ductility

Haynes 230

Element	Weight %
Ni	57[a]
Cr	22
W	14
Mo	2
Fe	3*
Co	5*
Mn	.5
Si	.4
Al	.3
C	.1
La	.02
B	.015*

Fluid Thrust Chamber Design

Combustion Chamber

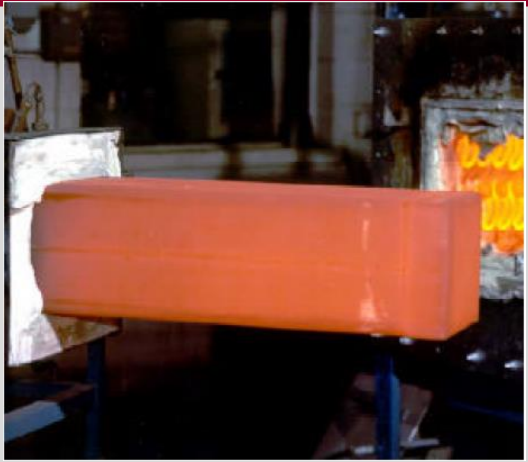
Machinability/Weldability

Can be:

- Forged (Cold Worked)
- Hot worked (at 1177 °C)
- Casted

Welding options:

- Gas Metal arc (GMAW)
- Gas Tungsten arc (GTAW)
- Resistance Welding



http://www.haynesintl.com/pdf/h3000.pdf (pg. 19)

http://www.haynesintl.com/pdf/h3000.pdf (pg. 17)

Fluid Thrust Chamber Design

Combustion Chamber

Working Temperature

- Working Temperature of at least 1150 °C
- Melting Temperature is 1300 °C
- Chamber Temperatures could be as high as 2500 °C

Strength at High Temperature

- Chamber pressures may be as high as 2 MPa

SMART Rockets (http://www.dglr.de/publikationen/2013/301353.pdf)

Vacuum Investment Castings (As Cast)

Test Temperature		Ultimate Tensile Strength	
°F	°C	Ksi	MPa
Room	Room	89.0	615
1000	538	65.6	450
1200	649	69.8	480
1400	760	55.8	385
1600	871	41.0	285
1800	982	29.4	205
2000	1093	12.9	89

http://www.haynesintl.com/pdf/h3000.pdf (pg. 9)

Fluid Thrust Chamber Design

Summary/Selections

First Choices

- **Injector:** Coax Element
- **Cooling System:** Regenerative Cooling
- **Thrust Chamber Material:** C-103

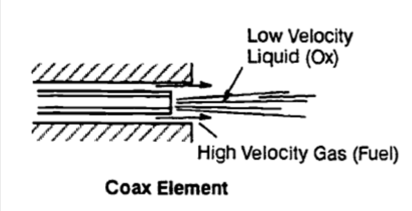
Secondary Options

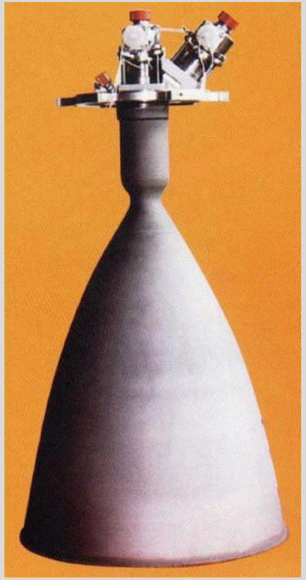
- **Injector:** Like Impinging Doublet
- **Cooling System:** Ablative Cooling
- **Thrust Chamber Material:** Haynes 230

Additional Considerations

- Acoustic design configuration

http://www.k-makris.gr/RocketTechnology/ThrustChamber/Thrust_Chamber.htm





https://cvdmaterialstechnology.files.wordpress.com/2013/03/1-s2-0-s0094576504001614-gr1.jpg

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Kevin Cavender, Den Donahou, Connor Halliday, Mario Reillo, Marshall Crenshaw

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Appendix: Combustion Chamber

Oxidation Resistance

- Mils (thousandths of an inch)

Comparative Burner Rig Oxidation Resistance 1000 Hour Exposure at 1800°F (982°C)

Alloy	Metal Loss		Average Metal Affected		Maximum Metal Affected	
	Mils	µm	Mils	µm	Mils	µm
230® alloy	0.8	20	2.8	71	3.5	89

http://www.haynesintl.com/pdf/h3000.pdf (pg. 15)

Fluid Thrust Chamber Design

Appendix: Combustion Chamber

Thermal Conductivity

- Important to maintain a lower internal combustion chamber temperature

Low when compared to softer metals (@ 973.2 K) like:
- Copper: 354 W/m-K
- Aluminum: 92 W/m-K
- Nickel: 71 W/m-K

Comparable to stronger metals (@ 973.2 K) like:
- Carbon Steels: ~30 W/m-K
- Low Alloy Steels: ~30 W/m-K
- Stainless Steels: ~24 W/m-K
- High Alloy Steels: ~23 W/m-K

Room	8.9 W/m-K
100	10.4 W/m-K
200	12.4 W/m-K
300	14.4 W/m-K
400	16.4 W/m-K
500	18.4 W/m-K
600	20.4 W/m-K
700	22.4 W/m-K
800	24.4 W/m-K
900	26.4 W/m-K
1000	28.4 W/m-K

http://www.haynesintl.com/pdf/h3000.pdf (pg. 12)