Water Rockets

Launch rockets high into the sky using nothing but air pressure and a bit of water! There's no better way to demonstrate the principle of momentum exchange.

Suggested grade level: 7-8

Activity length: 50-60 minutes

Required materials: Soda bottles, launcher (see details)

Relevant topics: Momentum, pressure, forces

Purdue Space Day, an educational outreach program of Purdue University's Department of Aeronautical and Astronautical Engineering, organizes the largest free STEM advocacy children's event in the Midwest, as well as myriad year-round outreach events throughout the surrounding metropolitan area. These activity write-ups are provided free of charge as an extension of Purdue Space Day's STEM programming.

PURDUE SPACE DAY

Questions? Comments? Contact Purdue Space Day via email at psd@purdue.edu. We'd love to hear your feedback to help us improve our activities and write-ups.

Activity Summary

Students construct a single-stage rocket propelled by pressurized water. Rockets are constructed from two-liter plastic bottles with fins attached for stability and a parachute included for recovery. Rockets are launched using a purpose-built launcher after being pressurized with a bicycle pump.

Key Concepts: Momentum, Pressure, Aerodynamic Forces

NGSS Summary: The key concepts of this activity align with NGSS Disciplinary Core Ideas for middle school science education. Specifically, they meet the following Physical Sciences standards:

- MS-PS2.A – Forces & Motion
- MS-PS3.A – Definitions of Energy
- MS-PS3.B – Conservation of Energy and Energy Transfer
- MS-PS3.C – Relationship Between Energy and Forces

This activity also connects to the following standards for Engineering, Technology, and Applications of Science:

- ETS1.A – Defining and Delimiting an Engineering Problem
- ETS1.B – Developing Possible Solutions
- ETS1.C – Optimizing the Design Solution

Learning Objectives

Students will be able to identify key components of a rocket and their functions, understand the relationship between net force and momentum, and develop an understanding of how to optimize an engineering system.

Scientific Background

Rockets work by expelling hot exhaust gases out of a nozzle. These gases exert a pressure on the rocket to push it forward, and pushing the weight of the gases backwards propels the rocket via the conservation of momentum.

The conservation of momentum can be easily expressed with Newton's second law of motion, which states that the net force exerted on an object is equal to its change in momentum (in this form it is also known as Euler's first law of motion). Momentum – the product of an object's mass and its velocity – is a fundamental property of matter, like mass or charge, so it is always conserved. The only way an object can gain or lose momentum is by exerting a force or having a force exerted upon it. So, as we push exhaust gases out of a rocket (expelling momentum downwards), the rocket must feel a force upwards. A good way to visualize this is to imagine yourself on roller skates. If you throw a heavy object – say, a bowling ball – away from you, you will start rolling in the opposite direction. This is the conservation of momentum in action! You're giving the bowling ball momentum by throwing it, so you will feel a force pushing you in the opposite direction. Why? Because the momentum of the system – you and the bowling ball – must be conserved. That means that any momentum the bowling ball gains from you pushing on it must be cancelled out by your momentum moving in the opposite direction, so you feel a force pushing you backwards. The bowling ball will have a decent amount of momentum, because it is quite heavy, but you could observe the same effect with a smaller mass. Imagine throwing a baseball as hard as you can while on your skates- once again, you would start rolling backwards. A rocket's exhaust is analogous to this baseball – it doesn't have a lot of mass (it's just hot gas), but it's moving incredibly quickly (thousands of miles per hour), so it has a lot of momentum as it leaves the rocket and the rocket feels a large force upwards. Since rocket exhaust doesn't have much mass, we want to expel it from the rocket's engines as quickly as possible. This is why rockets have big bell-shaped nozzles on their ends – the nozzle helps accelerate the exhaust until it is moving at thousands of miles per hour, giving it a lot of momentum.

Note that this is different from the most common explanation of rockets, which is that the rocket "pushes" itself upwards by exerting a force on the air around it using its exhaust gases. This is not entirely untrue, but it muddles the line between pressure forces and momentum forces. This explanation describes pressure thrust – the force which a rocket feels due to the differential pressure of the gases at its base. If the rocket exhaust is at a higher pressure than the surrounding air, then the rocket feels an additional force from the greater pressure. However, if the exhaust is at the same pressure or a lesser pressure than the ambient air, it will feel zero or even negative thrust from the pressure – which is why this simplistic explanation of rockets is not ideal. The predominant force which rockets feel comes from the momentum exchange process described above. Our water rockets are no different, except that instead of hot exhaust gases, we use water. Since water is much heavier, we don't have to accelerate it to such high velocities to create enough thrust to launch our rockets. The slender neck of the bottle will act as a nozzle, helping to accelerate the water to a higher speed. Just like in a real rocket, having the exhaust – in this case, water – move more quickly will provide greater thrust for the rocket.

Another engineering concept illustrated by the water rocket is aerodynamic stability, as well as that of aerodynamic resistance or drag. The addition of fins to the rockets helps ensure stability – i.e. a flight in a predictable, controlled trajectory. The reasoning behind this is pretty straightforward – as air flows over the rocket, it exerts a force on anything which it touches – a pressure force caused by the air ramming into the surfaces of the rocket (we call this "dynamic pressure"). The parts of the rocket with the most area feel the strongest forces, because there is more surface for the air to push against. By adding fins to a rocket, we are increasing the area at the rear/bottom end of it; this means that if the rocket starts to waver off-course, the wind flowing past will hit its fins and straighten it out. A good way to think about this is to imagine a weathervane. Weathervanes have a tail with lots of area and a pointier tip, just like a rocket. When the wind blows, the bigger tail feels a greater force and swings around, aiming the smaller nose into the wind. Fins on a rocket work the same way.

When the rocket needs to descend, we want to make sure that the airflow slows it down as much as possible. This is where the parachute comes in – a parachute creates a very large amount of area, which means that the air can exert a lot of force, counteracting the force of gravity and preventing the rocket from speeding into the ground.

Suggested Activity Practices

- Provide students an overview of the different components of the water rocket and how they are launched.
- Explain the principles of momentum conservation and how they relate to "real" rockets. Ask students to explain the momentum interchange process of the water rocket.
- Challenge students to think of how they could maximize the performance of the water rocket
    - Adding more water means more mass to accelerate (meaning more momentum, theoretically) but it gets harder to accelerate that mass (less space for air to pressurize) and the rocket gets heavier.
    - With less water, there is more space for air so the water will exit the rocket at higher speed, but there will be less mass to eject (i.e. less overall impulse/thrust).
    - The ideal water level lies somewhere between these two extremes!
- Challenge students to find the optimal amount of water to add to their rocket by launching several rockets with different levels of water – have the students follow good experimental procedure by pumping each rocket the same amount, etc.
- Explain the importance of aerodynamics for fins and nosecones. Demonstrate a rocket with no fins to show how it is less stable, or a rocket with no parachute to show how rapidly it returns to earth.

Assessment Techniques

Volunteers can observe participants for the following signs of comprehension or learning. For each, volunteers should assign a percentage to indicate how many of the students display an understanding of the concept.

Students indicate an understanding of a rocket's fins by designing identical fins and mounting them in a logical arrangement on the rocket.

Students are able to provide examples of momentum in real-world systems.

Students are able to provide examples of momentum exchange processes in real-world systems.

Students are able to explain the connection between the hot exhaust gases of a full-size rocket and the water of the water rocket.

Students are able to explain why having too much or too little water in a rocket is bad.

Participant learning can also be assessed using the following pre-activity and post-activity questionnaires.

Pre-Activity Questionnaire

Draw the most important parts of a rocket.

What makes a rocket fly?

What is momentum?

How do fins work?

Post-Activity Questionnaire

Draw and label the parts of your water rocket.

How does the water rocket fly?

What is momentum?

Did your rocket's fins keep it flying straight? If so, how did they do this?

Construction Directions

Note: These directions are provided as a sample to help educators and volunteers guide students through the process of building a water rocket. They should not be given or shown to the students, who should be encouraged to design their own rockets according to what they have learned about rocket propulsion. Building rockets of their own design encourages students to embrace the engineering design process and apply the scientific principles they have learned.

Materials Required:

- 2L plastic bottle
- Thick cardstock
- String
- Plastic bag
- Tape
- Hot glue
- Bicycle pump
- Rocket launcher*

* Devices to launch water rockets can be purchased from educational supply companies such as PITSCO; alternatively, there are several resources on the web which provide directions on how to build one. For example, see this document from NASA.

Directions:

Rocket Body

1. Cut fins from the cardboard – 3 or 4 fins are good, but you could experiment with adding more or fewer. Fins can be mounted on the cylindrical portion of the bottle, or shaped to fit farther down the neck.

2. Glue the fins to the 2L bottle, taking care to ensure that they are evenly spaced and mounted straight.

Parachute:

1. Cut a 24-inch square out of the garbage bag.

2. Fold the square in half, then fold it in half a second time along the short edges (“hamburger-style”). You should now have a square. Fold this square diagonally, bringing together two opposite corners to make a triangle.

3. Fold the bag one last time so that two adjacent edges lie on top of one another. You should now see one long, pointy triangle where the bag overlaps itself, and a much smaller triangle sticking out from this. Cut off the small triangle.

4. Unfold your parachute! You should have an octagon, with eight sides and eight corners. Reinforce each corner by sandwiching it with a very small piece of tape.

5. Punch holes through each corner, making sure to go through the middle of your tape reinforcements.

6. Cut four lengths of string 3 – 4 feet long and tie each end of a string into one of the holes which you have punched.

Final Assembly:

1. Make a nosecone out of cardstock. Ensure that the base of the cone is large enough to fit over the blunt end of the bottle.

2. Gather the parachute strings by the midpoint (so that the parachute dangles freely) and tape them to the blunt end of the bottle.

3. Loosely fold the parachute, placing it inside the nosecone, and place the assembly on top of the rocket body. You are now ready for launch!

Launch:

Fill the bottle partway with water and stopper the open end with the rubber stopper of the launcher. Carefully turn the rocket right-side up and place it on the launcher base, ensuring that the rim is captured by the latching arms. Pump up rocket using a bicycle pump, then count down and pull the string to launch!

Post-Launch

Discuss any observations which students were able to make about the launches. Did rockets with more water or less water go higher? Did rockets generally fly straight? Why? Encourage students to answer these questions by thinking about momentum exchange and aerodynamic stability, respectively. Ask students to think of ways they might improve their rocket, and to brainstorm possible uses for it. What could be measured or tested with a small rocket?