An Introduction to Space Propulsion

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What Is Propulsion?

• Initiating or changing the motion of a body
  • *Translational* (linear, moving faster or slower)
  • *Rotational* (turning about an axis)

• Space propulsion
  • Rocket launches
  • Controlling satellite motion
  • Maneuvering spacecraft

• Jet propulsion
  • Using the momentum of ejected mass (propellant) to create a *reaction force*, inducing motion

*At one time it was believed that rockets could not work in vacuum -- they needed air to push against!!*
Jet Propulsion Classifications

- **Air-Breathing Systems**
  - Also called *duct propulsion*.
  - Vehicle carries own fuel; surrounding air (an *oxidizer*) is used for combustion and thrust generation.
  - Gas turbine engines on aircraft.

- **Rocket Propulsion**
  - Vehicle carries own fuel and oxidizer, or other expelled propellant to generate thrust.
  - Can operate outside of the Earth’s atmosphere.
  - Launch vehicles, upper stages, Earth orbiting satellites and interplanetary spacecraft.
Space Propulsion Applications

- Launch Vehicles
- Ballistic Missiles
- Earth Orbiting Satellites
- Upper Stages
- Interplanetary Spacecraft
- Manned Spaceflight

- Titan IV
- ICBM
- Tracking & Data Relay Satellite
- Inertial Upper Stage with Magellan spacecraft
Space Propulsion Functions

- Primary propulsion
  - Launch and ascent
  - Maneuvering
    - Orbit transfer, station keeping, trajectory correction
- Auxiliary propulsion
  - Attitude control
  - Reaction control
  - Momentum management

NASA’s Stardust spacecraft performs an attitude control thruster burn.
A Brief History of Rocketry

- China (300 B.C.)
  - Earliest recorded use of rockets
  - Black powder
- Russia (early 1900’s)
  - Konstantin Tsiolkovsky
  - Orbital mechanics, rocket equation
- United States (1920’s)
  - Robert Goddard
  - First liquid fueled rocket (1926)
- Germany (1940’s)
  - Wernher von Braun
  - V-2
  - Hermann Oberth

The United States did not become seriously involved in rocket technology until the 1940’s
Space propulsion systems are classified by the type of energy source used.
Stored Gas Propulsion

- Primary or auxiliary propulsion.
- High pressure gas (*propellant*) is fed to low pressure nozzles through pressure regulator.
- Release of gas through nozzles (*thrusters*) generates thrust.
- Currently used for momentum management of the Spitzer Space telescope.
- Propellants include nitrogen, helium, nitrous oxide, butane.
- Very simple in concept.
Chemical Propulsion Classifications

- **Liquid Propellant**
  - Pump Fed
    - Launch vehicles, large upper stages
  - Pressure Fed
    - Smaller upper stages, spacecraft
  - Monopropellant
    - Fuel only
  - Bipropellant
    - Fuel & oxidizer

- **Solid Propellant**
  - Launch vehicles, Space Shuttle
  - Spacecraft

- **Hybrid**
  - Sounding rockets

The Delta II launch vehicle uses liquid and solid propellant primary propulsion systems.
Monopropellant Systems

- **Hydrazine** fuel is most common monopropellant.
  - \( \text{N}_2\text{H}_4 \)
  - Decomposed in thruster using catalyst to produce hot gas for thrust.
  - Older systems used hydrogen peroxide before the development of hydrazine catalysts.
  - Typically operate in *blowdown mode* (pressurant and fuel in common tank).
Bipropellant Systems

- A **fuel** and an **oxidizer** are fed to the engine through an **injector** and combust in the **thrust chamber**.
- **Hypergolic**: no igniter needed -- propellants react on contact in engine.
- **Cryogenic** propellants include LOX and LH2.
  - Igniter required
- **Storable** propellants include kerosene (RP-1), hydrazine, nitrogen tetroxide (N2O4), monomethylhydrazine (MMH)
Liquid Propellant Systems

- **Pump fed systems**
  - Propellant delivered to engine using *turbopump*
    - Gas turbine drives centrifugal or axial flow pumps
  - Large, high thrust, long burn systems: launch vehicles, space shuttle
  - Different *cycles* developed.

F-1 engine turbopump:
- 55,000 bhp turbine drive
- 15,471 gpm (RP-1)
- 24,811 gpm (LOX)
Rocket Engine Power Cycles

- **Gas Generator Cycle**
  - Simplest
  - Most common
  - Small amount of fuel and oxidizer fed to gas generator
  - Gas generator combustion products drive turbine
  - Turbine powers fuel and oxidizer pumps
  - Turbine exhaust can be vented through pipe/nozzle, or dumped into nozzle
  - Saturn V F-1 engine used gas generator cycle

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Rocket Engine Power Cycles - cont

• Expander
  • Fuel is heated by nozzle and thrust chamber to increase energy content
  • Sufficient energy provided to drive turbine
  • Turbine exhaust is fed to injector and burned in thrust chamber
  • Higher performance than gas generator cycle
  • Used on Pratt-Whitney RL-10
    • Atlas/Centaur stage
Rocket Engine Power Cycles - cont

- **Staged Combustion**
  - Fuel and oxidizer burned in *preburners* (fuel/ox rich)
  - Combustion products drive turbine
  - Turbine exhaust fed to injector at high pressure
  - Used for high pressure engines
    - SSME (2700 psia)
  - Most complex, requires sophisticated turbomachinery
  - Not very common

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Liquid Propellant System - cont’d

- **Pressure fed systems**
  - Gas pressure forces propellant to engine.
  - Small, medium thrust bipropellant systems
    - Upper stages
    - Apogee systems
  - Monopropellant systems
    - Primary propulsion
    - Auxiliary propulsion

Leakage of fuel and ox vapor past the check valves is considered the most likely cause of the MO mission failure.
Solid Propellant Motors

- Fuel and oxidizer are in solid binder.
- Single use -- no restart capability.
- Lower performance than liquid systems, but much simpler.
- Applications include launch vehicles, upper stages, and space vehicles.
Hybrid Motors

- Combination liquid-solid propellant
  - Solid fuel
  - Liquid oxidizer
- Multi-start capability
  - Terminate flow of oxidizer
- Fuels consist of rubber or plastic base, and are inert.
- Oxidizers include LO$_2$, hydrogen peroxide (N$_2$O$_2$) and nitrous oxide (NO$_2$)
- Shut-down/restart capability.
Liquid Fueled Rocket Engines

RD-180 engine (Atlas V)

Saturn F-1 engine (left & top left)
1,500,000 lb thrust.
Rocket Performance Calculations

- **Thrust & Specific Impulse**
  - **Thrust** is the amount of force generated by the rocket.
  - **Specific impulse** is a measure of engine performance (analogous to miles per gallon)
    - Units are **seconds**
    - \[ I_{\sigma} = \frac{\Phi}{\omega} \]
    - \( \Phi = \) rocket thrust
    - \( \omega = \) weight flow rate of propellant

- **Rocket Equation**
  - \[ \Delta \zeta = \gamma I_{\sigma} \ln \left( \frac{\mu_t}{\mu_\phi} \right) \]
  - \( \gamma = 9.8 \, \mu / \sigma \)
  - \( \mu_t = \) mass of fuel before
  - \( \mu_\phi = \) mass of fuel after
  - \( \mu_\pi = \) mass of propellant
  - \[ \mu_\pi = \mu_t \left( 1 - e^{-\gamma I_{\sigma}} \right) \]

*Rocket equation assumes no losses (gravity effects, aerodynamic drag). Actually very accurate for short burns in Earth orbit or in deep space!*
### Specific Impulse Comparison

<table>
<thead>
<tr>
<th>Propellant Type</th>
<th>Specific Impulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored gas</td>
<td>60-179 sec</td>
</tr>
<tr>
<td>Monopropellant hydrazine</td>
<td>185-235 sec</td>
</tr>
<tr>
<td>Solid rocket motors</td>
<td>280-300 sec</td>
</tr>
<tr>
<td>Hybrid rockets</td>
<td>290-340 sec</td>
</tr>
<tr>
<td>Storable bipropellants</td>
<td>300-330 sec</td>
</tr>
<tr>
<td>LOX/LH2</td>
<td>450 sec</td>
</tr>
</tbody>
</table>

Specific impulse depends on many factors: altitude, nozzle expansion ratio, mixture ratio (bipropellants), combustion temperature.

The MR-106E, used on the Genesis spacecraft, has a specific impulse of 235 sec. It is a monopropellant (hydrazine) thruster.
<table>
<thead>
<tr>
<th>Mission (duration)</th>
<th>Delta-V (km/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth surface to LEO</td>
<td>7.6</td>
</tr>
<tr>
<td>LEO to Earth Escape</td>
<td>3.2</td>
</tr>
<tr>
<td>LEO to Mars (0.7 yrs)</td>
<td>5.7</td>
</tr>
<tr>
<td>LEO to Neptune (29.9 yrs)</td>
<td>13.4</td>
</tr>
<tr>
<td>LEO to Neptune (5.0 yrs)</td>
<td>70</td>
</tr>
<tr>
<td>LEO to alpha-Centauri (50 yrs)</td>
<td>30,000</td>
</tr>
</tbody>
</table>

LEO = Low Earth orbit (approx. 274 km)
Propellant Calculation Exercise

• Determine the mass of propellant to send a 2500 kg spacecraft from LEO to Mars (0.7 yr mission).
  • Assume the 2500 kg includes the propellant on-board at the start of the burn.
  • Assume our engine has a specific impulse of 310 sec (typical of a small bipropellant engine).
  • Use the rocket equation:

\[ \mu = (2500) \left[ 1 - \frac{-5700}{(9.8)(310)} \right] = 2117 \ \text{kg} \]

Most of our spacecraft is propellant! Only 383 kg is left for structure, etc! How could we improve this?
Interplanetary travel will require advanced forms of propulsion technology:
- Antimatter
- Nuclear fusion
- Non-rocket methods

Considerable research is being conducted within NASA and major universities on advanced propulsion technologies.
References

• Theory and design
    • A classic; covers liquid and solid rockets
    • Dieter Huzel was one of the German engineers who came to the U.S. after WW II.
    • Covers chemical (liquid, solid, hybrid), nuclear, electric, and advanced propulsion systems for deep space travel
• Rocket engine history
    • The story of Werner von Braun, the V-2 and the transition of the German engineers to the United States following WW II
    • New, over 800 pages of rocket engine history