SESA 6071

Spacecraft Propulsion

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Contents

List of Figures

List of Tables

Definitions

$\boldsymbol{I_t}$	Total Impulse (Ns)	$\boldsymbol{I_{sp}}$	Specific Impulse (s)
$\boldsymbol{F}$	Rocket Thrust (N)	$\boldsymbol{g_0}$	Standard Gravitational Accel (m/s^2)
$\boldsymbol{\dot{m}}$	Propellent mass flow rate (kg/s)	$\boldsymbol{m_p}$	Expelled propellent mass (kg)
$\boldsymbol{c}$	Effective exhaust velocity (m/s)		

1. Lecture 1

1.1. What is Rocket Propulsion

Propulsion itself is the **act of changing the motion of a body**, typically by using newtons third law and it can be classified in various types of ways. A more colloquial way of defining rocket propulsion is as **mass drivers**, throwing out mass one way to yield an acceleration in the other.

1.2. Rocket Propulsion Family Tree

In **Figure 1** the rocket propulsion types are grouped by the energy source.

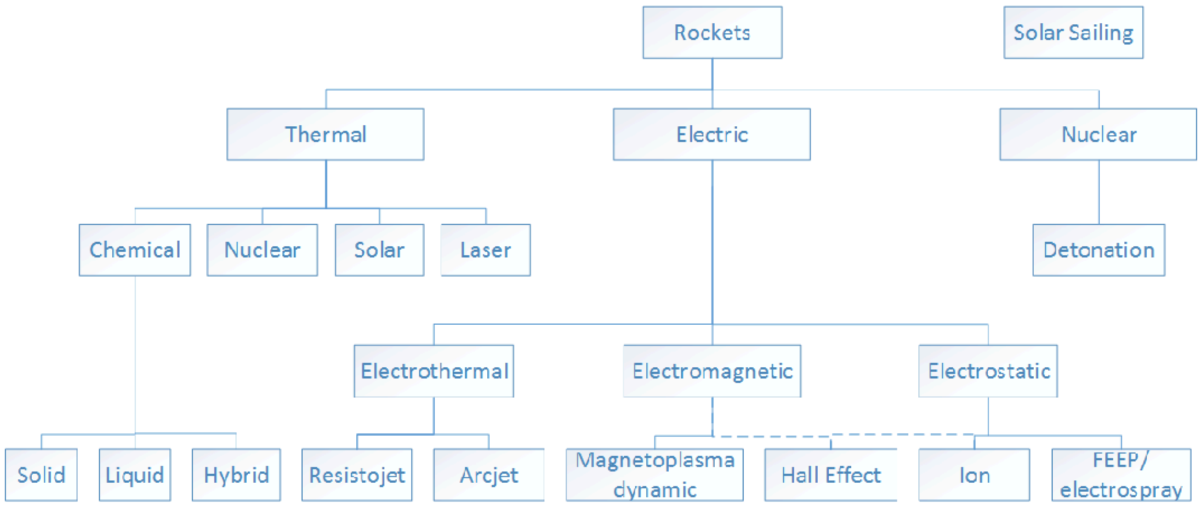

Figure 1: Flowchart of the rocket propulsion family tree

1.2.1. Chemical Rockets

These utilize either a chemical reaction or decomposition to generate energy. Gas is heated to between **700°C - 1300°C** and to speeds between **1.5 km/s - 4.5 km/s**. These require a **fuel and oxidizer** and come in the following types:

- **Solid:** Fuel and oxidizer mixed within into a solid grain which cannot stop burning once ignited. feature **high thrust with low performance**.
- **Liquid:** Burn a liquid fuel and oxidizer allowing for repeated firings and variable thrust. Feature **high performance and thrust with high complexity**.
- **Hybrid:** Have a liquid oxidizer but a solid fuel allowing for better performance than solid with lower complexity.

1.2.2. Electric Rockets

These use electrical energy to generate thrust without utilizing combustion. Typically have very high exhaust velocities ($\sim$ **$60,000$ m/s**) and therefore **very high performance** at the costs of **high complexities and very low thrust**. The four distinct groups are:

- **Electrothermal:** Uses electrical energy to heat a propellent (Resistojet). Are **simple to build** at the cost of **low thrust**.
- **Electrostatic:** Uses electrical energy to accelerate ionized fuel across an electric fields. Feature **good performance** at the cost of **being expensive and low thrust**.
- **Electromagnetic:** Accelerates an ionized fuel using a magnetic field. Fall issue to **low efficiency unless power input is high**.
- **Hall Effect Thruster:** Uses a mixture of both electrostatic and electromagnetic propulsion methods to accelerate propellent. These are the most **commonly used**.

1.2.3. Nuclear Rockets

Broadly speaking there are two types of nuclear rockets, these are:

- **Nuclear Detonation:** Use the shockwave produced when nuclear bombs are detonated to produce thrust (Orion Drive). **High performance and thrust** but are **very dangerous and have limited testing**.
- **Nuclear Thermal:** Uses the heat energy produced during nuclear fission to heat a propellent (typically hydrogen) which is then exhausted. These have **high performance and thrust** but are **dangerous and have limited testing**.

1.2.4. Solar and Laser Rockets

These systems use large diameter telescopes to focus in a laser or solar radiation to heat up a propellent. These systems feature **high theoretical performance and moderate thrust** but are **very complex and lack any real testing**.

1.2.5. Solar Sails

These systems use no propellent at all and instead produce thrust through the momentum gained when a photon is incident on the sail. These systems feature **good performance with no fuel** but fall victim to **low thrust and engineering complexity**.

1.3. Rocket Propulsion Applications

Instead of grouping together rocket propulsion methods using the energy source, the rocket application can also be used, for example:

- **High Thrust/Maneuverability:** Typically have the cost of **low performance** and use **chemical or solid** propulsion methods.
- **High Performance:** Typically have the cost of **low thrust** and use **electrical** propulsion methods.
- **Balanced Thrust and Performance:** Typically the middle ground is **nuclear thermal**.

2. Lecture 2

2.1. Definitions and Fundamentals

To develop a empirical measure of performance we should first consider **Eq. 1**.

$$I_t = \int_0^t F \ \ dt \tag{1}$$

Where:
- $\boldsymbol{I_t}$: Total Impulse (Ns)
- $\boldsymbol{F}$: Thrust Force (N)
- $\boldsymbol{t}$: Burn Duration (s)

Note that for **Eq. 1**, if F is constant then the equation simplified to $I_t = Ft$. A more useful measure of performance for rocket engines is shown in **Eq. 2**.

$$I_{sp} = \frac{\int_0^t F \ \ dt}{g_0 \int_0^t \dot{m} \ \ dt} = \frac{I_t}{g_0 \int_0^t \dot{m} \ \ dt} \tag{2}$$

Where:
- $\boldsymbol{I_{sp}}$: Specific Impulse (s)
- $\boldsymbol{g_0}$: Standard Gravitational Accel (m/s^2) = 9.81 m/s^2
- $\boldsymbol{\dot{m}}$: Propellent mass flow rate (kg/s)

There is no concrete reason on why g_0 is present in this equation, however one common theory is that it allows $I_{sp}$to be in seconds instead of featuring a length unit which would eliminate any error in conversion from metric to imperial. If F and $\dot{m}$ are both constant over the t then **Eq. 2** simplifies to **Eq. 3**.

$$I_{sp} = \frac{I_t}{g_0 m_p} \tag{3}$$

Where:
- $\boldsymbol{m_p}$: Expelled propellent mass $(kg) = \dot{m}t$

Another useful parameter for defining engine performance is shown in **Eq. 4**.

$$c = \frac{F}{\dot{m}} \tag{4}$$

Where:
- $\boldsymbol{c}$: Effective exhaust velocity (m/s)

The exhaust velocity is called as such as the **velocity profile of the exhaust is not uniform**, this is most seen in chemical rockets due to the **no slip condition** but is slightly seen in electrical rockets too. Rearranging all of the previous equations together yields a definition for I_{sp} in terms of c.

$$I_{sp} = \frac{c}{g_0} \tag{5}$$

Typical I_{sp} values for the rocket engine types defined in the previous lecture are shown in **Table 1**.

Rocket Engine Type	$\boldsymbol{I_{sp}(s)}$
Chemical Using H_2/O_2	450
Solid	260
Cold Gas	70
Gridded Ion Thruster	3000

Table 1: Typical values of I_{sp}

2.2. Maximum Chemical Performance

A typical chemical reaction used in chemical rockets is combustion shown in **Eq. 6**.

$$\mathrm{H_2} + 1/2\ \mathrm{O_2} \longrightarrow \mathrm{H_2O} + \mathrm{Energy} \tag{6}$$