How a rocket works

Introduction

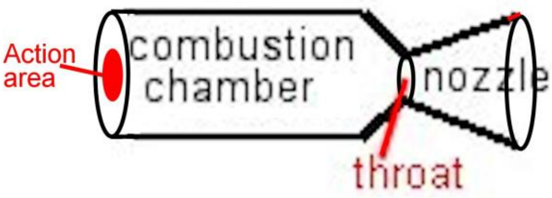
Rocket science is taken to mean something terribly complex and unfathomable. But actually, a rocket is a very simple device that can easily be explained.

Words in **bold** appear in the glossary at the end of this document.

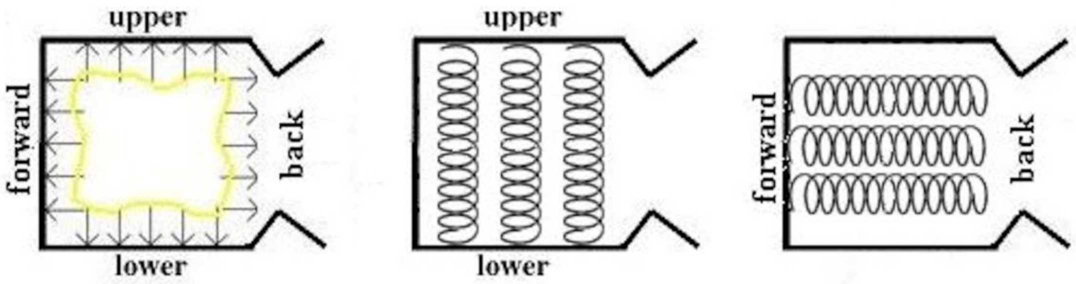
The rocket

The term ‘rocket’ actually means just the rocket engine. This consists of a ‘combustion chamber’, which you can think of as a large uncorked pill-bottle full of very high pressure gas (a pressure forty times higher than your car tyre.)

The hole at the neck end of the bottle is called the ‘throat’ because of its narrowness. Shine one of those expensive parallel-beam torches up the throat, and a circle of light will appear at the far end of the bottle, of the same size as the throat. Look up the throat and you’ll see it. We could call this circle the ‘action area’ because the high internal gas pressure pushing on this area of wall generates the majority of the rocket’s **thrust** force.



The internal gas pressure is, of course, pushing forcefully all over the inner walls of the bottle, but everywhere except the action area it cancels out. For example, the pressure is pushing equally on the left wall as on the right wall (picture a vertical bottle), so no net left-right force is generated. All that happens is that the walls get stretched. But opposite the action area there is just a hole, so a net thrust force prevails.



The downside (known as the ‘reaction’) is that the precious high pressure gas leaks out the hole so has to be continually replenished.

The rocket designer tailors the size of the throat, and hence the action area, to achieve the amount of thrust required for the Space mission: thrust force equals internal gas pressure times action area. Varying the size of the hole doesn’t affect the engine’s efficiency.

What *would* improve the rocket’s efficiency would be if we could somehow reduce the leakage of gas out the throat without affecting the thrust. As what comes out equals what goes in, then we wouldn’t need to replenish the gas at such a frenetic rate by feeding in veritable fire-hose flows of rocket **propellant**.

There *is* a way to do this; by heating the gas, typically by selecting propellants that will burn together: a fuel and an oxidiser.

The hotter the gas gets, the more it expands, thins out, its atoms move further apart, (its density drops). Being further apart means less gas atoms are physically able to leak out through the narrow throat area every second. So a hot gas will leak out of the throat at a lesser rate than a colder gas. So we use up less propellant to achieve the same thrust if the gas is hotter, ergo the engine is more efficient.

Heating the gas up doesn't increase the thrust, which may surprise you. In fact a hot or a cold flow produce exactly the same thrust. But a hot flow simply allows the use of less propellant to do it.

You may hear rocketeers talk of a number called **Specific impulse**, which is the amount of thrust you get per size of flow of propellant burnt (it's like the 'miles to the gallon/kilometres to the litre' metric of your car). A hot burn gives a better (higher) Specific impulse. If we can burn the propellants horrendously hot, by burning the fuel in 100 percent pure oxygen, then so much the better. Then we have to care about the whole engine melting, but that's an engineering issue.

Specific impulse has been contrived to be measured in seconds, which are the same in any system of units.

Internal flow

The flows into and out of the rocket engine are interesting: the throat can be visualised as a small hole at the bottom of a dam. As water flows into the reservoir behind the dam, the reservoir gets deeper, and so the water pressure at the hole in the bottom of the dam increases, which spews the water out faster. Eventually a balance is reached: what flows in exactly equals what flows out, and the depth of water increases no more.

By carefully adjusting the flow of water in versus the size of the hole, we can achieve whatever depth of reservoir we like.

And so it is with a rocket: by varying the flow of propellant in versus the throat size, we can achieve whatever internal gas pressure we like. (But we must beware anything shaking loose and blocking the nozzle throat even partially, as the pressure will then rise to a much higher equilibrium, which could exceed the strength of the walls, resulting in a catastrophic failure.)

For a rocket required to take off at sea-level, the higher the gas pressure, the more efficient it is, but then it needs thick walls to prevent it bursting, which are heavy. However, for a rocket that operates at high altitude, high internal gas pressure becomes much less important: a low pressure is all that is required, which results in a rocket which is lighter and much less prone to bursting.

The nozzle

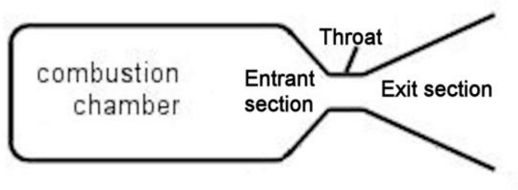
You can't have failed to notice that rocket engines have a large church-bell shaped nozzle bolted to their end, what is its function?

The gas leaking out of the throat is at high pressure. Rather than wasting this hard-won gas, we can give it more action area to push against (the inner wall of the bell nozzle) to generate a bit more thrust (perhaps a third more thrust). There are physical limits placed on how much more action area we can play with, one of which is clearly the weight of an overly large nozzle.

Heating the gas doesn't change the distribution of pressure inside the nozzle any more than it changed the pressure on the action area in the combustion chamber, so heating the gas doesn't increase the thrust. If the gas is hot, it'll happily expand to fill the bell nozzle just as a colder gas will, but yet again, less hot gas is needed to do it because its atoms are further apart: more efficiency.

The gas pressure progressively drops down the nozzle. Peak efficiency will be gained if the nozzle spews the gas out the end of the nozzle at *exactly* the same pressure as the air outside it. If the air outside is thinner (at high altitude) then a larger nozzle can be used to expand the gas pressure down to this lower outside pressure. This gives more action area, and hence more thrust: rockets work better at high altitude.

Actually, the nozzle is defined to encompass more of the hardware than I've previously indicated: the bell nozzle is termed the' nozzle exit section', the throat is the 'nozzle throat', and the sloping walls upstream of the throat that feed smoothly into the throat are the 'nozzle entrant section'.



So rockets can work in the vacuum of Space, where there is nothing outside to push against, because all the pushing goes on inside the engine, pushing with propellant that it brings along with it.

A rocketry analysis

So rockets work on gas pressure, and that's all there is to it. The above explanation is correct in principle, but in exact detail gets muddied somewhat; more of the picture is required:

The gas has mass - more than you'd think as there's a lot of it inside the combustion chamber - even if it is hot and diffuse. This gas mass picks up speed as it heads down the convergent section of the nozzle to spew through the throat because the throat is narrow: stick your thumb over a tap and see the speed the water spews through a small area.

Energy is required to accelerate this gas mass to this higher speed. This energy is robbed from the gas itself: the gas loses some pressure (pressure is a form of energy) so there's a steadily reducing pressure pushing on the convergent section. Bernoulii figured this out in the 18th century.

Now in one way this is a good thing; this reduced back-pressure on the converging section of the nozzle increases the effective area, increasing the thrust. The downside is that calculating the new effective area requires powerful mathematics and a computer to work out just exactly what the distribution of pressure over the convergent section of the nozzle is, and what component of this acts fore-aft. Frankly, it's really not worth the effort, there's another method of rocket analysis.

Rocket scientists adopt the Teutonic approach of the German war-time rocket engineers, who clearly didn't have modern computers and required a different approach.

Isaac Newton's third 'law' (observation) of motion states that forces come in pairs: for every action force applied to something, a reaction force magically appears; equal in magnitude to the action force, and which happens to act in the opposite direction to the action force.

It doesn't matter which force you label the action: I posited that the action force was the gas pushing on the front wall of the combustion chamber, and the ensuing reaction force squirted the gas out the throat. You can turn this on its head: analyze the mathematics of the flow of gas mass passing through the throat and call this the action, and then the equal reaction is the thrust.

For some reason, no-one quite knows why, all mass in our universe has **inertia**. The greater the mass, the more inertia it has. Inertia is why the table-cloth trick works: it's their inertia that keeps the glasses and cutlery on the table if you swiftly pull the cloth away from under them.

If you were to try to push an elephant on roller-skates - as one might - you'd find it very hard to accelerate. The property called inertia wants the elephant to remain moving at the same - possibly zero - speed, and not speed up. Without inertia, the lightest touch would send the elephant zooming away at high speed. Newton's second 'law' recognises inertia; it correctly states that the more mass '*m*' something has (therefore the more inertia) then the greater the force '*F*' required to accelerate it '*a*':

$$a = \frac{F}{m}$$

which is the fundamental reason why we must keep our spaceships as light (low mass) as possible.

Imagine, for illustration's sake, that you are inside a large combustion chamber, and you want to shove a cannon ball out of the throat.

You heave on the ball, but its inertia resists you, pushing back on your hands, and this resistive force travels through your body and out of your back, which you're bracing against the far wall of the chamber. So for your action force, pushing on the ball, a reaction force is generated by the ball's inertia, which gets transmitted to the far wall of the chamber as a thrust force, which will actually move the whole chamber in the opposite direction to the direction of travel of the cannon ball.

Now there's a surprising amount of gas in a rocket's combustion chamber, which has inertia. And its high pressure harshly accelerates the gas up to **Mach 1** as it passes through the nozzle throat. Like the cannon ball, there's an inertia reaction force to this action of the gas accelerating itself out the throat, which travels back through the gas and onto the action area of the far wall.

So is this new explanation of how a rocket's thrust is generated better than our original one? No, they're both just different sides of the same physics coin: the pressure exists because of the gas inertia, and the ensuing nozzle flow (of gas mass which has inertia) exists because of the pressure. Let me explain:

If the gas within the combustion chamber had no inertia, the pressure would squirt the gas out of the chamber instantly so the pressure would fizzle out instantly. With zero gas 'residence time' within the chamber there would be no high pressure in the chamber.

It's the gas's inertia and the ensuing flow of gas mass down the nozzle that sustains the pressure difference between inside the chamber and outside: the gas's flow down the nozzle and its steadily dropping pressure down the nozzle support each other in a reciprocal arrangement.

No gas inertia would mean no pressure difference and hence no thrust. No pressure would mean no flow, and by the Teutonic analysis (see below): no thrust.

In gas flows, we often find this kind of backwards and forwards causality: cause and effect going both ways at once. See our paper 'How a wing lifts'.

Focusing further on the gas accelerating through the nozzle, as a side effect of the efficient use of the pressure of the gas within the nozzle exit section, the gas happens to leave the end of the nozzle (the 'nozzle exit') at a screamingly high speed (around Mach 3).

The Teutonic analysis shows that if you multiply this nozzle exit velocity '*Ve*' (known as the 'exhaust velocity', measured in metres per second) times the mass flow rate of gas through the throat ('$\dot{m}$' in kilograms per second) then the answer is equal to the rocket's thrust '*T*' in Newtons. (All metric forces are measured in Newtons.)

$$T = \dot{m} \times V_e$$

The above Germanic thrust equation is just a mathematical quirk courtesy of Isaac Newton's second law of motion, but rocket scientists favor this approach.

[Pedantically, this equation actually multiplies the exhaust velocity by the 'mass flow rate' (in kilograms per second) of the flow as it leaves the nozzle exit, but this flow of gas mass is constant all along the nozzle as no mass is being added nor subtracted anywhere along the nozzle. So the nozzle exit mass flow rate is the same as the throat mass flow rate. (The gas *speed*, which is a separate entity to the mass flow rate, *does* alter along the nozzle, it constantly increases along the nozzle.)]

Confused by the distinction between mass flow rate and exhaust velocity? A major river may have a slow meandering speed (velocity) as it nears the sea. But by this point, the river is wide and deep: thousands of tonnes of water mass pass along every second. Small speed, large mass flow rate. In contrast, at its source the river is narrow and shallow. It may have a high speed as it rolls down the mountainside, but the quantity of water it carries along - its mass flow rate - is small.

Further mathematics relate the nozzle mass flow rate to the gas pressure inside the combustion chamber, and the size of the nozzle throat.

Analysing the thermal energy of the hot gas inside the combustion chamber, and the geometry of the nozzle, you can calculate the exhaust velocity. The hotter the gas, the greater the reservoir of thermal energy that is used to expand the gas within the combustion chamber. This expansion energy then converts into greater movement energy (higher exhaust velocity) of the gas.

A hot gas passes through the throat at a lower mass flow rate, which ought to lower the thrust, but it actually passes through at a higher speed, which means that it leaves the nozzle exit at a higher speed. This higher exhaust velocity exactly compensates for the reduced mass flow rate, and gives the same thrust when the two are multiplied together in the Teutonic thrust equation. This is no coincidence, the two are intimately linked by the density of the gas. (The density controls the speed of the gas at the throat too.)

It turns out that the Specific impulse '*Isp*' (see earlier) is related to the exhaust velocity '*Ve*': it is simply the exhaust velocity divided by one metric gee (g = 9.81)

$$Isp = \frac{Ve}{g}$$

What the Specific impulse is actually saying is that a higher exhaust velocity implies a lower mass flow rate which as we learnt earlier means less propellant needs to be burnt to get the same thrust.

Finally, this energy analysis can bring us full circle: it gives us a number called the 'nozzle thrust coefficient C_F'. If we take our original thrust force definition (our original action area, which was equal to the nozzle throat area '*Ae*', times the combustion chamber internal gas pressure '*Pc*') and multiply the answer by this corrective coefficient, the answer is the true thrust, which includes the extra thrust from both the entrant and exit sections of the nozzle.

$$T = P_c \times A_e \times C_F$$

The nozzle thrust coefficient 'C_F' collects all the factors that describe the nozzle alone, but not the combustion chamber. For balance there's also a number called 'characteristic velocity' C* (pronounced 'See star') that collects all the factors that affect the combustion chamber alone but not the nozzle. This deliberate division between combustion chamber and nozzle is useful, as you can then mix and match different combustion chambers (*C**) with different nozzles (C_F) to suit your rocketry needs. Multiply *C** times C_F and the answer is the exhaust velocity. This isn't a coincidence, they were designed this way.

$$V_e = C^* \times C_F$$

C_F completely ignores gas temperature, but *C** depends intimately on it: higher temperature, higher *C**.

Of course, you don't have to resort to pen and paper to do all this math. There are computer programs such as the free-to-download PROPEP3 which do all the above analyses for you. By inputting the propellant chemistry and your desired combustion chamber pressure, it'll work out the required throat area to get this pressure, and then work out the Specific impulse. (Actually, it'll work out two Specific impulses: one called 'frozen' which you would use, and an overly optimistic one called 'shifting' which you can ignore.)

Design your engine thusly: once you have your propellant's Specific impulse, multiply it by 9.81 to get its exhaust velocity. Then divide your desired thrust by this exhaust velocity and the answer is the mass flow rate you'll need to provide from the propellant tanks:

Rearranging: $T = \dot{m} \times V_e = \dot{m} \times (Isp \times g)$ to get: $\dot{m} = \frac{T}{Isp \times g}$

Almost immediately after ignition, the nozzle mass flow rate (out) becomes exactly equal to the mass flow rate of propellant that you feed in.

As the mass flow of propellant flows out of the tanks, the remaining mass in the tanks decreases, until eventually it all runs out and the rocket stops thrusting. This is known as **burnout**. The time that the rocket fires for - known as the **burn time** - can be calculated as:

$$burn\ time = \frac{total\ propellant\ mass}{average\ \dot{m}}$$

By the way, the cross sectional area of the nozzle exit divided by the cross sectional area of the nozzle throat defines the nozzle performance, and is called the **Area ratio** (or 'expansion ratio'), of the nozzle. Sometimes given the symbol $\in$.

$$Area\ ratio = \frac{area\ across\ the\ exit\ A_e}{area\ across\ the\ throat\ A^*}$$

The larger the area ratio, the higher the Mach number will be at the nozzle exit so the higher the exhaust velocity. Note that labels applied to the throat, such as *A** are given a star. (Except C*)

Glossary

Area ratio (or expansion ratio): the ratio of the nozzle exit cross-sectional area to the throat cross-sectional area.

Burn time: the time that the rocket fires for, from ignition until **burnout.**

Burnout: when the rocket stops thrusting.

Inertia: the property associated with mass that resists acceleration.

Mach 1: the speed of sound.

Propellant: the collective name for the substances that a rocket burns: a fuel and an oxidiser.

Specific impulse: the force produced per unit weight of propellant burned in a second.

Thrust: the force produced by a rocket, measured in Newtons.

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