Hypersonics STEM Curriculum

Kinematics at Hypersonic Speeds

Grade	Time	Subject Area	Key Concepts
High School	45 min	Physics	Speed/velocity Acceleration

Lesson Overview

In this lesson, students will have objects moving at hypersonic speeds in "typical" physics kinematics problem situations. Students will use the problems to better understand the magnitude of hypersonic.

NGSS Standards

HS-PS2-1 Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.

Learning Objectives

By the end of this lesson, students will be able to:

- Solve kinematics problems with objects traveling at hypersonic speeds.
- Discuss their understanding of the magnitude of hypersonic speeds.
- Explain what external factors effect objects traveling at hypersonics speeds that would create different theoretical and experimental results.

Essential/Overarching Question

How fast is hypersonic?

Key Vocabulary

Speed – the rate at which an object is moving. Speed is calculated by dividing the distance travelled by the time it took to travel that distance.

Speed of Sound – the rate at which sound moves through a medium. The speed of sound depends on both the density and the temperature of the medium. The speed of sound through air at 20° C (68° F) at sea level is 343 m/s (767 mph).

Mach – the ratio of the speed of an object to the speed of sound or how many times the speed of sound an object is moving. It is often followed by a number indicating the ratio; for example: Mach 1 is the speed of sound, Mach 2 is twice the speed of sound, Mach 5 is five times the speed of sound.

Sonic – speeds equal to the speed of sound (Mach 1).

Subsonic – speeds smaller than the speed of sound (less than Mach 1).

Transonic – speeds near (Mach 0.8-1.2) the speed of sound where drag is highest (e.g. sound barrier).

Supersonic – speeds greater than the speed of sound (Mach 1 and greater).

Hypersonic – speeds greater than five times the speed of sound (Mach 5 and greater).

Fluid – a substance with no fixed shape; a liquid, gas, or plasma. A substance that flows when an external force is applied to it.

Flow – the motion of a fluid (liquid, gas, or plasma) when it experiences unbalanced forces.

Acceleration – the rate an object changes velocity; a change in velocity over time.

Acceleration due to Gravity – the acceleration, rate of change of velocity, at which an object free falls due to the gravitational attraction between the object and a celestial body; on Earth g = 9.8 m/s^2 towards Earth's center.

Displacement – the change in position of an object.

Friction – resistance to movement. A force that opposes motion.

Height – an object's vertical position relative to a plane of reference (0 m). Typically, the position above or below sea level or ground level.

Velocity – the speed of an object is a given direction. Speed is calculated by dividing the displacement of the object by the time interval in which the displacement occurred.

Science Concepts Overview

Different objects move at different speeds. With such a large possible range of object speeds, it can sometimes be hard to compare. In many cases, we compare the speed of an object to the speed of sound. The speed of sound tells you how fast a sound wave travels from its source to its receiver. The speed of sound depends on what medium the sound wave is traveling through (air, water, metal, etc.). It varies directly with both the density of the medium and temperature. The speed of sound of air at 20° C (68° F) is 343 m/s (767 mph).

When we compare the speed of an object to the speed of sound, we do so with a ratio called the Mach number. The Mach number is calculated by dividing the speed of an object by the speed of sound. And the Mach number can be a whole number (Mach 3) or a decimal (Mach 0.6). Additionally, we categorize speeds by the size of their Mach number. Speeds less than

Mach 1 are subsonic. Speeds greater than Mach 1 are supersonic. And speeds greater than Mach 5 are hypersonic.

Materials List

- ☐ Kinematics at Hypersonic Speeds handout (one per student)
- ☐ Calculators (one per student)

Lesson Preparation

Prior to the lesson, the instructor should make copies of the Kinematics at Hypersonic Speeds handout and gather calculators if needed.

Safety

There are no additional safety concerns beyond normal classroom procedures for this lesson.

Procedure

Engage (10 minutes)

1. Pose the following questions to students for a class discussion:
   - What comes to mind when I say the word “hypersonic”?
   - How fast is hypersonic?
2. As a class, or individually, read the introduction on the Kinematics at Hypersonic Speeds handout.

Explore & Explain (20 minutes)

3. Students can work either individually or in small groups.
4. Students will work on four problems on the Kinematics at Hypersonic Speeds handout that put typical physics problem situations at hypersonic speeds:
   - Many car commercials claim that their car can go from zero (0 m/s) to sixty (26.8 m/s) in 5 s.
     - Draw a sketch of the problem.
     - What would that car’s acceleration be? (5.36 m/s^2)
     - If an aircraft went from zero to Mach 5 in that same amount of time, what would that aircraft’s acceleration be? (343 m/s^2)
   - You are dropping a ball from a hypothetical building. Assume gravity is constant and there is no friction.
     - Draw a sketch of the problem.
     - How high would the building need to be so that the ball reaches a hypersonic speed (Mach 5) as it hits the ground? (150,062.5 m)
     - How tall is that relative to the tallest building in the world which is the Burj Khalifa in Dubai which stands 828 m tall. (181 times taller)
   - A sounding rocket is launched straight up at a speed of Mach 5. Assume gravity is constant and there is no friction.
     - Draw a sketch of the problem.
     - How long will it take to come back to the ground? (350 s)
     - How high will the sounding rocket go? (150,062.5 m)

- A sounding rocket is launched at a 75° angle from the ground at a speed of Mach 5. Assume gravity is constant and there is no friction.
  - Draw a sketch of the problem.
  - How long will it take to come back to the ground? (338s)
  - How high will the sounding rocket go? (140,010.2 m)
  - How far from the launch site will it land? (75,014.8 m)

Elaborate (5 minutes)

5. Students will answer two questions on the Kinematics at Hypersonic Speeds handout that ask them to reflect on the magnitude of hypersonic:
   - If you were to explain how fast hypersonic speeds are to a friend so that they really understood the magnitude of those speeds, how would you do so?
   - Many of the calculations that you did above (theoretical results) would vary from experimental results.
   - What assumptions did we make?
   - How would those assumptions account for the difference between theoretical and experimental results?

Evaluate (10 minutes)

6. Have students (or groups of students) share their work and their reasoning for each of the four problems with the rest of class.
7. The Kinematics at Hypersonic Speeds handout can also be collected to evaluate student work.

STEM Career Connections

- Aerospace engineering
- Physicist
- Atmospheric scientist
- Testing engineer
- Pilots

Extensions

As a further *elaborate* and *evaluate*, students could find videos of sounding rocket launches and analyze the speed and trajectory of the launches.

References & Resources

NASA Wallops. (2021, September 11). *HOTShot sounding rocket launch* [Video]. YouTube. https://www.youtube.com/watch?v=xGjdE7JdsK8

National Air and Space Museum. (n.d.) *Hypersonic vehicles*. https://howthingsfly.si.edu/structures-materials/hypersonic-vehicles

National Science Foundation. (2015, January 22). *Projectile motion & parabolas [Science of NFL football]* [Video] YouTube. https://www.youtube.com/watch?v=HB4ws7RoA3M

Professor Dave Explains. (2017, February 2). *Kinematics part 3: Projectile motion* [Video]. YouTube. https://www.youtube.com/watch?v=aY8z2qO44WA

SciShow. (2019, July 8). *A surprisingly simple secret to supersonic flight* [Video]. YouTube. https://www.youtube.com/watch?v=kGefMLHJBKA

Talented Tuber. (2017, April 11). *Difference between subsonic, supersonic and hypersonic speed* [Video]. YouTube. https://www.youtube.com/watch?v=LBJ3tXCjzN0

TestTube 101. (2015, November 11). *Flying at hypersonic speeds* [Video]. YouTube https://www.youtube.com/watch?v=vL1qAfS0gic

UVA Engineering. (2021, September 27). *"Need for speed: A hypersonics lecture"- Need for speed video contest* [Video]. YouTube. https://www.youtube.com/watch?v=at2v5LJ0SUU

Dr. Lori M. Stiglitz
JHTO Workforce Development Lead

Dr. Stephanie Stehle
JHTO Curriculum Specialist

Name: ____ Date: __________________

Kinematics at Hypersonic Speeds

✈ Introduction

A growing area of research is in ***hypersonic*** travel. Hypersonics refers to an object going five times the speed of sound. The ***speed of sound***, the speed at which sound waves travel from its source to the observer, depends on both the density and the temperature of the medium. But in general, the speed of sound through air at 20° C (68° F) at sea level is 343 m/s (767 mph) meaning that hypersonic travel is 1715 m/s (3836 mph) or greater. The ***Mach number***, the ratio of the object's speed to the speed of sound, is frequently used to represent the speeds at this magnitude. For example, Mach 1 is the speed of sound; less than Mach 1 is ***subsonic***; from Mach 0.8-1.2 is considered ***transonic***; greater than Mach 1 is ***supersonic***; and Mach 5 and greater is hypersonic.

One of the struggles of studying hypersonic speeds is understanding the magnitude of those speeds. The following problems are designed to help you grasp how fast hypersonic truly is.

✈ Problems

1. Many car commercials claim that their car can go from zero (0 m/s) to sixty (26.8 m/s) in 5 s.
    a. Draw a sketch of the problem.
    b. What would that car's acceleration be?
    c. If an aircraft went from zero to Mach 5 in that same amount of time, what would that aircraft's acceleration be?

2. You are dropping a ball from a hypothetical building. Assume gravity is constant and there is no friction.
    a. Draw a sketch of the problem.
    b. How high would the building need to be so that the ball reaches a hypersonic speed (Mach 5) as it hits the ground?
    c. How tall is that relative to the tallest building in the world which is the Burj Khalifa in Dubai which stands 828 m tall.

3. A sounding rocket is launched straight up at a speed of Mach 5. Assume gravity is constant and there is no friction.
    a. Draw a sketch of the problem.
    b. How long will it take to come back to the ground?
    c. How high will the sounding rocket go?

4. A sounding rocket is launched at a 75° angle from the ground at a speed of Mach 5. Assume gravity is constant and there is no friction.
    a. Draw a sketch of the problem.
    b. How long will it take to come back to the ground?
    c. How high (y-direction) will the sounding rocket go?
    d. How far (x-direction) from the launch site will it land?

5. If you were to explain how fast hypersonic speeds are to a friend so that they really understood the magnitude of those speeds, how would you do so?

6. Many of the calculations that you did above (theoretical results) would vary from experimental results.
    a. What assumptions did we make?
    b. How would those assumptions account for the difference between theoretical and experimental results?