How Does Rocket Propulsion Work?

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The most common answer to the above question is – hot jet of gas comes out of the nozzle of the rocket engine at high speeds and as a reaction the rocket moves (is propelled) in the opposite direction [1]. But is this answer right? Let us explore what goes on inside a rocket engine and arrive at the right answer.

Generally while explaining the working of a rocket engine, the analogy of the movement of a rubber air balloon is given. We too will make use of this example to understand the phenomenon of propulsion. Let us consider a blown-up rubber air balloon (not the ones filled with helium gas; otherwise they will rise up before you can experiment with them!). Also assume that there is no wind or breeze in the room in which the balloon is kept. Hence the balloon is stationary in the room.

The shape and size of the balloon is maintained by the equilibrium of forces acting on the balloon. Let us understand these forces first. When you blow the balloon, the air from your lungs enters the rubber balloon. The rubber material of the balloon is stretched due to the pressure of the air in it. As more mass of air is pushed in, the balloon is stretched further. After a while you stop blowing the air into the balloon and tie a knot at the mouth of the balloon. The pressure exerted by the air molecules on the walls of the rubber balloon is balanced by the tension/stress induced in the material of the balloon, plus the atmospheric pressure acting on the surface of the balloon. The pressure exerted on the interior walls of the balloon by the air in it, P_{air}, is the same across any given area of the balloon. P_{air} is the value of the pressure inside the balloon above the atmospheric pressure value. See *Figure* 1. As a result the pressures acting on geometrically opposite walls of the balloon *balance (cancel) each other*. Hence the net force acting on the balloon is zero.

Keywords
Propulsion, thrust, reaction.

Now, let us remove the knot on the mouth of the balloon. See

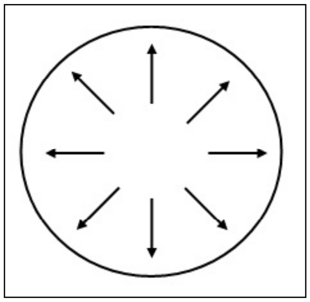


Figure 1.

Figure 2. The air starts escaping through the mouth of the balloon. Since there is no wall now at the mouth of the balloon, no pressure is exerted by the escaping air over that area. Hence less force is exerted on that side of the balloon. This causes *imbalance in the forces* acting on the interior walls of the balloon. Net unbalanced force is now acting on the area diametrically opposite the mouth of the balloon. This unbalanced force is the thrust T_b, acting on the balloon, which moves/propels the balloon in its direction. The magnitude of the thrust is equal to the force that would have been exerted on that area had there been a wall at the mouth of the balloon.

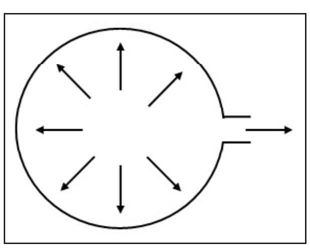
Hence,

$$T_b \simeq P_{air} \times A_{mouth}, \tag{1}$$

where A_{mouth}, is the area of the mouth of the air balloon. Note, there will be an extra contribution to the thrust due to lower pressure (Bernoulli effect), on an annular area on the inside balloon surface surrounding the exit [2]. The velocity of the existing air is approximately given by Bernoulli equation.

$$V_e = \sqrt{\frac{2P_{air}}{\rho}}\ .$$

Figure 2.



Now let us carry this insight to understand the working of a liquid propellant rocket. See *Figure* 3. These types of rockets have internal combustion engines. The fuel or propellant is stored in the fuel tank. Here we will consider liquid hydrogen as the fuel. For the combustion to take place in outer space or in the absence of atmospheric oxygen the rocket carries along an oxidizer; here we will consider liquid oxygen as the oxidizer. The oxidizer or in this case liquid oxygen is stored in a separate tank. The fuel and oxidizer are pumped into the combustion chamber. In the combustion chamber, hydrogen and oxygen undergo combustion reaction:

$$2H_2 + O_2 \longrightarrow 2H_2O \text{ (gas)} + \text{Heat}.$$

That is, the fuel undergoes combustion or burns in the combustion chamber. Combustion is an exothermic reaction (chemical reaction which releases heat energy). In the present case, the amount of heat energy that is released is 483.6 kJ/mole of O_2. This heat energy is absorbed by the products of combustion, in this case water vapour. These high energy products of combustion, in this case super-heated steam, exert high pressure on the walls of the combustion chamber. When high pressure steam escapes through the nozzle of the rocket engine, it creates *imbalance in the forces* acting on the interior walls of the combustion chamber (in the same way as explained in the case of a balloon). The net unbalanced force is now acting on the area diametrically opposite the nozzle. This unbalanced force is the thrust T_R, which propels the rocket. The magnitude of the thrust is equal to the force that would have been exerted on that area had there been a wall at the throat of the nozzle.

Hence,

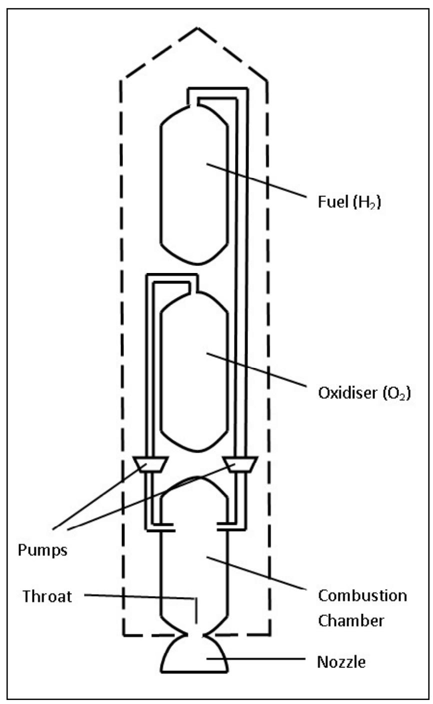
$$T_R \simeq P_{steam} \times A_{nozz}\,, \qquad (2)$$

where P_{steam} is the pressure of the steam in the combustion chamber and A_{nozz} is the area of the throat (the narrowest section) of the nozzle. The flow downstream of the throat is usually supersonic with the flow at the throat being sonic. As in the case of the balloon, pressures on the walls of the nozzle and rocket body will be different from P_{steam} and relation (1) is only approximately correct.

The pressure of the gases inside the rocket engine has to be greater than the atmospheric pressure to escape through the nozzle of the rocket engine. Of course when the rocket is moving in free space you have no atmospheric pressure to bother about.

Every rocket engine is designed to generate a desired amount of thrust. From (2), it is clear that the thrust is proportional to the pressure generated inside the rocket

Figure 3.



engine and the area of the throat of the nozzle. To increase the thrust generated by the rocket engine we have to increase the pressure inside the engine by increasing the rate of combustion reaction. We may also increase the thrust by increasing the area of the throat of the nozzle, but that will lead to increased rate of ejection of the steam. To maintain steady pressure within the combustion chamber, the rate of ejection of steam through the nozzle should be no more than the rate at which combustion reaction occurs in the combustion chamber. Thus there is a limit to the size up to which the diameter of the throat of the nozzle can be increased.

Hence, it is clear that the escaping air in the case of a balloon does not push/propel the balloon. And escaping gases in the case of the rocket do not push/propel the rocket ahead. It is the imbalance in the forces exerted by the gases inside the rocket engine that propel it. The higher pressure inside acts on the gas exiting the balloon/rocket and imparts a momentum change to it. Therefore, evaluating the momentum change acquired by the gas can be indirectly used to calculate the thrust. The momentum flux of the exiting gas is related to the thrust. This is what people usually do because it is easier than to evaluate the imbalance of forces over a geometry that is as complicated as a rocket.

Suggested Reading

[1] Gilbert Rowell and Sidney Herbert, *Physics*, Cambridge University Press, pp.80–81, 1987. (Though many physics textbooks give similar explanations, this above text is picked purely at random)

[2] G K Batchelor, *Introduction to Fluid Dynamics*, Cambridge University Press, 1967.

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[6] V Sharadha and Jaywant H Arakeri, Propulsion of the Putt-Putt Boat – I, *Resonance*, Vol.9, No.6, pp.66–73, 2004.

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