Basics of Rocket Propulsion

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ENGL 1120: Exposition and Argumentation

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October 19, 2025

Introduction

"It's not rocket science" is a common phrase used to describe the ease of something to the comparatively hard subject of rocket science. The core principles behind rocket science and propulsion, though, are surprisingly simple and readily understood once broken down.

By starting from the core physics principles of rocket propulsion, one can grasp the fundamental concepts necessary to understand how even the most advanced and complicated rockets ever conceived propel themselves out of the atmosphere and beyond.

Core Physics Principles

Almost everyone has heard some form of Newton's third law: Every action has an equal and opposite reaction. This simple law of nature is the very foundation which all of rocketry and rocket propulsion are built upon.

But what does the third law actually mean? It's best understood through an example: Imagine a person named John jumping; when John jumps, he is exerting a force down into the ground. This force is called the *action force*. However, that force alone would not push John into the air. He becomes airborne due to a force exerted on him by the ground of equal magnitude and in the opposite direction. This force is called the *reaction force*.

Rockets take advantage of action-reaction forces to accelerate themselves at great speed, even outside the presence of an atmosphere. By expelling mass at great speed, the rocket undergoes a reaction force of equal magnitude in the opposite direction, propelling the rocket.

Another fundamental concept of physics that is core to how rockets function is the *conservation of momentum*. Momentum is the mass of an object multiplied by the velocity of the same object (for the sake of simplicity, vector quantities will be ignored). The equation for the momentum of an object is $p = mv$, where p is the momentum of the object, m is the mass of the object, and v is the velocity of the object.

The law of conservation of momentum states that momentum can neither be created nor destroyed, and that the amount of momentum in a system remains constant (Hall 2021). Because rockets constantly expel propellants and thus decrease their mass, the velocity of the rocket must increase to conserve momentum.

The Rocket Equation

Luckily for rocketeers everywhere, an equation called the rocket equation, credited to Konstantin Tsiolkovsky, wraps all the previously mentioned physics principles up into one nice mathematical derivation given in Equation 1.

$$\Delta v = v_e ln \frac{m_0}{m_f} \tag{1}$$

Where Δv is the maximum change in velocity, v_e is the velocity of exhausted propellants, m_0 is the initial mass of the fully loaded rocket (called wet mass), and m_f is the final mass of the rocket (called dry mass).

The change in velocity, or Δv is the single most important quantity of a rocket. This is because the Δv determines how far and fast a rocket can go and thus is the limiting factor of spacecraft maneuvers and orbits.

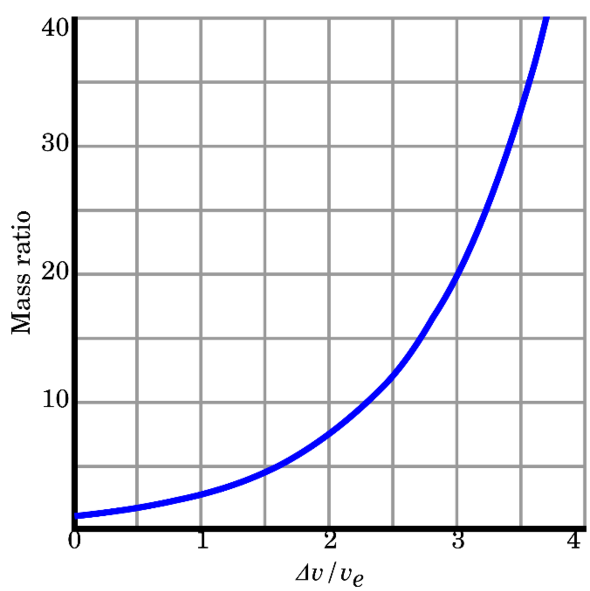
Much to the dismay of rocketeers everywhere, the equation reveals a massive issue with rockets. If we solve the equation for the required propellant mass to reach a desired Δv, we get Equation 2.

$$m_0 - m_f = m_f\left(e^{\frac{\Delta v}{v_e}} - 1\right) \qquad (2)$$

To some, the issue may already be apparent. To make it clearer, we will graph the required rocket mass ratio as a function of the effective exhaust velocity ratio. This graph is given in Figure 1. As it turns out, the mass of the propellant required to achieve a desired Δv increases at an exponential rate. This relationship makes sense, as to increase Δv, a rocket must accelerate all its current propellant, as well as the propellant required to gain more Δv. The problem is that, if we want to make rockets achieve bigger orbits or travel to further planets, we must use exponentially more propellant.

Figure 1

Graph of the Tsiolkovsky rocket equation



Note. *Image by Krishnavedala/ CC0*

There is a solution to this inherent property of rockets, however. By *staging* a rocket, it can drop off the unnecessary weight of spent tanks or boosters mid-flight. This decreases the dry mass of the rocket, increasing the mass ratio without having to add additional propellant.

Staging can be accomplished in many ways. Some rockets, like the Saturn V, employ *tandem staging*, where each stage fires one after another (Schulman 2025, p. 12). Other rockets, like the Space Shuttle, use *parallel staging*, where multiple stages fire at the same time, and are jettisoned at different times (Carrie & Hurley 1972). No matter what type of staging is used, though, it invariably increases rocket performance significantly. In fact, staging is so impactful to performance that only multi-stage rockets have ever reached orbital speed.

Introduction to the Rocket Engine

The engine's job is to take the stored chemical energy of the propellants and convert it into kinetic energy through high velocity exhaust.

Rocket engines all have three very important and fundamental components: the propellant, the combustion chamber, and the nozzle (Sutton & Biblarz 2001).

Propellant is where the chemical potential energy of the rocket is stored and is the mass that the engine exhausts out at high speeds. Rockets must operate in the vacuum of space, where there is no atmosphere and thus no oxygen. Because of this, they must bring both fuel and a propellant to supply oxygen, called an *oxidizer*.

The combustion chamber, as the name suggests, is the part of the engine where the propellants are combined and "exploded". This is where the chemical potential energy, stored in the bonds between the atoms, is released in the form of extreme pressure and temperature.

The nozzle of the engine is where the magic of rocket propulsion takes place. It converts the massive amounts of energy stored in the temperature and pressure of the combusted propellants into velocity. The goal of the nozzle is to match the pressure of the exhaust gases to the pressure of the ambient environment, converting as much energy as possible into speed.

Efficiency Metric

When purchasing a car, one of the most important factors that affects your choice is likely the vehicles fuel economy. The same is true for engineers when designing and building rocket engines. If the engine is inefficient, it wastes valuable and heavy fuel that could be used propelling the rocket forward. Because efficiency is so important, engineers compare rocket engine efficiency with a metric called *specific impulse*, or I_{sp} (Sutton & Biblarz 2001). Equation 3 details the equation for I_{sp}.

$$I_{sp} = \frac{I_{total}}{m \cdot g} \tag{3}$$

Where I_{total} is the total impulse (total change in momentum), m is the mass of used propellant, and g is the acceleration due to the force of gravity on earth.

I_{sp} is typically given in seconds because of unit cancellation; this means that both metric and imperial units will give you the same value. This may seem confusing, but I_{sp} can be thought of as the amount of time that an engine given one mass unit of fuel can produce one mass unit of thrust.

Propellant Types

Rocket engines primarily fall into two categories: liquid engines and solid engines. Each type has its own applications, advantages, and disadvantages. Many rockets even use a combination of both liquid main engines and solid rocket boosters – like the Space Shuttle and Atlas V (Sutton & Biblarz 2001).

Liquid rocket engines are the most common engine found in professional launch vehicles. Liquid engines, as their name implies, use propellants stored as liquids in tanks. The propellants must be pressurized before being injected into the combustion chamber. The process of pressurizing the propellants adds significant complexity and is the primary downside to liquid engines. These engines are still chosen for most rockets, however, due to their superior performance, efficiency, reusability, and versatility.

Solid rocket motors are the simplest type of rocket motor and are most commonly found in rocket boosters and hobbyist rockets. In this type of motor, the propellant is stored as a solid, which is cast into a casing and burnt in a similar fashion to a candle. Solid motors are less complex than their liquid counterparts, but they come with a myriad of downsides. These motors aren't throttleable, meaning that you are unable to control their amount of thrust after ignition, meaning that once you ignite it, it doesn't stop until it completely burns. Additionally, the chemicals that must be used in order to make the propellant solid decrease thrust performance and can often be toxic. In recent years, the biggest downside to solid motors is their lack or reusability, contrary to the industry's shift away from expendable rockets.

Conclusion

Rocket propulsion and rocketry seem like daunting and complex subjects. However, when broken down and examined, the beautiful simplicity of them can truly shine. I hope that, by reading this article, you can gain a level of conceptual understanding where you feel as though you could have discovered and derived the concepts yourself. Although you may not be the next Wernher von Braun building a space program from the ground up, you certainly can continue to break difficult concepts up into their basic, fundamental ideas like you did while reading this text.

References

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