Curriculum Units by Fellows of the Yale-New Haven Teachers Institute
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Thermodynamics

Curriculum Unit 16.04.07
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In the thermodynamics unit, students will learn the main concepts about temperature, temperature scales, kinetic molecular theory, ideal gas laws and the Stirling engine. In this unit, we will discuss and learn aspects of physics and chemistry that govern the behavior of an ideal gas.

Thermodynamics is the branch of physics and chemistry that deals with the relationships between properties of a substance, such as pressure, temperature, volume and the flow of energy associated with changes in these properties. Thermodynamics explains how the ice cubs that melt slowly in a beverage help to keep that beverage cold. Thermodynamics explains how the clothes someone wears keep that person warm. The human body itself is a complex thermodynamic system: some of the chemical energy released from digesting food is used to maintain body's temperature at a healthy value, while some of the thermal energy is transferred to the air around the body.

Unit Content

Students will perform experiments and do computations to solve real life problems involving moles, pressure, volume and temperature of gases. This unit will be tied into students' math and physics courses strengthening the use of physics by taking their equations from paper to solve problems they encounter in everyday life. The thermodynamics unit will help students recognize how physics, chemistry and math can be used to better understand the world around us.

This unit will cover the concepts of temperature (definition and what it represents, from the physical point of view), temperature scales (including explanations of how these scales were established), the basic concepts of kinetic molecular theory, mathematical equations and explanations of the ideal gas laws (including examples and applications). It will also cover basic considerations about heat engines, how do they work, with a focus on Stirling engines.

1. Temperature and Temperature Scales

One of the most important parameters in thermodynamics is the temperature of an object. The concept of temperature, similar to the concept of force, originates with the sensory perceptions of humans. Temperature is rooted in the notion of the “hotness” or “coldness” of objects. Humans use their sense of touch (and sometimes sight) to distinguish hot objects from cold objects and to arrange these objects in their order of “hotness”. But, no matter how sensitive one’s touch may be, the humans are unable to gauge this quality in a quantitative manner over a large temperature range.

A better approach to define the temperature of a substance is by understanding what happens at the microscopic level – that is, how the individual molecules that make up that substance behave. It is known that molecules in any substance are always in motion The molecules move faster higher temperatures, with the result that they have more kinetic energy.

Temperature is defined as a measure of the average kinetic energy of the particles in matter. In everyday usage, temperature indicates a measure of how hot or cold an object is. Temperature is an important measurement parameter in chemistry. When a substance changes from solid to liquid, it occurs because of an increase in its temperature. Chemical reactions almost always proceed faster when the temperature is increased.

Unfortunately, this microscopic definition of temperature is not very helpful in a practical sense. The relationship between the average kinetic energy of the molecules and temperature is different for each type of matter (gas, liquid, or solid) and often depends on the type of molecule that makes up that substance. In addition, this definition does not indicate how to measure the temperature. From the practical point of view, it is impossible to analyze each individual molecule in a substance in order to determine the temperature of that substance.

A more practical approach to measure temperature is to state that temperature is an intensive property of matter that can be measured with a thermometer. There are many types of thermometers that work in different ways, but all of them work on the basic principle that substances change their properties when the temperature changes. A good example is that almost all liquids increase their volume as the temperature increases. One of the first thermometers ever built was a long glass tube filled with mercury. The height of the liquid in that column increases as the temperature increases causing the liquid to expand and decreases when the temperature decreases and the liquid contracts.

Temperature Scales

The first thermometers were glass and contained alcohol, which expands and contracts as the temperature changes. Alcohol has one of the largest coefficients of volumetric thermal expansion (0.00149/ºC). It is 8.3 times larger than that of mercury (0.00018/ºC) and 7.0 times greater than water’s coefficient (0.000214 /ºC).

The German scientist Daniel Fahrenheit started his work in thermometry as early as 1706 and at first he used tubes filled with alcohol only, but after few years he used tubes filled with mercury. One reason is that mercury can be used to measure temperatures above the boiling point and below the freezing point of water. Another reason is that mercury, due to its surface tension, does not stick to the tube as the alcohol does, thus making the readings more accurate. For eighteen years, Fahrenheit kept his method to manufacture thermometers a secret, for commercial reasons, but between 1724 and 1726 he published five brief papers in the “Philosophical Transactions”, a scientific journal from The *Royal Society* (England). In the fifth paper, Fahrenheit describes the way he used to build his thermometers [5]:

“The scales of thermometers begin with 0 ° and go to 96 °. The division of the scale depends upon three fixed points which are obtained in the following manner: the first point below, at the beginning of the scale, was found by a mixture of ice, water and sal-ammoniac (ammonium chloride) or also sea salt; when a thermometer is put in such a mixture the liquid falls until it reaches a point designated as a zero. […] The second point is obtained when water and ice are mixed without the salts named; when a thermometer is put into this mixture the liquid stands at 32 ° and this I call the commencement of freezing, for still water becomes coated with a film of ice in winter when the liquid in the thermometer reaches that point. The third point is at 96 °; the alcohol expands to this height when the thermometer is placed in the mouth, or the arm-pit, of a healthy man and held there until acquires the temperature of the body.”

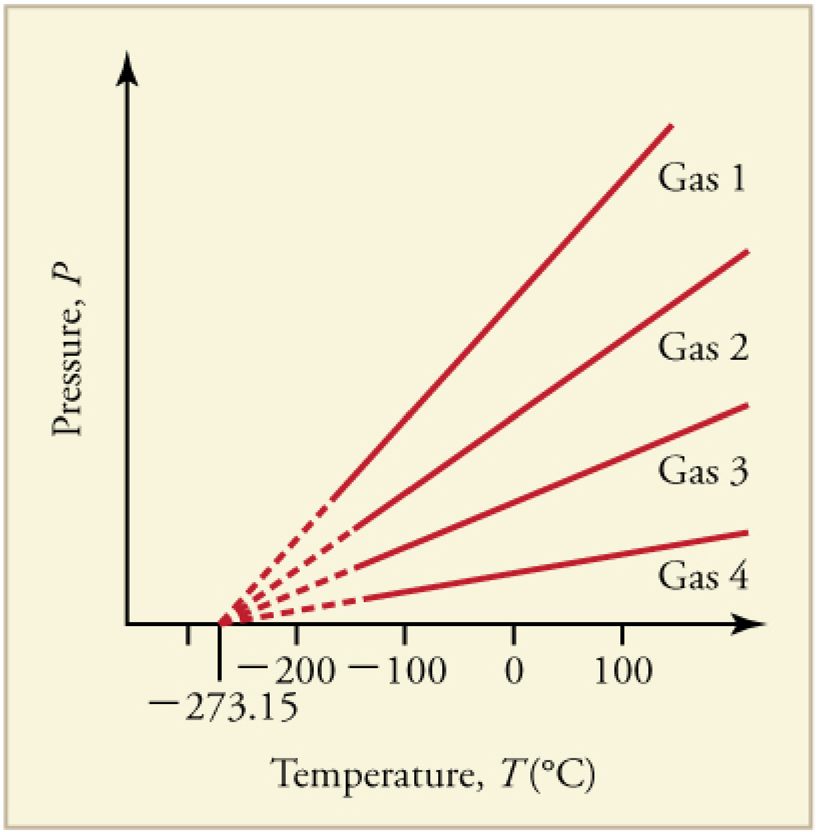
The freezing point of water is 32 °F and the boiling point is 212 °F on this scale. The Fahrenheit scale is typically not used for modern scientific purposes.

The Celsius scale of the metric system is named after Swedish astronomer Anders Celsius (1701-1744). The basis of Celsius scale is represented by the freezing and boiling points of water at 0°C and 100°C respectively. The distance between those two points is divided into 100 equal intervals, each of which is one degree. An outdated term sometimes used for the Celsius scale is “centigrade” because there are 100 degrees between the freezing and boiling points of water on this scale. However, the preferred term is “Celsius.”

The two scales are related using the equation: $T(^{\circ}F) = T(^{\circ}C) \times 9/5 + 32$

The Celsius and Fahrenheit scales were based on the properties of a particular substance (water) under particular circumstances (normal atmospheric pressure on Earth). A scale that has its basis in much more fundamental physics is the Kelvin scale, first proposed in the nineteenth century.

The Kelvin temperature scale is named after Scottish physicist and mathematician Lord Kelvin (1824-1907). It is based on molecular motion, with the temperature of 0 K, also known as absolute zero, being the point where all molecular motion ceases. The Kelvin scale was created by observing the relationship between pressure and temperature of low-density gases. Experiment shows that the pressure in a sealed volume of gas decreases as temperature decreases, and that a graph of pressure versus temperature is a straight line. For a given volume, both the slope of this line and the pressure at a given temperature depend on the quantity of gas in the volume. But no matter of what kind of gas or what quantity of gas is used, if we extrapolate the lines to low temperatures and pressures, we find that the pressure goes to zero at the same temperature. Each line should be extrapolated, because at sufficiently low temperatures, any gas becomes liquid.



Source: http://cnx.org/contents/2ou0Jg2y@3/Temperature

This temperature is referred to as **absolute zero** , because lower temperatures are not physically possible, so temperatures on the Kelvin scale are **never** negative.

The unit of temperature used in the Kelvin scale is the Kelvin, abbreviated K. The value of the Kelvin is based on a reproducible temperature that can be precisely measured, which is the temperature of the **triple point** of water. The triple point of a substance is the pressure and temperature of that substance at which the solid, liquid, and vapor phases of the substance all simultaneously coexist. For water, the triple point pressure is 0.00603 atmospheres and the triple point temperature is defined to be 273.16 K. With this choice of the value of the Kelvin, a change of 1 ºC is exactly equal to a change of 1 K. The triple point of water turns out to be at 0.01 ºC, so 0 ºC corresponds to 273.15 K and 0 K (absolute zero) corresponds to – 273.15ºC. To convert from a temperature in Kelvin to degrees Celsius, simply subtract 273.15 and to convert a Celsius temperature to a Kelvin temperature just add 273.15.

Therefore, the conversion equation is: T(K) = T(ºC) + 273.15

Water freezes at approximately 0 ºC = 273.15 K and boils at approximately 100 ºC = 373.15 K. It is good to remember that the precise values of these temperatures depend on the atmospheric pressure. It is very important to remember to use Kelvin when performing calculations described below that involve temperature.

Temperature and Temperature Scales Lesson Plans (two class periods)

Learning Objectives

Students will be able to:

- convert temperature scales.

- read a thermometer with different temperature scales (Celsius and Fahrenheit)

Materials & Teacher-developed Resources

- Paper, pencils, textbooks, software

- Student handouts

- Transparencies with conversion chart agenda, chart (comparing various weather forecasts)

- A classroom set of thermometers

Learning Activities

- The teacher will review the concepts of temperature and heat

- Then, he introduces new vocabulary on board: thermometer, Celsius, Fahrenheit, Kelvin unit and scale. The teacher will ask students “How can we measure temperature?” Answer: with a thermometer.

- The teacher passes out thermometers (one per student) and discusses the features of a thermometer and how to read both scales (Fahrenheit / Celsius).

- Students pair up, read room temperature, discuss with partner and share with class

- Teacher introduces the equations to convert temperature on different scales (Celsius, Fahrenheit, Kelvin)

- Then he practices few examples (on the board) of temperature conversions

- Students read temperature on a thermometer

- The teacher brings cups with ice water, cold and hot water.

- Students make predictions, and record the actual data.

- Students practice on their own to convert these temperatures on different scales using their Algebra skills

- The teacher will emphasize the temperature conversions and the importance of practicing these conversions

- Review the key points of the lesson, providing examples and asking questions

Homework

The teacher will provide the students with a temperature conversions practice worksheet

2. Basic Concepts of the Kinetic Molecular Theory

The description of the behavior of a gas in terms of the macroscopic state variables such as pressure, volume and temperature can be related to simple averages of microscopic quantities, such as the mass and speed of the molecules in the gas. The resulting theory, called the kinetic molecular theory of gases, provides a detailed model of dilute gases. From the point of view of kinetic theory, a confined gas consists of a large number of rapidly moving particles. In a monatomic gas, like helium and neon, these particles are single atoms, but in polyatomic gases, like oxygen and carbon dioxide, the particles are molecules. In kinetic theory, it is common practice to refer to the constituent particles of a gas as “molecules”, even if they are actually atoms.

In a gas at room temperature, a very large fraction of molecules are moving at speeds of a few hundred meters per second. These molecules are in constant motion and make elastic collisions, both with each other and with the walls of the container. In the context of the kinetic theory, any effects due to gravity are neglected, so there are no preferred velocity vectors (i.e., directions) either. The molecules are separated, on average, by distances that are large compared with their diameters. They also exert no forces on each other except when they undergo elastic collisions. This assumption is equivalent to assuming a very low gas density, which is the same as assuming that the gas is an ideal gas. Because momentum is conserved, the collisions that the molecules make with each other have no effect on the total momentum in any direction. Thus, such collisions may be neglected.

The kinetic molecular theory of gases begins with five postulates that describe the behavior of molecules in a gas. These postulates are based upon some basic scientific notions, but they also involve some simplifying assumptions.

They are:

1. A gas consists of a collection of small particles traveling in straight-line motion and obeying Newton’s Laws.
2. The diameter of a molecule in a gas can be assumed to be negligible compared to the distance between collisions.
3. Gas molecules exert no attractive or repulsive force on each other except for when colliding and collisions between molecules are perfectly elastic, which is to say that no energy is gained or lost during the collision.
4. The particles are considered to be in constant random motion. The pressure exerted by a gas in a container is a result of collisions between the gas molecules and the container walls.
5. The average kinetic energy of a molecule is proportional to the absolute temperature of the gas. More specifically, $KE= 3kT/2$, where T is the absolute temperature in Kelvin and k is the Boltzmann constant.

Kinetic Molecular Theory of Gases Lesson Plan (two class periods)

Learning Objectives

Students will be able to list five characteristics of an ideal gas according to the kinetic molecular theory of gases.

Materials & Teacher-developed Resources

- Paper, pencils, textbooks, software

- Student handouts

- Popcorn, margarine, hot plate, beakers, food color

Learning Activities

- The teacher reviews basic properties of solids, liquids, and gases

- Few video clips will be inserted into a Power Point presentation to help students visualize aspects of kinetic molecular theory of gases.

- The teacher will perform the “Kinetic Molecular Theory with Popcorn” demo

- On the second day, the teacher will perform an experiment showing the students that the diffusion rate in a liquid (also a fluid) is influenced by temperature

Students will answer the following questions:

- When the temperature increases, do the particles move faster or slower?

- The particles of a gas are moving in a pattern or randomly? Explain

- What happens to the pressure inside a coke plastic bottle when you shake the bottle? Why?

- If you increase the number of molecules inside a balloon, what happens to the pressure inside?

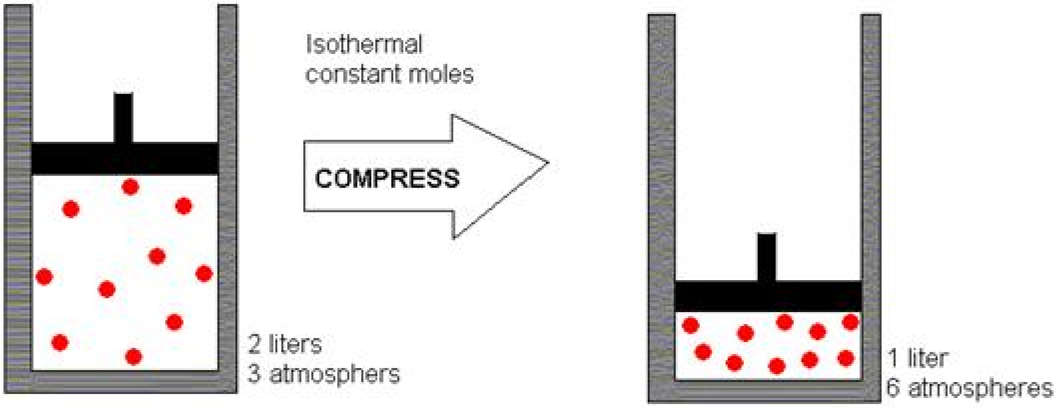
3. Laws of Ideal Gas

The mathematical equations that relate the properties of an ideal gas will be presented in this section. The properties of actual gas samples with low densities led the concept of an ideal gas. If a gas is compressed while keeping its temperature constant, the pressure increases. Similarly, if a gas expands at constant temperature, its pressure decreases. That is, pressure and volume are inversely related at a given temperature. To a good approximation, the product of the pressure and volume of a gas sample that has a low density is constant ($PV = \text{constant}$) at a constant temperature. This result was discovered experimentally be Robert Boyle (1627- 1691), and is known as **Boyle’s Law.** Another way to define Boyle’s law is the following postulate:

At a **constant temperature (T= constant)** , the volume of the gas decreases as the pressure increases

$P_1 V_1 = P_2 V_2$ or equivalently $\frac{P_1}{P_2} = \frac{V_2}{V_1}$

Since the temperature remains the same, a decrease in volume would result in increased gas pressure, as depicted in the following illustration (where “isothermal” means “constant temperature”).



Source: http://dlrgenchem.com/LECTURES/Gaslaw.htm

Boyle’s Law Lesson Plan (one class period)

Learning Objectives

Students will be able to:

- sketch a graph of the pressure-volume relationship for a gas.

- calculate the pressure or volume of a gas after a change in conditions

Materials & Teacher-developed Resources

- Paper, pencils, textbooks, software

- Student handouts

- Balloons, syringe, hot plate, pressure gauge

Learning Activities

- What happens to the pressure inside a syringe when you squeeze the plunger?

- The teacher will perform the demo with a marshmallow inside a syringe and ask the students to explain what happens

- Ask the students to draw the graph and write the equation for the relationship between volume and pressure of a gas

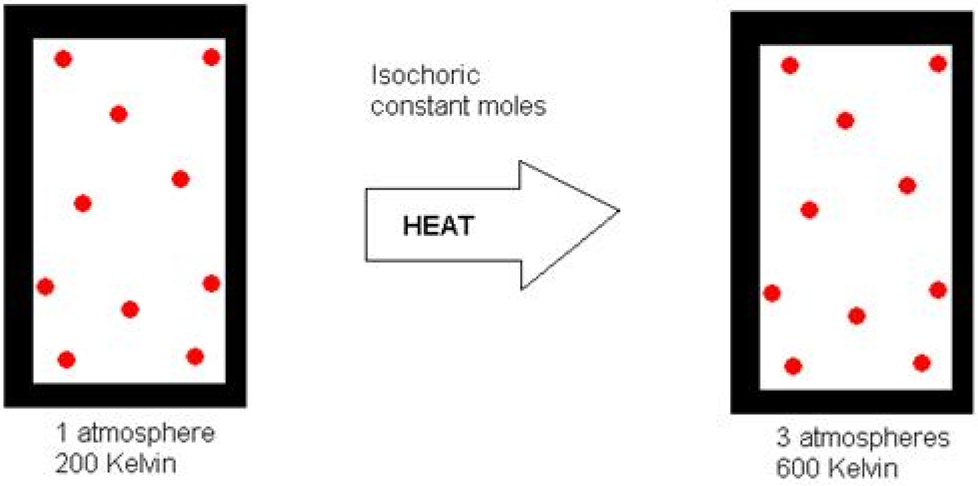
- have students perform computations involving Boyle's Law

Gay-Lussac's Law

The Gay-Lussac law states that at a **constant volume (V=constant),** the pressure of a gas is directly proportional to its absolute temperature as shown in the first figure above: The pressure of a gas increases as the temperature of that gas increases and the pressure decreases when the temperature decreases.

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

The kinetic molecular theory of gases accounts for this behavior because when the temperature of a gas increases, the speed of its particles increases, the particles hitting the wall with greater force and greater frequency. Since the volume remains the same, this would result in increased gas pressure, as depicted in the following illustration (where "isochoric" means "constant volume").



Source: http://dlrgenchem.com/LECTURES/Gaslaw.htm

Gay-Lussac’s Law Lesson Plan (one class period)

Learning Objectives

Students will be able to:

- sketch a graph of the pressure-temperature relationship for a gas.

- calculate the pressure or temperature of a gas after a change in conditions.

Materials & Teacher-developed Resources

- Paper, pencils, textbooks, software

- Student handouts

- Balloons, hot plate, 2L coke bottle, ice

Learning Activities

- The teacher will ask students to predict what happens to the pressures of a car’s tires in a very hot day

- Also the teacher will ask students to explain why the pilot of a hot air balloon heats the air inside the balloon to make it rise

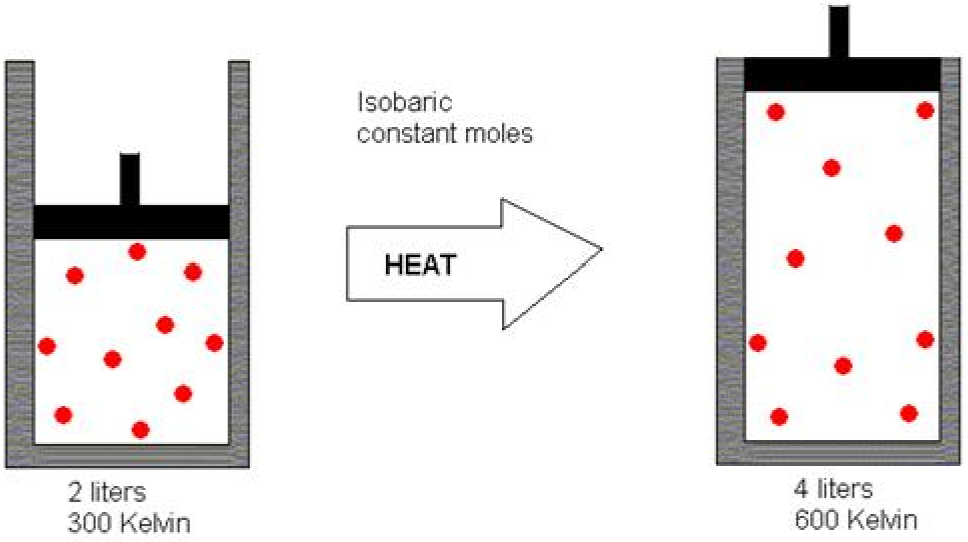
- Have students try to describe what is happening on a molecular level when the temperature of a closed bottle (containing air) drops suddenly

Charles’ Law

At a **constant pressure** , the volume of a gas is directly proportional to its absolute temperature: The volume of a gas increases as the temperature of that gas increases and the volume decreases when the temperature decreases,

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Since the pressure remains the same, this would result in increased gas volume, as depicted in the following illustration (where “isobaric” means “constant pressure”).



Source: http://dlrgenchem.com/LECTURES/Gaslaw.htm

This can be easily understood by again referring to the kinetic molecular theory of an ideal gas. When a gas is heated to increase its temperature, the speeds of its molecules increase and thus they hit the walls more often and with more force. The only way to maintain a constant pressure in this situation is to increase the volume of the container. This compensates for the increased particle speeds since pressure is defined as force per unit area.

Charles' Law Lesson Plan (one class period)

Learning Objectives

Students will be able to:

- sketch a graph of the volume-temperature relationship for a gas.

- calculate the volume or temperature of a gas after a change in conditions.

Materials & Teacher-developed Resources

-Paper, pencils, textbooks, software

-Student handouts

-Balloons, hot plate, ice

Learning Activities

- The teacher will ask the students to predict what would happen to the size of an inflated balloon if the balloon is placed in the ice?

- What would happen if a balloon of the same size is placed over a hot plate?

- Ask the students to describe the relationship between the volume and temperature of a gas and write the mathematical equation

Moles and the Ideal Gas Law

The ideal gas law is an equation of state for a gas, where the state of that gas is its condition at a given time. A particular state of a gas is described by its pressure (P), volume (V), temperature (T) and number of moles (n). It is important to recognize that the ideal gas law is an empirical equation - it is based on experimental measurements of the properties of gases. A gas that obeys this equation is said to behave ideally. In other words, an ideal gas is defined as a gas for which PV/(nT) is constant for all pressures, volumes and temperatures. Therefore, the ideal gas is a hypothetical substance. However, most gases obey the ideal gas law closely enough at pressures below one atmosphere (1 atm), that only minimal errors result from assuming the ideal gas behavior.

The number of moles of a gas (**n**) inside a container, is closely related to its temperature, pressure, and volume. This is summarized by the **ideal gas law** which itself is derived from the combined gas law (**Clapeyron-Mendeleev Law**).

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

The ideal gas law is given by the equation PV = nRT.

The proportionality constant or gas constant, R, is approximately 0.082 (liter x atmosphere) **/** (Kelvin x mole), or 8.31 Joule/ (mole x Kelvin), or 1.987 calories / (mole x Kelvin). If higher densities of gases are being studied, then corrections to this equation must be made, since they will not behave ideally.

Combined Gas Law Lesson Plan (two class periods)

Learning Objective

Students will be able to calculate the pressure, volume, or temperature of a gas after a change in conditions.

Materials & Teacher-developed Resources

- Paper, pencils, textbooks, software

- Student handouts

Learning Activities

-The teacher will review the relationships that were taught in the previous lesson between pressure, volume and temperature

- Using the combined gas law, have the students explain how does a fire extinguisher work

- The students will complete a worksheet solving problems that include all three variables

- Students will answer the following question:” Why does it make sense to pump gas in your car in the morning rather than in the evening?”

4. Stirling engine

A system or device that converts heat into work is a heat engine. Heat engines are cyclic: some part of the system absorbs energy, work is done and the system returns to its original state in order for the cycle to begin again. Although the term “engine” might call to mind the complex device that powers an automobile, in thermodynamics a heat engine can be as simple as gas in a piston that expands as heat is added and contracts as the gas cools. There are also tiny molecular engines in living cells. Although they are much smaller than a piston or the engine in a car, these tiny engines perform the same function, transforming energy into motion.

We can describe heat engines of all kinds by a simple generic model. The engine is thermally connected to a reservoir of higher (hotter) temperature (T_h) and to a reservoir of lower (cooler) temperature (T_c). A reservoir is a part of a system large enough either to absorb or supply heat without a change in temperature. In an old-time steam engine, for example, the furnace serves as the hot reservoir and the surrounding atmosphere acts as the cold reservoir. Energy Q_h flows from the hot reservoir into the engine; during this process some of the energy goes into work W, and the remainder Q_c flows out of the engine and into the cold reservoir in the form of heat.

A perfect engine would be one in which all of the energy Q_h taken in from the hot reservoir is converted to work, with no heat at all going into the cold reservoir (that is, $Q_c=0$). This would be 100% efficient engine: None of the energy from the hot reservoir would be “thrown away” to the cold reservoir. Unfortunately, the second law of thermodynamic stipulates that such a perfect engine is impossible. To understand why, note that there is an increase in order of the hot reservoir because energy flows out of this reservoir and therefore some of the molecules of the reservoir must decrease their random motion and so become more orderly. This corresponds to a decrease in entropy, which is not allowed in an isolated system.

The conclusion is that we simply cannot build a perfect engine that is 100% efficient. The **Kelvin-Planck** statement is a rewording of the second law of thermodynamics that describes the inherent efficiency limits of heat engines: **No process is possible in which heat is absorbed from a reservoir and converted completely into work.**

In order for a heat engine to satisfy the second law of thermodynamics, some heat must flow into the cold reservoir in order to make the cold reservoir less ordered. This happens because the energy added to the cold reservoir increases the random motion of the reservoir’s molecules. This corresponds to an increase in entropy that offsets the decrease in entropy in the hot reservoir.

In the early stages of the industrial revolution, most of the energy needed to run mills and factories came from water power. Water in a high reservoir will naturally flow downhill. A waterwheel can be used to harness this natural flow of water to produce useful energy because some of the potential energy lost by the water as it flows downhill can be converted into other forms such as electricity.

It is possible to do something similar with heat. Thermal energy is naturally transferred from a hot reservoir to a cold reservoir; it is possible to take some of this energy as it is transferred and convert it to other forms. This is the job of a heat engine as described above.

As stated above, no heat engine can operate without exhausting some fraction of the heat into a cold reservoir. This is not a limitation on our engineering abilities. It is a fundamental law of nature.

The maximum possible efficiency of a heat engine is determined by the second law of thermodynamics. We will not perform a detailed derivation, but simply note that the second law gives the maximum efficiency of a heat engine as $e_{max} = 1 - T_c/T_h$

It is seen that the efficiency is 0 when $T_c = T_h$, and it is 1 when $T_c = 0$ (absolute zero). The maximum efficiency of any heat engine is therefore determined by the ratio of the temperatures of the hot and cold reservoirs. It is possible to increase the efficiency of a heat engine by increasing the temperature of the hot reservoir and/or decreasing the temperature of the cold reservoir. The efficiency of the above equation is also called the *Carnot* efficiency, after a theoretical heat engine that achieves this maximum possible efficiency. The actual efficiency of real heat engines is usually about 10% to 50% than the theoretical maximum.

A Stirling engine is a heat engine that operates by cyclic compression and expansion of air or other gas (the working fluid) at different temperatures, such that there is a net conversion of heat energy to mechanical work. More specifically, the Stirling engine is a closed-cycle regenerative heat engine with a permanently gaseous working fluid. “Closed-cycle” refers to a thermodynamic system in which the working fluid is permanently contained and recycled within the system. The term “regenerative” describes the use of a specific type of internal heat exchanger and “thermal store”, known as the regenerator. The inclusion of a regenerator differentiates the Stirling engine from other closed cycle hot air engines.

The Stirling engine was invented and patented by Robert Stirling in 1816. It followed earlier attempts to build an air engine but was probably the first put to practical use when, in 1818, an engine built by Stirling was employed pumping water in a quarry. The main subject of Stirling's original patent was a heat exchanger, which he called an “economizer” for its enhancement of fuel economy in a variety of applications. The patent also described in detail the employment of one form of the economiser in his unique closed-cycle air engine design in which application it is now generally known as a “regenerator”. Subsequent development by Robert Stirling and his brother James, an engineer, resulted in patents for various improved configurations of the original engine including pressurization, which by 1843, had sufficiently increased power output to drive all the machinery at a Dundee cast iron factory, in Scotland.

In addition to saving fuel, the inventors were motivated to create a safer alternative to the steam engines, whose boilers frequently exploded, causing many injuries and fatalities.

Although the Stirling engine was conceived in 1816 as an industrial machine to rival the steam engine, its practical use was largely confined to low-power domestic applications for over a century.

Stirling engines have a high efficiency compared to steam engines, being able to reach 50% efficiency. They are also capable of quiet operation and can use almost any heat source. The heat energy source is generated external to the Stirling engine rather than by internal combustion as with the Otto cycle (used in gasoline engines) or Diesel cycle engines.

Because the Stirling engine is compatible with alternative and renewable energy sources it could become increasingly significant as the price of conventional fuels rises, and also in light of concerns such as depletion of oil supplies and climate change. This type of engine is currently generating interest as the core component of micro combined heat and power (CHP) units, in which it is more efficient and safer than a comparable steam engine. However, it has a low power-to-weight ratio, rendering it more suitable for use in static installations where space and weight are not factors of primary importance.

How does the Stirling engine work?

The engine is designed so that the working gas is compressed in the colder portion of the engine and expanded in the hotter portion resulting in a net conversion of heat into work. An internal regenerative heat exchanger increases the Stirling engine’s thermal efficiency compared to simpler hot air engines lacking this feature.

As a consequence of closed cycle operation, the heat driving a Stirling engine must be transmitted from a heat source to the working fluid by heat exchangers and finally to a heat sink. A Stirling engine system has at least one heat source, one heat sink and up to five heat exchangers. Some types may combine or dispense with some of these

The heat source may be provided by the combustion of a fuel and, since the combustion products do not mix with the working fluid and therefore do not come into contact with the internal parts of the engine, a Stirling engine can run on fuels that would damage other engines internal parts.

Other suitable heat sources include concentrated solar energy, geothermal energy, nuclear energy, waste heat and bioenergy. If solar power is used as a heat source, regular solar mirrors and solar dishes may be utilized, a good example in this direction being the point focus parabolic mirror with Stirling engine at its center at Plataforma Solar de Almería (PSA) in Spain. (See the image below)

(Source: http://ifisc.uib-csic.es/raul/CURSOS/TERMO/Stirling%20engine.pdf)

The use of Fresnel lenses and mirrors has also been advocated, for example in planetary surface exploration.

In a Stirling engine, the regenerator is an internal heat exchanger and temporary heat store placed between the hot and cold spaces such that the working fluid passes through it first in one direction then the other, taking heat from the fluid in one direction, and returning it in the other. It can be as simple as metal mesh or foam, and benefits from high surface area, high heat capacity, low conductivity and low flow friction. Its function is to retain within the system that heat that would otherwise be lost to the environment at temperatures intermediate to the maximum and minimum cycle temperature, thus enabling the thermal efficiency of the cycle (though not of any practical engine) to approach the limiting Carnot efficiency.

The primary effect of regeneration in a Stirling engine is to increase the thermal efficiency by recycling internal heat that would otherwise pass through the engine. As a secondary effect, increased thermal efficiency yields a higher power output from a given set of hot and cold heat exchangers. These usually limit the engine’s heat throughput. In practice this additional power may not be fully realized as the additional “dead space” (unswept volume) and pumping loss inherent in practical regenerators reduces the potential efficiency gains from regeneration.

The design challenge for a Stirling engine regenerator is to provide sufficient heat transfer capacity without introducing too much additional internal volume (“dead space”) or flow resistance. These inherent design conflicts are one of many factors that limit the efficiency of practical Stirling engines.

The regenerator is the key component invented by Stirling and its presence distinguishes a true Stirling engine from any other closed cycle hot air engine. Many small “toy” Stirling engines, particularly low-temperature difference (LTD) types, do not have a distinct regenerator component and might be considered hot air engines; however a small amount of regeneration is provided by the surface of the displacer itself and the nearby cylinder wall, or similarly the passage connecting the hot and cold cylinders of an alpha configuration engine.

Cooler / cold side heat exchanger

In small, low power engines this may simply consist of the walls of the cold space(s), but where larger powers are required a cooler using a liquid like water is needed to transfer sufficient heat.

Heat sink

The heat sink is typically the environment at ambient temperature. In the case of medium to high power engines, a radiator is required to transfer the heat from the engine to the ambient air. Marine engines can use the ambient water. In the case of combined heat and power systems, the engine’s cooling water is used directly or indirectly for heating purposes.

Alternatively, heat may be supplied at ambient temperature and the heat sink maintained at a lower temperature by such means as cryogenic fluid or ice water.

Displacer

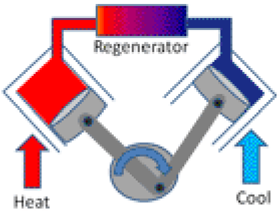
The displacer is a special-purpose piston, used in Beta and Gamma type Stirling engines, to move the working gas back and forth between the hot and cold heat exchangers. Depending on the type of engine design, the displacer may or may not be sealed to the cylinder, i.e. it may be a loose fit within the cylinder, allowing the working gas to pass around it as it moves to occupy the part of the cylinder beyond.

Configurations

There are three major types of Stirling engines, that are distinguished by the way they move the air between the hot and cold areas:

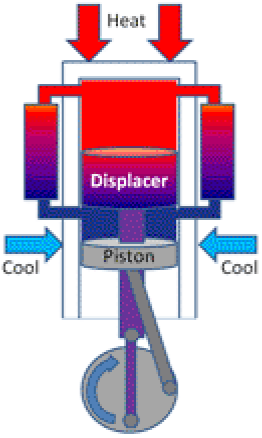
1. The **alpha** configuration has two power pistons, one in a hot cylinder, one in a cold cylinder, and the gas is

driven between the two by the pistons; it is typically in a V-formation with the pistons joined at the same point on a crankshaft.



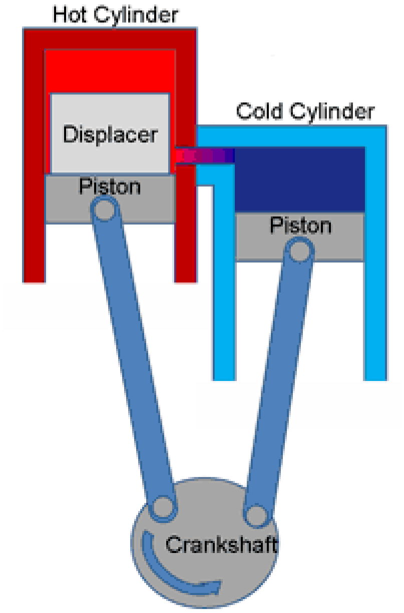
Source: http://www.mpoweruk.com/stirling_engine.htm

2. The **beta** configuration has a single cylinder with a hot end and a cold end, containing a power piston and a “displacer” that drives the gas between the hot and cold ends. It is typically used with a rhombic drive to achieve the phase difference between the displacer and power pistons, but they can be joined 90 degrees out of phase on a crankshaft.



Source: http://www.mpoweruk.com/stirling_engine.htm

The **gamma** configuration has two cylinders: one containing a displacer, with a hot and a cold end, and one for the power piston; they are joined to form a single space with the same pressure in both cylinders; the pistons are typically in parallel and joined 90 degrees out of phase on a crankshaft.

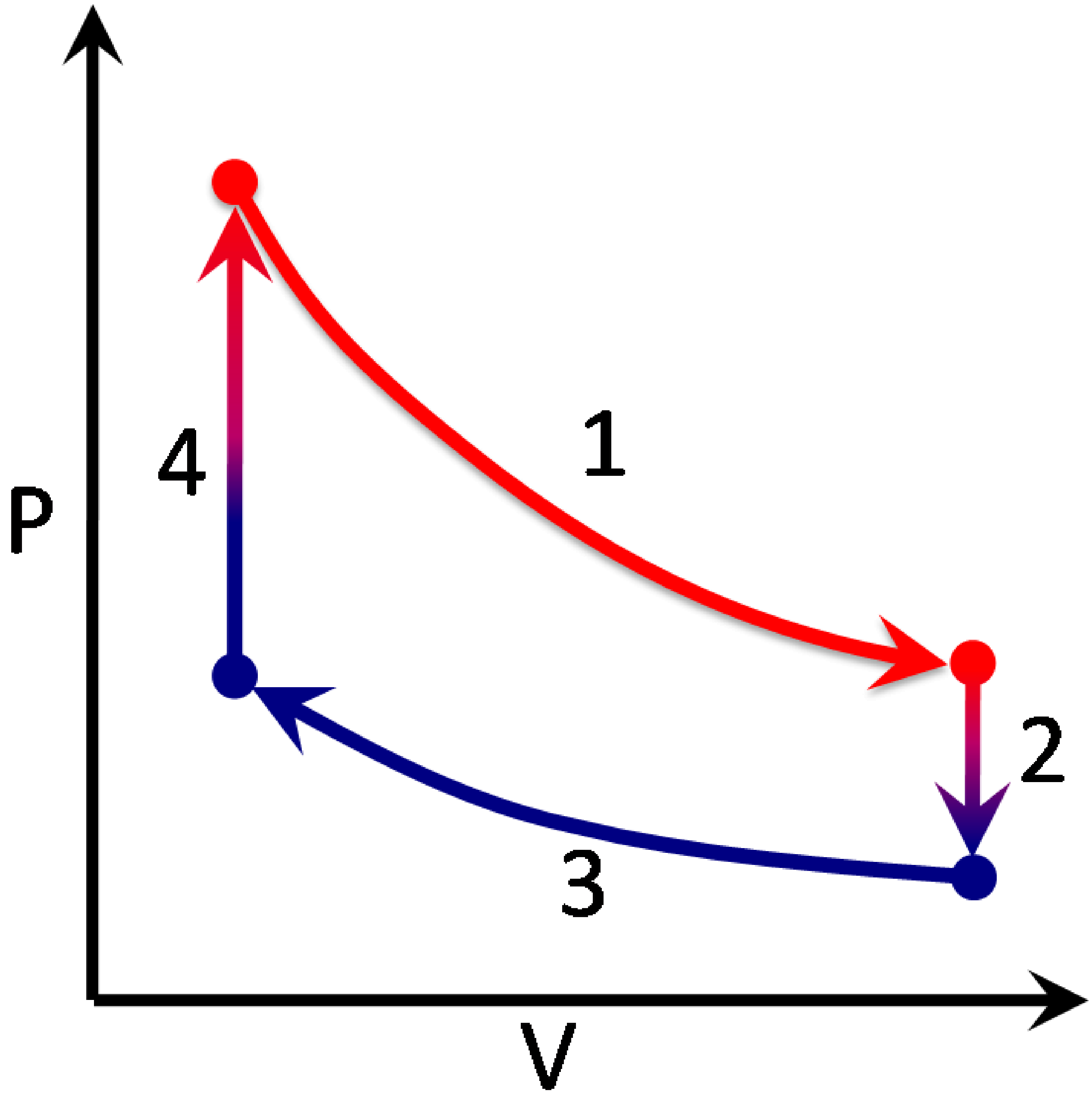


Source: http://www.mpoweruk.com/stirling_engine.htm

The ideal Stirling cycle consists of four thermodynamic processes acting on the working fluid:

1. Isothermal expansion. The expansion-space and associated heat exchanger are maintained at a constant high temperature, and the gas undergoes near-isothermal expansion absorbing heat from the hot source.
2. Constant-volume (known as isovolumetric or isochoric) heat-removal. The gas is passed through the regenerator, where it cools, transferring heat to the regenerator for use in the next cycle.
3. Isothermal compression. The compression space and associated heat exchanger are maintained at a constant low temperature so the gas undergoes near-isothermal compression rejecting heat to the cold sink
4. Constant-volume (isochoric) heat-addition. The gas passes back through the regenerator where it recovers much of the heat transferred in 2, heating up on its way to the expansion space.

Theoretical thermal efficiency equals that of the hypothetical Carnot cycle – i.e. the highest efficiency attainable by any heat engine.



(Source: https://en.wikipedia.org/wiki/Stirling_engine#/media/File:Stirling_Cycle_color.png)

The thermodynamic cycle of a Stirling engine can be driven in reverse with the aid of an outside power source. This will cause one side to be heated and the other side of the engine to be cooled. Simply put, a Stirling engine can be used as a heat pump. By spinning the engine through its mechanical cycles, the gas inside is compressed and expanded, heated and cooled, respectively. Cooling with the Stirling cycle is currently used commercially for cryogenics and refrigeration.

Stirling Engine Lesson Plans (two class periods)

Learning Objective

Students will be able to:

- explain the working principle of a heat engine

- describe the parts of a heat engine

- identify and describe the different configurations of Stirling engines

- calculate the efficiency of a heat engine

Materials & Teacher-developed Resources

-Paper, pencils, software (www.animatedengines.com)

- a “Mini Hot Air Stirling Engine Model Educational Kit” (it can be bought from “ebay” with less than $30.00)

-Student handouts

Learning Activities

-The teacher will review the laws of thermodynamics

- As a practical application of the Second Law of Thermodynamics, the teacher introduces the heat engines, describing their parts and how do they work

- Students will play the software simulating the operation of a heat engine, identifying the four processes of an ideal Stirling cycle

- Using the software, the teacher will compare and contrast the different configurations of a Stirling engine

- The teacher will demonstrate how does the Stirling engine work, using the model educational kit

- using the handouts, students will perform computations related to the efficiency of a heat engine

Appendix (Implementing District Standards)

CT New Generation Science Standards:

At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy. (HS-PS3-2) (HS-PS3-3)

Energy cannot be created or destroyed, but it can be transported from one place to another and transferred between systems. (HS-PS3-1),(HS-PS3-4)

The availability of energy limits what can occur in any system. (HS-PS3-1)

Uncontrolled systems always evolve toward more stable states - that is, toward more uniform energy distribution (e.g., water flows downhill, objects hotter than their surrounding environment cool down). (HS-PS3-4)

Although energy cannot be destroyed, it can be converted to less useful forms—for example, to thermal energy in the surrounding environment. (HS-PS3-3), (HS-PS3-4)

Create a computational model or simulation of a phenomenon, designed device, process, or system. (HS-PS3-1)

Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system. (HS-PS3-3)

Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions - including energy, matter, and information flows - within and between systems at different scales. (HS-ETS1-4)

District Standards:

Identify the three basic assumptions of the kinetic molecular theory.

Describe the basic differences between solids, liquids, and gases in terms of the kinetic theory.

Describe energy changes accompanying a change of state.

Describe the physical properties of gases.

Describe volume, temperature, and pressure of a gas and their units of measurement.

Apply the relationships between pressure, temperature, concentration and volume to gas behavior (i.e. Boyle’s Law, Charles’ Law).

D INQ.7 Assess the reliability of the data that was generated in the investigation.

D INQ.8 Use mathematical operations to analyze and interpret data, and present relationships between variables in appropriate forms.

D INQ.10 Communicate about science in different formats, using relevant science vocabulary, supporting evidence and clear logic.

Resources

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1. http://ifisc.uib-csic.es/raul/CURSOS/TERMO/Stirling%20engine.pdf
2. http://smarthome.duke.edu/sites/smarthome.duke.edu/files/KTH_Stirling_Engine.pdf
3. http://www.nextgenscience.org/sites/default/files/NGSS%20Combined%20Topics%2011.8.13.pdf
4. http://www.nhps.net/Chemistry

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2. Zumdahl & Zumdahl (2007). *Chemistry,* Houghton Mifflin (7 th)
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4. Shipman, James, Wilson, Jerry, Higgins, Charles, Torres, Omar (2015). *An Introduction to Physical Science.* Brooks Cole (14 th)
5. Bolton, Henry Carrington (1900). Evolution of the Thermometer, 1592-1743. Easton, Pennsylvania: The Chemical Publishing Company. p. 68–70.
6. Moran, Michael J., Shapiro, Howard N., Boettner, Daisie, D., Bailey, Margaret B. (2014). *Fundamentals of Engineering Thermodynamics,* Wiley (8 th)
7. Walker, Graham, Senft J.R., (1985). *Lecture Notes in Engineering (Free Piston Stirling Engines).* A. Brebbia & S.A. Orszag, (1 st ed.)
