KENAN FELLOWS PROGRAM

Physics of the Jet Engine (Part I - Forces)

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Course: Physics

Introduction

Jet engines are commonly used to transport people and materials all over the world either by air- or water- craft in an efficient manner. They are also used for propelling land vehicles to pass the speed of sound. The purpose of this lesson is to provide a real-world example of utilizing the physics learned in class to understand the theory of operation of such an important device.

This lesson will provide an opportunity for students to conduct their own analysis of a jet engine, and then report their findings to their colleagues (the class). Students will apply their knowledge of Newton's 2^{nd} and 3^{rd} laws to study how a jet engine imparts motion to an object and what key variables are needed to determine a jet engine's performance.

Upon completion of the student analysis, students will then be provided problems to predict various parameters from real jet engines: the thrust or mass of air processed from a jet engine given parameters from a real jet engine design. Finally, they can use the model they develop to design an engine given design targets.

This lesson will occur after students have had some practice implementing Newton's 2^{nd} and 3^{rd} laws on the typical model problems encountered in such a unit. After this and related lessons involving practice, students will then be posed questions on a quiz or test involving Newton's laws of motion.

For this particular lesson to work effectively, instruction in the course should be conducted using the modeling physics pedagogy. Modeling physics is an inquiry-based approach of instruction, but with the added component of student groups independently developing and applying models applicable to a given physical scenario. This is accomplished by the students within the class acting as a scientific community. The instructor acts as a facilitator for the community.

The class-generated models can have up to 4 representations: i) graphical; ii) mathematical; iii) pictorial; and iv) written or verbal. At this point in the physics curriculum when this lesson is to be encountered, students are expected to work as independent groups of up to 3 students each. The instructor's role provides guidance only by "reflecting" guiding questions back to the students who have questions or are having difficulty. Students are regarded as principal investigators in the class.

The jet engine model derived in this lesson can also be extended to determine the impulse, changes in momentum, energy and power of the jet engine / air system. This will be accomplished as an extension of the jet engine model in the energy/power and momentum/impulse units (essential standards Phy. 1.3 and Phy. 2.1). This will be covered in a separate lesson.

Learning Outcomes

Students will develop a model of a jet engine by applying Newton's 2nd and 3rd laws of motion to analyze the operation of a jet engine. Once they have completed their analysis, they will then apply their model of jet operation to practice problems to calculate operating parameters such as thrust or mass of air processed in the engine. Problems are given for practice in 1-D kinematics with an airplane equipped with a jet engine. In the energy and momentum units, this model also can be used to calculate the energy, power and momentum of the jet engine/air system. Energy and momentum will be covered in Part II of this lesson, which can be given at the appropriate time within the physics curriculum.

Curriculum Alignment

This lesson is aligned to the following essential standards in physics:

Phy. 1.1: Analyze the motion of objects

Clarifying Objectives of Phy. 1.1 Covered in Lesson:

> Phy.1.1.1: Analyze motion graphically and numerically using vectors, graphs and calculations.
>
> Phy.1.1.2: Analyze motion in one dimension using time, distance, displacement, velocity, and acceleration

Phy. 1.2: Analyze systems of forces and their interaction with matter

Clarifying Objectives of Phy. 1.2 Covered in Lesson:

Phy. 1.2.1: Analyze forces and systems of forces graphically and numerically using vectors, graphs and calculations.

Phy. 1.2.2: Analyze systems of forces in one dimension and two dimensions using free body diagrams.

Phy. 1.2.3: Explain forces using Newton's Laws of Motion as well as the Universal Law of Gravitation

Note that with respect to Phy. 1.2.3, Newton's Law of Gravitation is not directly addressed in this lesson.

This lesson also is aligned with the National Science Education Standards:

Content Standards: 9-12

Standard A:

- Abilities necessary to do scientific inquiry; and
- Understandings about scientific inquiry.

Standard B:

- Motions and Forces.

Classroom Time Required

1 block period (90 min.) or 2 traditional class periods (50 min. each).

Teacher Preparation

Prepare the following: 1) Setup fan apparatus; and 2) video of jet engine in operation. An option is to prepare a cart and track system with a fan attached to the cart.

To setup fan apparatus:

1) Attach two ropes or cords to ceiling as shown in Figure 1, below;
2) Attach other end of each rope to hook as shown in Figure 1;
3) Situate fan so students do not see it but can later be hooked to the ropes. Holes may need to be drilled in the fan housing in order to allow hooks to be attached. Make sure

the two attachment points on the fan are as far apart from each other horizontally so the fan will not twist when operating;

4) Prepare extension cord hanging from ceiling shown in Figure 1;

5) Have force measurement equipment ready (either spring gauge, force sensor or angle measurement device with mass of fan);

6) If optional cart, track. fan and force sensor apparatus is available, setup for demonstration.

Materials Needed

1. Box fan: high speed capable with large diameter / weight ratio. The inexpensive box fans found at the typical hardware store should work well.

2. Rope or string: strong enough to support the fan weight. It should be long enough to hang the fan from the room ceiling and allow access to the fan control(s).

3. Two hooks. Each hook will be tied to a rope end and will hook to the fan when the fan is brought out from hiding from the students.

4. Extension cord: long enough to go from electrical outlet to fan power connection when hanging extension cord from ceiling.

5. Force measurement device, either a spring gauge or force sensor for direct measurement. Make sure the thrust force of the fan is within the range of forces the gauge or sensor can measure. The thrust force will depend on the specific fan obtained. The thrust can be measured in a couple ways: 1) measure the force needed to pull the fan (turned off) to the same position which gives the same rope angle as when the fan is on; or 2) force needed to keep fan from moving from the starting position (rope vertical).

   OR

   For an indirect force measurement, measure the angle (with a protractor, or measure the sides of the right triangle shown in Figure 2 with a ruler) the fan makes with vertical (when fan is running) along with the mass (weight) of fan to find the force of air on the fan. For reference (not for student use), the equation to find the thrust force from the angle is given in Figure 2. Also provided is the equation to find the tension in the supporting rope.

6. Jet engine operation video: A number of jet engine operation videos can be found on the internet, such as YouTube. The video should show somehow that air enters one end of the engine, and then exits out the other side. Since it is difficult to see air, the GE90 engine test video on YouTube http://www.youtube.com/watch?v=5xlObdXF8VE is useful because they inject water- or ice- laden air into the engine, so it is easier to see water/air mixture entering, and then subsequently exiting the engine at a higher speed.

7. Physics of the Jet Engine Worksheet (found in appendix to this lesson).

8. Optional: A cart / track system with fan propulsion. For example, the PASCO dynamics cart with fan propulsion unit (Pasco cat. No. ME-6977) can be used, however, this system can be constructed inexpensively with a simple plastic cart, and a small battery powered fan. A force sensor can be used to measure the force on the cart when the fan is turned on.

9. Whiteboard (2 x 3 foot size) and whiteboard marker (1 per student group).

Technology Resources

Computer with internet connection and projector to show video.

Pre-Activities for Students

Prior to this lesson, students will have experience with applying Newton's laws of motion to various situations. They will have had experience is drawing force diagrams on a system, then applying Newton's 2^{nd} law to that system. This lesson serves as practice applying Newton's laws of motion.

Students should be learning physics by the modeling approach for this lesson to achieve maximum effectiveness. The modeling approach for forces involves defining a "system" that is studied and identifying and quantifying the forces that act on the system. They will be accustomed to the modeling approach if regularly used up until this point in the curriculum. An introduction to modeling physics can be found at http://modeling.asu.edu .

Lesson Activities

1. Students first observe a video of a jet engine in operation and are then instructed to report their observations to the class and to share their initial idea on an initial model of the system. They should be experienced enough at this point in the curriculum to come up with ideas. The instructor can ask guiding questions if needed.

For example, after the video, the teacher can ask: "What did you notice in the video?" Students should respond that air was taken into the front of the engine and exhausted out the back with possibly higher speed. The teacher can then ask: "Was there any object in the video you saw that its motion had changed?" The students then should answer that the air's motion changed. The teacher then can ask: "What would be a suitable choice of the system to study?" Students should be at the point where they would respond "air". The system is the object or objects that we wish to study. Some students may indicate the engine is the system. The teacher can respond with a question like: "Does the engine's motion change?" The answer to that question should get the student to respond with "no". Then the teacher can ask: "Would it be interesting to study something whose motion does not change? Wouldn't that be boring?"

The teacher then could ask: "What air should be the system?" "All the air in the earth's atmosphere, or what part of the atmosphere?" Some of the students should recognize that only the air that is processed by the engine should be part of the system. The teacher may ask the students what is a proper name for this volume of air processed by the engine. The teacher may have to state that it is called a "parcel" of air, if students do not come up with that name.

After the students establish that the system is the air processed through the engine, then the teacher can proceed with the next part of the lesson.

2. If the optional fan/cart apparatus is available, it can be run next and students can approach the system for closer observation and use their observations of the fan propelled cart to refine their idea of a model for the system.

3. Next, students are asked how we can simulate a jet engine with a common household item (a fan). The teacher can ask: "What device takes in air and ejects it at a faster speed on the other side?" The students should be able to answer "a fan". If they do not, the teacher may have to drop some hints, such as: "What device allows people to pass air over themselves to cool off when it is warm?" After the students reach the answer, a box fan is then suspended from the ceiling and students are asked to predict

what will happen when the fan is turned on. When the fan is turned on, students are allowed to observe the fan operation up close.

4. At this point, it should be clear to the students a force is generated which causes the fan to shift forward and cause the ropes to be slanted from the vertical. Students are then asked how to determine the force due to thrust on the fan. They are encouraged to measure the force, either directly with a force measurement device, or indirectly, by measuring the angle the cord makes from vertical and the weight of the fan.

5. If the angle is measured, Figure 2 provides one way students can determine the thrust force using trigonometry. They should have enough experience with analyzing force diagrams to determine this without guidance. They can also find the tension in the rope.

6. Students are then are instructed to construct a model of the jet engine based on what happens to a given mass of air ("the system") before and after its encounter with the engine. The teacher can ask: "What is the speed of the air parcel before it goes into the engine (or fan)?" The students should say "zero", or "at rest", based on their previous experiences. Then the teacher asks: "How can we represent the speed of the air after it leaves the engine (or fan)?" The students should reply with "final velocity" or "final speed". The teacher then asks: "What quantity describes a change in velocity in a time period?" The students should respond with "acceleration". The teacher then asks: "What causes the air to change velocity?" The students should be able to say "the engine (or fan)". The teacher then instructs the students to find the following quantities based on what is provided (either numerical data or honors – symbolic data): acceleration of the air, force on a given mass of air and how much thrust does the engine generate? Students will be provided numerical data on the key operating parameters to help them develop their model. In mixed level classes (honors and standard students), honors students will be asked to derive their mathematical model algebraically.

7. Students will next be instructed to draw a force diagram of each the air parcel and engine separately. This should help them develop a Newton's 2nd law expression for the air and engine. With this expression and Newton's 3rd law, they should be able to determine the following from the data provided: acceleration of air parcel, force on air parcel by engine, force on engine by air parcel (thrust) and which variables determine the amount of thrust the engine produces.

Students then report to their colleagues what they have found, and the class reaches a consensus on a proper model for the jet engine and the associated equations derived from Newton's laws.

An example of model development of the engine is given in Figure 3 with the associated equations developed from Newton's 2^{nd} and 3^{rd} laws.

Once the model has been finalized, the instructor can pose questions regarding the relationship between thrust, rate of air processed and exhaust speed.

Practice

After the model has been developed, students will be provided a worksheet (Physics of the Jet Engine Worksheet 1) to solve problems which utilize their model. At this point in the curriculum, they should be experienced in using mathematical models to solve problems. The worksheet is given in the appendix.

Assessment

After this lesson, a quiz will be given to check the student's ability to develop and apply the jet engine model.

At the end of the Newton's law unit, a test will be administered which will have some questions pertaining to this lesson. Honors students will have 1-2 honors level questions to answer regarding this lesson.

Modifications

Honors Physics

An honors level worksheet is provided. Students have to develop a model when the engine is moving at a constant velocity instead of at rest. Relative motion concepts are developed here.

Standard Physics:

A standard level worksheet is provided. Honors students must also complete the standard worksheet.

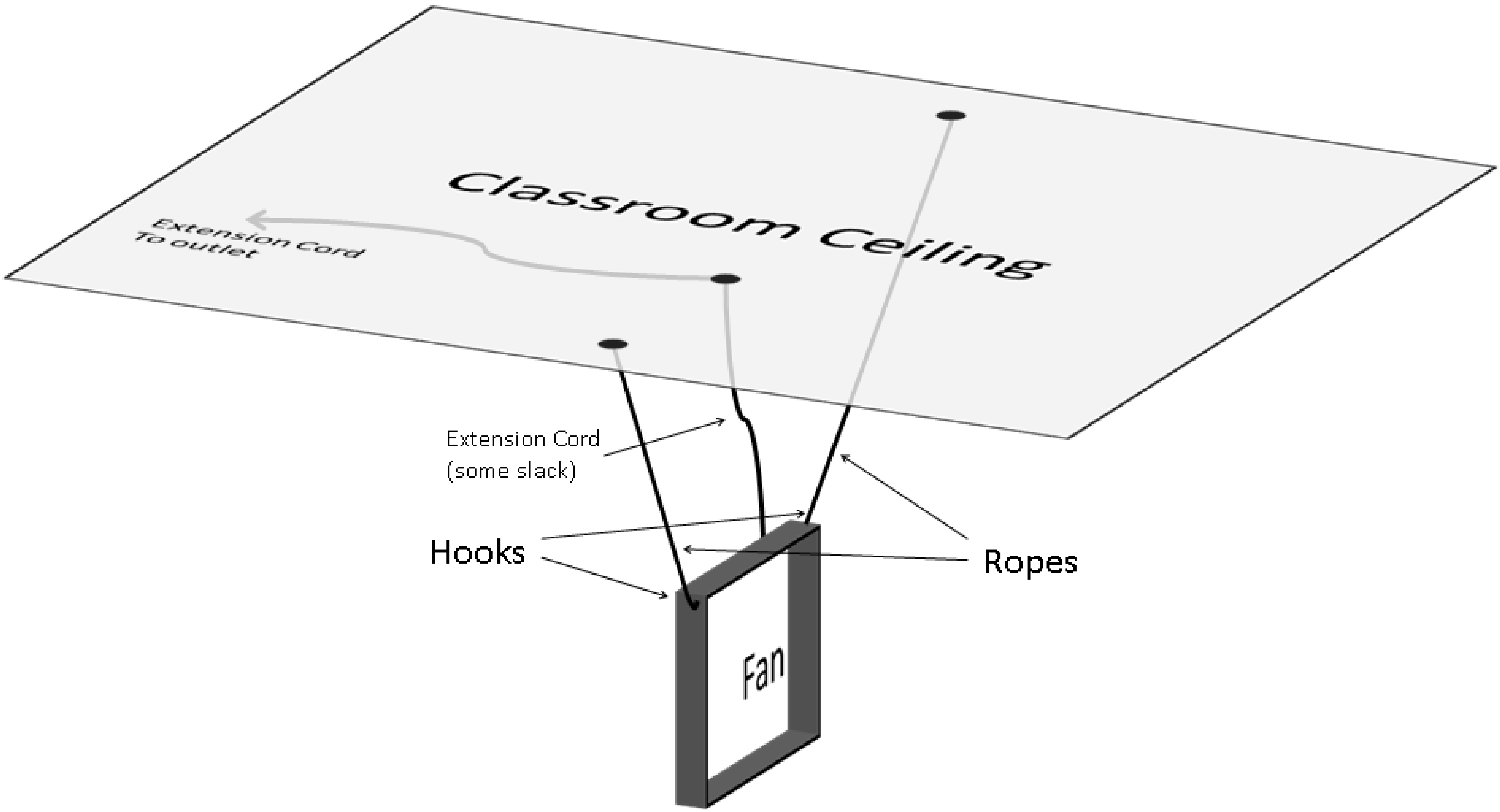

Figure 1. Box Fan Apparatus

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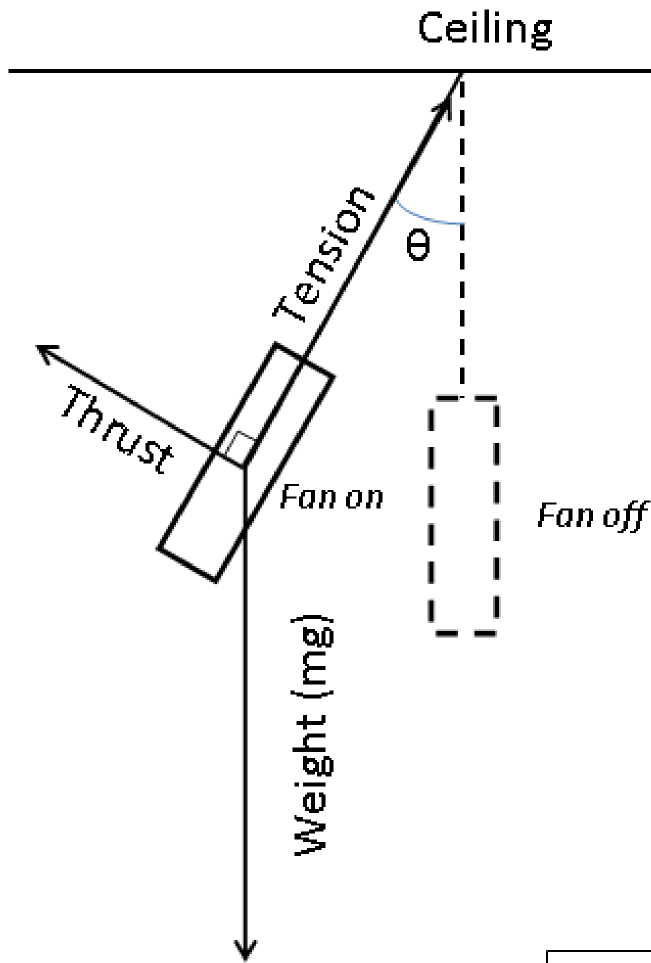
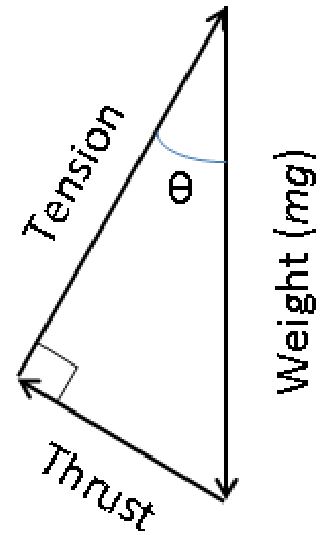


Side view of fan
with forces shown



Force Diagram

(with forces drawn giving a sum of zero)
m – mass, g – acceleration due to gravity

Forces will add to zero at equilibrium. Since the weight and angle are known, the other forces can be found. The solutions are:

Students should recognize:

$$\sum \vec{F} = 0$$

since there is no acceleration

$$Thrust = mg\sin\theta$$

$$Tension = mg\cos\theta$$

Figure 2. Determination of Box Fan Thrust (Instructor Notes)

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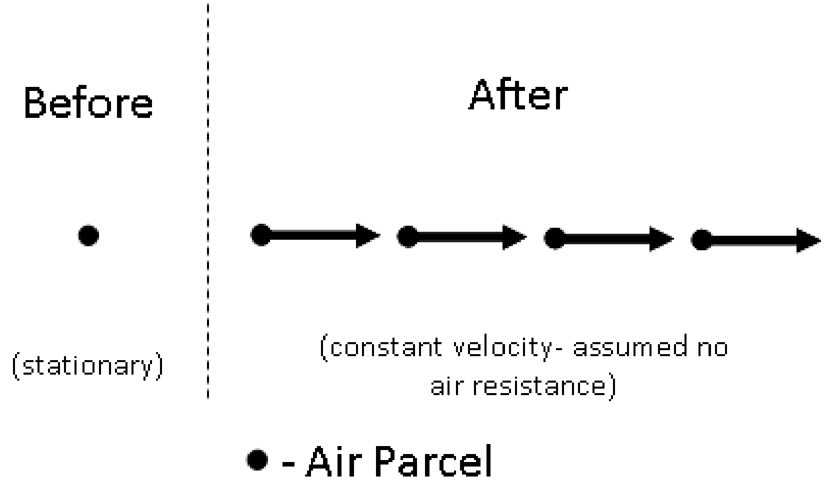
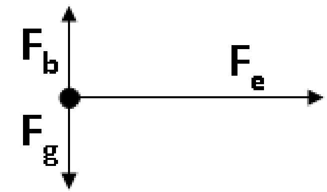
Motion Map



Parcel Force Diagram



F_b – buoyancy force

F_g – gravity force

F_e – engine force

$$\sum \vec{F} = F_e$$

Acceleration of Parcel

$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{v_f}{\Delta t}$$

Assume $v_i = 0$

Thrust Magnitude

$$\sum \vec{F} = F_e = ma = m\frac{v_f}{\Delta t}$$

$$m\frac{v_f}{\Delta t} = v_f \frac{m}{\Delta t} = -(Thrust)$$

$$\frac{m}{\Delta t} = rate\ of\ air\ processed\ by\ engine$$

Direction of Thrust is opposite of F_e

Figure 3. Sample Model of Stationary Jet Engine

Supplemental Information

Critical Vocabulary

No new physics vocabulary would be introduced in this lesson, however, students would learn vocabulary specific to jet engine propulsion. The key word learned in this lesson is Thrust.

Websites and Resources

Interested students can study propulsive devices in more detail at the NASA website http://www.grc.nasa.gov/WWW/K-12/airplane/shortp.html . Discussion focuses on theory of operation of the different jet engines: turbojets, turbofans, turboprops, turboshafts and afterburners. The site contains many equations, and it is targeted to college level students, but the site is suitable for high school students who desire further study.

EngineSim: a NASA Java Applet which simulates jet engine performance. The simulation is found at http://www.grc.nasa.gov/WWW/K-12/airplane/ngnsim.html . The simulator is part of an online tutorial on jet engine theory described above.

Comments

Author Information

The author, Jeffrey LaCosse, has been involved in secondary, university and professional levels of education since 1984. He is currently a science instructor at Jordan High School in Durham, NC.

He holds a Doctor of Philosophy in physical chemistry from the University of Illinois at Urbana-Champaign and a Bachelor of Science in chemistry from Michigan Technological University.

Dr. LaCosse is also experienced in model rocketry, and has coached teams in the Team America Rocketry Challenge since 2007. Jeffrey is a member of the National Association of Rocketry. He is also the coach for the district's NASA Student Launch Initiative Team.

The author is also the Durham Public Schools Scientifica program director. Scientifica is an extracurricular science enrichment program.

He also holds a Federal Communications Commission Amateur Extra amateur radio license since 1981 and held other class licenses since 1977.

The author also is President and Principal Scientist of Spectral Insights LLC, an air quality measurements and consulting company since 2000. He has pioneered the use of Fourier

Transform Infrared Spectroscopy (FTIR) for a number of source category emission air measurements since 1992.

This lesson was developed to help students gain appreciation of and to understand how key technology used in our society works. The lesson is also intended to help students analyze a practical system to help understand its physical operation.

Mentor Biographies

David Eatman, General Electric Aviation

Dave Eatman is currently the Program Leader for the GE Aviation Durham Repair Station. In this role, Dave is responsible for implementing maintenance, repair, and overhaul capability at Durham, supporting efforts to drive GE Aviation Supply Chain and Services integration, and providing additional needed capacity to the current GE Aviation MRO network.

Dave joined GE at the Durham Engine Facility in 1998, beginning as an Assembly and Test technician on the CF6 and CFM56 programs, followed by Leadership roles as CF6, GE90, and CF34-10 Technical and Quality Leader. Most recently, Dave has been responsible for obtaining FAA FAR 145 and EASA Part 145 certification and establishing GE90 and GEnx maintenance and repair capability.

Prior to GE, Dave served for 4 years as an F/A-18 Flightline and Powerplant Mechanic in the United States Marine Corps. Outside of work, he enjoys spending time with his wife Laurie, and three kids, Austin, Devin, and Whitney.

(biographies continued)

Jamie Stewart, General Electric Aviation

Jamie Stewart is currently a HR representative at the Durham Engine Facility where she focuses on employee relations and strengthening the teaming culture.

Jamie started with GE in 2008 when she joined the Human Resources Leadership Program (HRLP). While on program Jamie completed her first assignment at the repair shop in McAllen, TX where she worked as the HR Generalist. Her second assignment was in Cincinnati, OH with the Commercial organizations where she provided HR leadership to the GE90, Engine Alliance, and Marketing teams, and was involved in developing the Commercial Engagement strategy, the Commercial Leadership Program, and the One Commercial Team structure. Jamie completed her last assignment as a Supervisor in EMO supporting the F110 Frames Cell. Prior to starting her current role, Jamie assisted the Commercial Engine Organization with a bubble assignment at the Dallas, TX facility.

Jamie earned her B.S.B.A. in Finance and Management at The University of North Carolina at Charlotte and her M.A. in Human Resources from the University of South Carolina.

Appendices

1. Physics of the Jet Engine Worksheet 1 – for all students.
2. Solutions for Physics of the Jet Engine Worksheet 1.
3. Physics of the Jet Engine Honors Worksheet.
4. Solutions for Honors Worksheet.
5. Sample Quiz: Physics of the Jet Engine
6. Sample Quiz: Physics of the Jet Engine Key

Physics of the Jet Engine Worksheet 1

Name: _________________________________Period: ________ Date: __________

A General Electric GE90-115B jet engine at rest accelerates 1900 kg of air from rest to 288 m/s in 1 second. Assume the amount of air going into the engine equals the amount exiting the engine.

Honors students: When possible, write algebraic solutions first then compute the requested quantities with the data provided.

1. Draw a force diagram of the air parcel (the 1900 kg of air) traveling through the engine. Assume that the force of gravity on the air and the weight of the air above it is balanced by an upwards force from the air below it. Draw a vector representing the net force on the air.

2. Draw two motion maps: one each of the air before and then after it leaves the engine.

3. What is the acceleration of the air parcel due to the engine?

4. What is the force on the air parcel by the engine?

5. What is the force on the engine by the air parcel?

   How do you know this?

   What is a descriptive name for this force on the engine?

6. What force in kiloNewtons does the engine produce?

7. Convert the force into pounds (4.45 N = 1 lb.):

   If you are wondering, the abbreviation "lb." for pound weight originates from the Latin *Libra pondo*. The word *pondo* is Latin for "weigh". *Libra* is the Latin word for "balance", or "the scales", which are devices that are used to measure weight.

8. How many kg of air travel through the engine every minute?

9. If the engine is attached to a Boeing 777-300ER aircraft with giving a total engine/aircraft mass of 350,000 kg, what is the acceleration of the aircraft with this engine thrust? Assume there is no air resistance or friction.

10. Assuming the thrust stays constant, how long would it take the aircraft to reach a takeoff speed of 85 m/s ?

11. What length of runway is required to allow the aircraft to start at rest and reach takeoff speed? Assume there is no air resistance or friction.

12. If air resistance is significant, how would that affect the length of runway needed to reach takeoff speed compared to the no air resistance case?

13. The Boeing 777 actually has two GE90 engines, one mounted under each wing, instead of 1 in our scenario. If the two engines were operated at full thrust, how would that change the length of the runway needed to takeoff? Why?

14. What happens to the thrust if we reduce the amount of air going through the engine to 1100 kg per second? Calculate this new thrust in kN.

15. Instead of reducing the amount of air going through the engine, we reduce the final velocity to 200 m/s instead. What happens to the thrust? What is the new thrust in kN?

16. What happens to the thrust if we change both the amount of air to 1100 kg/s and final speed to 200 m/s? Calculate this new thrust in kN.

17. In another model jet engine, the thrust produced by the engine is 125 kN. If 760 kg of air travel through the engine each second, what is the final velocity of the air after it goes through the engine if the air starts at rest?

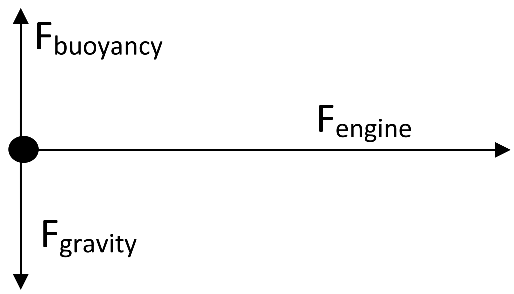
18. A General Electric CF6 engine (which can be found in the Boeing 747 or the Airbus A300 or A330 aircraft) produces 270 kN of thrust. If the air leaving the engine travels at 210 m/s, how many kg of air travel through the engine per second?

19. Can we use jet engines in outer space? Why or why not?

Solutions for Physics of the Jet Engine Worksheet 1

Numerical answers are rounded to a reasonable number of significant figures.

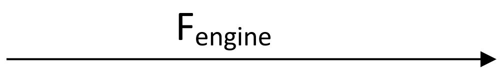
1.



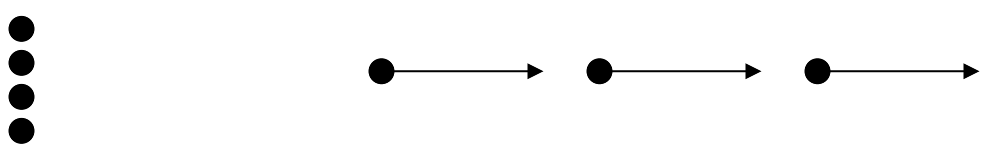
This diagram assumes the air is exhausted from the engine to the right.

Net Force is equal to force by the engine:

$\sum F =$



2. Before **After**



(stationary – students may have different ways to represent this) **(constant velocity)**

3. $a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{288\frac{m}{s} - 0\frac{m}{s}}{1\,s} = 288\,m/s^2$ Note the acceleration numerically equals the final velocity of the air in this problem. This is because the mass given is the mass processed per second by the engine.

4. Since net force equals the force from the engine, and using Newton's 2^{nd} Law:

$$\sum F = F_{engine} = ma = 1900\ kg \times 288\,m/s^2 = 547{,}200\ N = 547\ kN$$

5. Since the engine pushes on the air, the air pushes back on the engine (Newton's Third Law) so the force on the engine = 547 kN. Thrust is the commonly used term to describe the force that the air pushes on the engine, which is also the force on the aircraft, since the engine is attached to the aircraft.

6. Convert Newtons into kiloNewtons:

(Multiply force in Newtons by $\frac{1\ kiloNewton}{1000\ Newtons}$) > 547,200 N x $\frac{1\ kiloNewton}{1000\ Newtons}$ = 547 kN

7. 547,200 N x $\frac{1\ Pound}{4.45\ Newtons}$ = 123,000 pounds

8. 1900 kg are processed every second, so 1900 kg/s x 60 sec/min = 114,000 kg are processed every minute

9. The net force on the aircraft is the thrust of 547 kN. Using Newton's 2nd Law, $\sum F = ma$:

$547\ kN = 350{,}000\ kg \times a$. Solving for acceleration gives an acceleration of 1.56 m/s^2.

10. Start with $a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{v_f}{\Delta t}$ and solve for time: $a = \frac{v_f}{\Delta t} \rightarrow \Delta t = \frac{v_f}{a}$ **:**

$$\Delta t = \frac{v_f}{a} = \frac{85\, m/s}{1.56\, m/s^2} = 54.5 \text{ sec}$$

11. One method of solution is to use from kinematics: $v_f^2 = v_i^2 + 2a\Delta x$ and solve for Δ*x*.

Another method is to use $\Delta x = \frac{1}{2}(v_i + v_f)\Delta t$. Either method using the numbers specific to this problem gives a takeoff distance of 2,320 meters.

12. The length of runway needed would be greater since the actual acceleration would be somewhat less than 1.56 m/s^2 since there would be a force of air resistance opposing the thrust force, which would reduce the net force on the aircraft. Less acceleration translates to longer time to reach takeoff speed, and using one of the methods of solution for #11 would translate into a longer takeoff distance.

13. Two engines would reduce the length of runway needed to about one-half the original amount needed since the acceleration (assuming no air resistance) would be about twice the one-engine case.

14. The acceleration of the air is the same, so the net force on the air (and the corresponding engine thrust) would be 1100 kg x 288 m/s^2 = 317 kN.

15. Acceleration of the air would now be 200 m/s2, so the thrust would be 1900 kg x 200 m/s^2 = 380 kN.

16. As before, but with the reduced mass and acceleration: 1100 kg x 200 m/s^2 = 220 kN

17. Solve Newton's second law for acceleration: 125,000 N / 760 kg = 164 m/s^2. Since the air travels through the engine in 1 second, the change in velocity (which equals final velocity since the air starts at rest) equals acceleration times time (1 second) which numerically equals the acceleration: 164 m/s.

18. Solve Newton's second law for mass. The acceleration is the change in velocity (210 m/s) divided by one second, so a = 210 m/s2. Then 270,000 N / 210 m/s^2 = 1290 kg of air processed per second.

19. Jet engines take air outside the engine and accelerate in one direction. If there is no air outside the engine, it cannot accelerate any air, and therefore no thrust can be produced. Jet engines cannot be used in outer space since there is virtually no air (or any gas) present in sufficient quantities to generate sufficient thrust. This is why jet engines have a upper limit to altitude that they can be used at, since air density decreases with altitude. Rocket engines contain their own matter that is expelled out the engine which generates thrust and this is why they are used in space travel.

Physics of the Jet Engine Honors Worksheet 1H

(Bonus for Physics Students)

Name: ______________________________________Period: _________ Date: ___________

Consider the situation where the jet engine is NOT at rest, but is moving at a constant velocity v_o. This is the normal situation we expect with a jet engine. Pretend you are traveling along with the engine. Assume the air exiting the engine is measured to have the same velocity measured by you traveling along with the engine as it did in the stationary case. Let's call the exhaust velocity of the air measured by someone riding along with the engine as v_e. Also assume the amount of air exiting the engine equals the amount entering the engine. There is no wind in the atmosphere, which means the air is still above the ground. Use symbols and find algebraic solutions to these questions when applicable. Assume that *m* kilograms of air are processed by the engine every 1 second.

1H) From your perspective riding along with the engine (called a "frame of reference"), draw a motion map of the air parcel as it enters and exits the engine. Label the velocity vectors with appropriate symbols. How does this compare with the motion map when the engine is at rest (from the 1st worksheet)?

2H) Draw a motion map of the air parcel before and after it travels through the engine observed from someone on the ground. Label the velocity vectors with appropriate symbols. Assume there is no wind in the atmosphere measured by someone standing on the ground.

3H) Using your motion map, write an equation for the acceleration of the air parcel from your frame of reference riding along with the engine.

4H) Write an equation of the acceleration of the air parcel as observed by someone in the "standing on the ground" frame of reference.

5H) What do you notice about the acceleration as seen by both observers, one on the ground and the other riding along with the engine?

6H) What is the equation for the force on the air parcel?

7H) What is the equation for the thrust produced by the engine?

8H) Is there a maximum travel speed that the engine can produce thrust? What is it?

9H) If the jet engine is traveling at 150 m/s, and 1900 kg of air are passing through the engine per second, what is the thrust produced by the engine when the air leaves the engine at 288 m/s as measured by someone riding along with the engine? How does this compare to the original situation of when the engine is at rest?

10H) At high altitudes where jet airplanes typically fly, the density of air is significantly less than at ground level. How do you think that affects the mass of air traveling through the engine? (Hint: The volume of air taken in by the engine is the same at altitude or at ground level at a given aircraft speed – how do you prove this?) Would this cause the thrust to be less or greater compared to when the engine is at ground level moving at the same speed?

Bonus/Research Questions:

The speed of sound at ground level is about 340 m/s.

1B) What does the speed of sound mean?

2B) What is a shock wave? A sonic boom?

3B) What would you think would happen if the engine accelerated the air to the speed of sound or faster? Do not write down “the engine would blow up”.

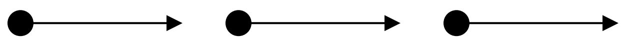
4B) Why is the air that is discharged out the engine is designed to be less than the speed of sound?

Solutions for Physics of the Jet Engine Honors Worksheet 1H

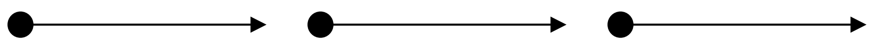
1H. The person riding along with the engine observes the air coming towards them at a velocity of v_o. The air leaves the engine with a velocity ve. These two velocities may not be the same. The example below is when the two velocities are not the same ($v_e > v_o$)

<u>Observer riding with engine:</u>

Air entering the engine:

Speed v_o 

Air leaving engine:

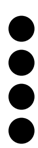
Speed v_e: 

The only difference between this case and the original case is that the original case $v_o = 0$.

2H. For someone standing on the ground, the air entering the engine is at rest, and the air leaving the engine is exhausted with a velocity v_e relative to the engine, but we have to add to v_e the motion of the engine observed by the ground observer. This sum will give the motion of the air relative to the observer. Since the engine is moving in the opposite direction, the overall motion is the difference of the speeds ($= v_e - v_o$). By drawing vectors, students will be able to see this more clearly.

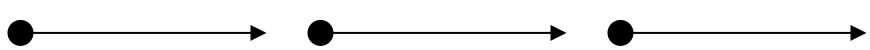
<u>Observer on ground:</u>

Air entering the engine (at rest):



(stationary – students may have different ways to represent this)

Air leaving engine:

Speed v_e-v_o: 

(case shown is when $v_e > v_o$, and resultant motion of air is moving to the right). When $v_e = v_o$, then the air is also at rest after discharge from engine.

3H. As seen from the observer riding along with the engine:

$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{v_e - v_0}{\Delta t} = \frac{v_e - v_o}{\Delta t}$$

4H. As seen from the ground observer:

$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{(v_e - v_0) - 0}{\Delta t} = \frac{v_e - v_o}{\Delta t}$$

5H. They are the same. If students have not studied Galilean relativity, this can serve as a starting point to discuss this topic.

6H. The net force on the air equals the force on the air by the engine. This net force can be found from Newton's 2nd Law:

$$\sum F = F_{engine} = ma = \frac{m(v_e - v_o)}{\Delta t}$$

7H. The thrust is simply the equal magnitude/opposite direction reaction force on the engine by the air. Its magnitude is the same as the previous question:

$$\sum F = F_{thrust} = ma = \frac{m(v_e - v_o)}{\Delta t}$$

(direction opposite of force on air parcel)

8H. When the speed of the engine/aircraft reaches v_e, the thrust will drop to zero. There is an upper limit to the speed that an aircraft can move. The speed of the aircraft/engine cannot exceed v_e, because once the aircraft reaches v_e, the thrust is zero and cannot accelerate further. In reality, the highest speed the aircraft can attain will be slightly less than v_e, since there has to be some thrust to overcome air resistance.

The aircraft engine must have an exhaust velocity slightly greater than the highest speed required for the aircraft. Military supersonic fighter jets will have exhaust velocities that are higher than the speed of sound so they can travel faster than the speed of sound.

9H. Use the equation from #6H or #7H:

$$\sum F = ma = \frac{m(v_e - v_o)}{\Delta t} = \frac{1900\ kg(288\,m/s - 150\,m/s)}{1\sec} = 262\ kN$$

This is less than the case when the engine is at rest on the ground (547 kN).

10H. The volume of air taken in by the engine can be thought of as a cylinder that has the same diameter as the engine intake, and the length of the cylinder equals the velocity of the aircraft times time. If the aircraft speed is constant, then it does not matter how high above the ground the aircraft is located. The mass of the air processed by the engine equals the volume of the air times the density. If air density decreases, then the mass of air processed by the engine decreases as well. That means the thrust produced by the engine is reduced (see the equation from problem #7H).

Bonus Question Responses

Students may find answers to these questions on the internet. The responses below are based on standard definitions and some of the findings from the exercises above.

1B. The speed of sound is the speed that a disturbance of the air (a sound wave) travels.

2B. A shock wave is a disturbance of the air that is created by an object traveling through the air faster than the speed of sound. The air "cannot get out of the way" fast enough for the particle and so the object compresses the air in front of it. The air behind a shock wave is rarefied (opposite of compression). A shock wave is observed when significant changes in air (or any fluid that the object is traveling through) properties (pressure, temperature, density, etc.) occur almost instantaneously. A shock wave created by an aircraft flying faster than the speed of sound is also known as a sonic boom.

3B. If the air leaving the engine is traveling faster (measured from an observer on the ground) than the speed of sound, it will create small sonic booms, which may sound like a "popping" or a "bumping" type sound. The air exiting the engine faster than the speed of sound (supersonic) will encounter significantly greater resistance and will make it more difficult for the engine to "push" the air through it. For commercial jet engines, the average exhaust velocity is designed to be slightly below the speed of sound, but some of the exhaust will be greater than the speed of sound. This is due to fluctuations in the air speed that naturally occur. This effect contributes to the characteristic sound of a jet engine at full throttle. When the aircraft speeds up, then the speed of the exhaust relative to the atmosphere drops. The exhaust sound typically quiets down since less exhaust exits the engine at a supersonic speed compared to the still atmosphere.

4B. In most aircraft that do not exceed the speed of sound, the exhaust velocity is slightly less than the speed of sound because the exhausted air encounters less resistance and the engine is more efficient. The design of the engine with subsonic air exhaust velocity is also simpler. Aircraft that exceed the speed of sound will exhaust air from the engines greater than the speed of sound so the engines can still generate thrust the higher speeds. However, as the aircraft speeds up, the velocity of the exhausted air from the engine decreases relative to the atmosphere, and some of the issues with supersonic exhaust are reduced or virtually eliminated.

When the aircraft travels at supersonic speed, the air resistance climbs dramatically and the engines must provide greater thrust to maintain a given supersonic speed. The fuel consumption requirements can double or triple when traveling supersonic compared to subsonic speed. That is why commercial aircraft travel slightly below sonic because efficiency is much greater at subsonic speed.

1.

Quiz: Physics of the Jet Engine

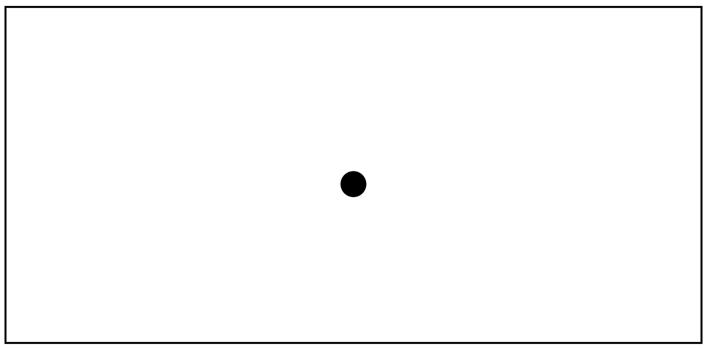
Name: ___________________________________Period: _________ Date: ___________

Show work and relevant equations to receive partial credit.

1. Draw a force diagram of a 250 kg parcel of air that starts at rest and exits a jet engine at 290 m/s in one second. Use the dot provided to draw the forces on. Assume the force holding up the air parcel equals the force of gravity. Label the forces with appropriate symbols.

Front of engine:

Air intake



Back of engine:

Air exhaust

2. What is the acceleration of the air parcel (include units)?

3. What is the net force on the air parcel (include units)? What force is this equal to?

4. What force does the air exert on the engine? Explain. What is this force called?

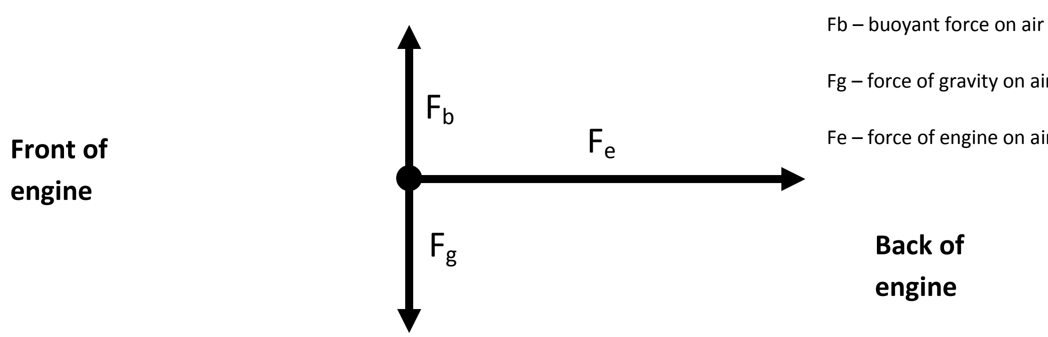
5. The force that the air exerts on the engine can be used for what purpose?

Quiz: Physics of the Jet Engine Key

Name: ____________________________________Period: _________ Date: ___________

Show work and relevant equations to receive partial credit.

1. Draw a force diagram of a 250 kg parcel of air that starts at rest and exits a jet engine at 290 m/s in one second. Use the dot provided to draw the forces on. Assume the force holding up the air parcel equals the force of gravity. Label the forces with appropriate symbols.



2. What is the acceleration of the air parcel (include units)?

$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{290 - 0}{1} = 290\frac{m}{s^2}$$

3. What is the net force on the air parcel (include units)? What force is this equal to?

$$\sum F = ma$$

$\sum F = 250\,kg \times 290\frac{m}{s^2} = 72500\ N$ towards the right or rear of the engine.

4. What force does the air exert on the engine? Explain. What is this force called?

   72,500 N towards the front of the engine. Newton's 3^{rd} law: Force of air on engine is equal to and opposite of the force of the engine on air. Thrust.

5. The force that the air exerts on the engine can be used for what purpose?

   To provide a force that can propel an aircraft forward to accelerate or overcome air resistance.