EVALUATING
ACADEMIC READINESS
FOR APPRENTICESHIP TRAINING
Revised for
ACCESS TO APPRENTICESHIP

SCIENCE SKILLS
COMBINED GAS LAWS

AN ACADEMIC SKILLS MANUAL
for
The Industrial Maintenance Mechanic Trades

This trade group includes the following trades:
Boiler Maker,
Facilities Maintenance Mechanic & Technician, and
Industrial Mechanic (Millwright)

Workplace Support Services Branch
Ontario Ministry of Education and Training

Revised 2011

In preparing these Academic Skills Manuals we have used passages, diagrams and questions similar to those an apprentice might find in a text, guide or trade manual.

This trade related material is not intended to instruct you in your trade. It is used only to demonstrate how understanding an academic skill will help you find and use the information you need.

SCIENCE SKILLS
GAS LAWS

An academic skill required for the study of the Industrial Maintenance Mechanic Trades

INTRODUCTION

Because gases are usually invisible, we are not often aware of their existence. But these invisible gases have an important role in the way machine such as welders, engines and cooling units work. For example, the fuel that burns in an engine is first vapourized into a gas. The pressure created by the rapid expansion of this gas when it ignites is transmitted to the piston. It is this combustion of a gas that generates the power of an engine.

In an air conditioner or a cooling unit, the refrigerant reacts to changes in pressure and temperature by changing from a liquid to a gas and then back again. The heat absorbed when the refrigerant changes to a gas enables it to remove heat from the inside of the unit to the outside, where it is released.

In the workshop, gases are used in pneumatic tools. Pneumatic tools are driven by the pressure from compressed gas, which is supplied by a gas compressor. Gases such as oxygen and hydrogen are burned as fuels for welding. At the same time, the gases that form the atmosphere around the welding site can influence the quality of the weld. Understanding how gases react to temperature and pressure can help you work with gases on the job in a safe and effective way.

Gases respond to changes in pressure, temperature and volume in a specific way. An understanding of this relationship can help you interpret the way a gas will react. In this skills manual, we look at the following topics:

- What is a gas?
- Pressure exerted by a gas
- Changes of state
- Pascal’s Law
- Boyle’s Law
- Charles’ Law
- Combined Gas Laws

WHAT IS A GAS?

All substances are formed from molecules, which are made of atoms that are bonded together. Every molecule moves or vibrates with a certain amount of ***kinetic energy*** − the energy of motion. The amount of kinetic energy of a substance determines its ***physical state***, whether it exists as a solid, liquid or gas.

We will briefly look at the three states to see how a gas differs from a solid or a liquid.

- ♦ The molecules of ***solids*** have a relatively low amount of kinetic energy and stay close together. Because their molecules stick together, solids have a definite shape and volume.
- ♦ The molecules of ***liquids*** have more kinetic energy so they move and flow over each other. They are close enough together to maintain a definite volume, but they flow into the shape of their container.
- ♦ ***Gas*** molecules have a large amount of kinetic energy. They move so quickly that there is no close bonding between individual gas molecules. Gas molecules basically exist as independent particles. Gases have no definite shape or volume but if they are contained, they expand to take the shape of their container.

In the open air, gases move about randomly in every direction. Some escape into the atmosphere, but some, like water vapour, condense into a liquid when they reach the cooler upper atmosphere and fall back to earth as rain. Other gases react chemically and combine to form new substances. For example, when wood burns, the carbon in the wood combines with oxygen gas in the air to form carbon dioxide and carbon monoxide gas.

PRESSURE EXERTED BY A GAS

Force

Pressure is closely related to the concept of force. ***Force*** *is defined as a push or pull exerted on an object; a force produces motion or has a tendency to do so.*

- *A force applied to a solid object* results in movement in that object. If the force is not strong enough or the object is not free to move, the object feels a stress or pressure but it doesn't move.
- *A force applied a liquid in a container,* causes the liquid to transmit that force to the walls of its container.
- *A force applied to a gas in a container* causes the gas take up less space – the gas becomes compressed. At the same time, the gas now exerts more force back on the walls of its container.

In the metric system, force is expressed in ***newtons (n)***, the same unit as that of weight. In the imperial system, the unit of force is the ***pound (lb).***

Pressure

Pressure is the force measured over a definite area. The term ***pressure*** *is defined as the force per unit area.* When we talk about a gas exerting pressure, we indicate that the force exerted by the gas extends over a defined area – the surface area of its container.

To calculate the pressure, the amount of force exerted is divided by the area that the force is exerted over.

The formula for pressure is:

Pressure = Force ÷ Area

or

P = F/A

In the imperial system, units of pressure are pounds per square inch (psi). In the metric in system, pressure is measured in newtons per square meter (N/m^2), which is called a pascal (Pa). One kilopascal (kPa) is equal to 1000 pascals.

All objects, whether they are solids, liquids or gases, exert pressure. When we talk about an object exerting pressure, we are saying that the force it exerts extends over a definite area.

- Solids exert pressure in a downward direction only. This pressure comes from the pull of gravity on the mass of the solid.
- Liquid molecules exert pressure in a downward direction but they also exert pressure on the walls of their container, which can be a pail or the edges of a lake. As they flow, they bump into the surface of the solid walls and exert a sideways and downward pressure.
- Gases have so much kinetic energy that they are constantly moving. As they move, they bounce against the walls of the container they are enclosed in, exerting pressure evenly on all surfaces.

Atmospheric Pressure

Air molecules are gases. They exert pressure on everything they encounter. We don't usually feel air pressure when it is applied equally on all sides of our body. However, when gas molecules are driven in one direction, as when a wind blows, we feel the air pressure and see its effects.

Air pressure is called atmospheric pressure. Atmospheric pressure can be measured using a barometer. At sea level, mercury in a barometer rises to a height of 29.9 inches or 760 mm. This amount of pressure is called 1 atmosphere. Atmospheric pressure is also measured in kilopascals (kPa), which is close to 100 atmospheres.

Compressed Gas

Air, like any gas, can be compressed (reduced in volume) by forcing it into a small space. Gases used for industrial purposes are often compressed. The oxygen gas used in welding is held at a very high pressure. To compress a gas, a pump called a compressor pushes the gas molecules close together. A large number of gas molecules are compressed into a small volume. As a result, the gas is under high pressure.

- Car tires are filled with compressed air. The compressed air inside exerts pressure on the walls of the tire, enabling the tire to hold its shape even when it supports the weight of a vehicle.

CHANGES OF STATE

Significant change in temperature and pressure can cause matter to change from one state to another.

Temperature has an effect on changes of state from a gas to a liquid and vice versa:

- The amount of heat determines the kinetic energy of a substance, and the amount of kinetic energy determines its physical state.
- If a liquid substance gains enough heat, it changes to a gas. The temperature at which a substance will rapidly change from a liquid to a gas is called the boiling point.
- If a vapour or gas loses enough heat, it will change into a liquid. The temperature at which a substance changes from a gas to a liquid is called the condensation point.

Pressure also has an effect on changes of state:

- The boiling point of a substance becomes lower if the pressure is reduced.
- On the other hand, the boiling point becomes higher if pressure is increased.
- Water boils at a temperature that is less than 100°C if the pressure is lower than 1 atmosphere.

Remember: The condensation point and boiling point of a substance occur at the same temperature. So:

- The condensation point of a substance becomes lower if the pressure is reduced.
- In the same way, the condensation point becomes higher if the pressure is increased.

Changes of state in a cooling system

As a substance changes from a liquid to a vapour state, it absorbs heat from the atmosphere. As it changes from a vapour to a liquid state, it gives up heat to the atmosphere. In general, a cooling system uses these principles to remove heat. The cooling cycle operates in the following way:

- A liquid, such as a refrigerant, absorbs heat.
- As it absorbs heat, it changes from a liquid state to a gas.
- The gas moves to where it can release heat to the outside air.
- As it gives up heat, the gas changes back to a liquid.
- The cycle begins again.

PASCAL'S LAW

As gas molecules move around with high energy, they exert pressure on the objects they bounce against. A scientist named Pascal described how gases exert pressure on the walls of their container.

Pascal's Law states: *Pressure exerted by a confined gas at rest is transmitted equally in every direction and is applied at right angles to the surface of the container.*

Gas Pressure
As gas molecules move around with high energy, they bump into objects such as the walls of their container – a balloon, a tire, or the walls of a cylinder. The gas molecules transmit a pressure equally and in every direction on the walls. If the container is flexible, interesting things happen:

Example: In Figure 1 we see the effects of air pressure on a flexible container. The pressure exerted by the gas blown into the balloon causes the balloon to expand. When too much air is blown into the balloon, the pressure exerted by the air eventually causes it to break.

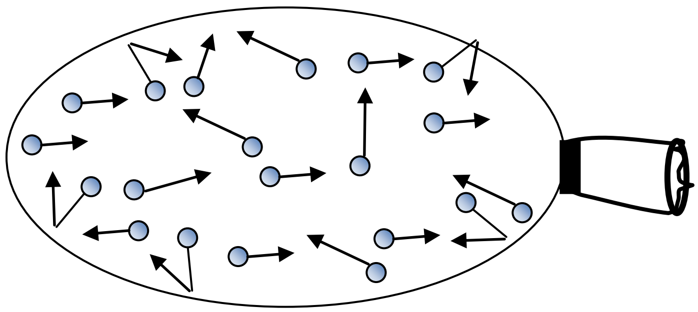

FIGURE 1: Gas Pressure

In brief:
- Gas molecules have a certain amount of kinetic energy (or heat), causing them to move around in all directions at high speed.
- The more energy the molecules move around with, the more pressure they exert when they collide with an object.
- If the walls of their container are flexible, this increase in pressure causes the container to expand, increasing the volume of the gas.
- Since the energy of a molecule is directly related to the amount of heat it has (measured as its temperature), the higher the temperature of a gas, the more pressure it exerts.

If the container is not flexible but is rigid, interesting things still happen:

Example: A can of spray paint contains both the paint and a pressurized gas on top of it. The warning on these cans says, "*Contents under pressure. Do not expose to heat.*"
- When you press the nozzle of the can, it opens the tube that runs to the bottom of the container into the paint.
  - The upward and sideways pressure of the gas pushes against the walls of the spray can but the container does not expand.
  - The downward pressure of the gas forces the paint through the tube and out through the spray nozzle.
  - You use the spray of paint to do useful work.
- If you toss the spray can into a hot cabinet, or into a fire, the pressure of the pressurized gas increases on all of the walls and on the leftover paint.
  - The increased pressure on the walls of the spray container can cause the walls to burst open with an explosive force.

Example: When fuel explodes in the cylinder of an engine, the rapidly expanding gas molecules exert pressure in all directions, including the top of the piston.

- The walls of the cylinder are strong enough to stay rigid under the pressure of the rapidly expanding gas.
  - The piston is not flexible like a balloon but it is free to move.
  - The pressure is strong enough to force the piston to the bottom of the cylinder.
  - This causes the connecting rod to drive the crankshaft, which in turn drives the wheels, or a propeller.

In brief:

- ♦ Gas molecules have a certain amount of kinetic energy (or heat), causing them to move around in all directions at high speed.
- ♦ The more energy the molecules move around with, the more pressure they exert when they collide with an object.
- ♦ If the walls of their container are flexible, this increase in pressure causes the container to expand, increasing the volume of the gas.
- ♦ Since the energy of a molecule is directly related to the amount of heat it has (measured as its temperature), the higher the temperature of a gas, the more pressure it exerts.

BOYLE'S LAW

The pressure, volume, and temperature of a gas are all related to each other. Because the gas laws that describe these relationships use absolute pressure and absolute temperature in their calculations, we will first define the *absolute scale of temperature and pressure.*

Absolute Temperature and Pressure

Temperature is usually measured using the Fahrenheit or Celsius scale. Both these scales are based on the freezing and boiling points of water. *The absolute scale is based on* ***absolute zero****, which is so cold that molecular motion stops*. Heat is expressed as the kinetic energy of molecules. If molecular motion ceases, then there is no heat present.

In the metric system, absolute temperature is measured using the Kelvin scale. Absolute zero occurs at 0° Kelvin (K). Absolute zero or 0°K is the same as − 273° Celsius and the same as −460° Fahrenheit.

At ***absolute pressure****, there is no pressure.* Molecules have no motion at absolute pressure and so they cannot exert any pressure. A perfect vacuum occurs at 0 pounds per square inch absolute (psia) or 0 pascals (Pa).

Note: *Some gauges are calibrated so that 0 psi occurs at atmospheric pressure and absolute pressure occurs at -15 pounds per square inch gauge (psig), a negative number.*

A scientist named Boyle looked at how the volume of a gas in a container is affected by the pressure exerted on it.

- Contained gas molecules exert pressure on the walls of their container.
- The walls exert a certain pressure back.
- This external pressure can be increased or decreased, as when the force of another object presses down on the contained gas.
- This causes changes in the volume of the gas, *as long as the enclosing container is flexible, so that it can also change in volume*.

Adding more heat or increasing the temperature of gas molecules causes them to move faster and exert more pressure. Boyle had to keep the temperature constant to look at the relationship between pressure and volume.

The volume of solids and liquids varies only slightly with changes in pressure. However, the volume of a gas in a flexible container can change considerably when the pressure on it is increased. When pressure is increased on a gas, the gas is compressed into a smaller space. In other words, *if pressure increases, the volume of the gas decreases*. This is somewhat stating the obvious, since, if the temperature remains the same, the only way to increase pressure on an enclosed gas is to compress it into a smaller volume.

To show this relationship, Boyle confined a gas in the end of a J-shaped glass tube by pouring a certain amount of mercury into the tube. See Figure 2.

- The mercury exerted a certain amount of pressure on the gas.
- He then poured more mercury into the tube, increasing the amount of pressure on the gas.
- When more mercury was added to the tube, which increased the pressure on the gas, the volume of the gas was reduced.
- If mercury was removed from the tube, the volume of the gas increased.

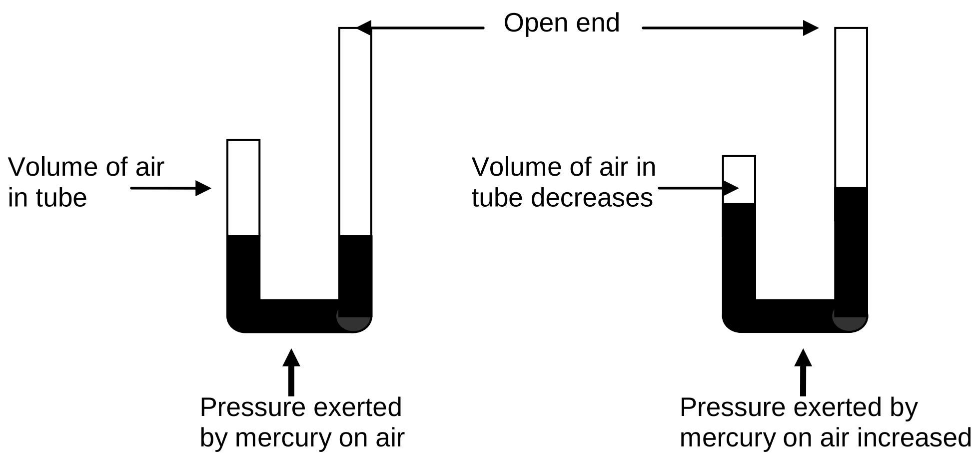

FIGURE 2: Volume of a Gas Decreases as Pressure Increases

Boyle concluded that, as the pressure increased, the volume decreased and, as the pressure decreased, the volume increased.

He stated this relationship as Boyle's Law: T*he volume of a gas* ***varies inversely*** *(or changes in the opposite way) with the pressure exerted on it, provided the temperature remains constant.*

This means that as the pressure becomes greater, the volume becomes less and if the pressure becomes less, the volume becomes greater.

For your information
There are two common ways that one property of an object can change with regard to another property. If one property changes in a certain way, the other property can change *in the same way.* For example, if one property increases, the other property also increases. If one property decreases, the other property also decreases. Both properties change in the same way. In this case, ***the properties are directly proportional (or vary directly) to each other.***

Quantities can also change in relation to each other so that as one property increases, the other property decreases. As one property changes in one way, the other property changes in the opposite way. In this case, ***the properties are inversely proportional (or vary indirectly) to each other.*** This is the way Boyle explained the relationship between pressure and volume in gases. For example, if one quantity such as pressure is increased in value by a factor of 2, the other quantity, volume, decreases in value by ½ .

These terms are often used in defining relationships between quantities, so it is a good idea to recognize what they mean.

When quantities ***vary directly,*** *or are* ***directly proportional*** to each other:

- As one quantity changes, the other one changes in the **same** way;
- If one quantity gets larger, the other one also increases;
- If one quantity gets smaller, the other one also decreases.

When quantities ***vary inversely*** or are ***indirectly proportional*** to one another:

- As one quantity changes, the other one changes in the **opposite** way;
- If one quantity gets smaller, the other one gets larger or increases;
- If one quantity gets larger, the other one gets smaller or decreases.

Calculating the Effect of Pressure on the Volume of a Gas

Boyle's Law states that the volume of a gas will vary inversely with the pressure. When the pressure changes, the new volume a gas occupies can be found by using this equation based on Boyle's Law:

$$V \times P = V_1 \times P_1$$

The original volume (V) multiplied by the original pressure (P) is equal to the new volume (V_1) times the new pressure (P_1). All pressure calculations are in absolute pressure. (Refer to the section on absolute pressure on page 4 if you need to in order to understand this section.)

If three quantities are known, such as the original volume, the original pressure and the new pressure, the fourth quantity, the new volume, can be found. In this type of equation, you can do any mathematical operation with the numbers on one side of the equal sign as long as you do the same operation with the numbers on the other side. You can also reverse the equation or invert it without changing its value.

The first step is to isolate the letter of the quantity we are looking for, V_1, by itself on one side. First, reverse the equation.

$$V_1 \times P_1 = V \times P$$

The quantity we are looking for is isolated by dividing both sides by P_1. This removes P_1 from the left side, leaving V_1 by itself

$$V_1 = \frac{V \times P}{P_1}$$

The last step is to fill in the known quantities and solve the equation.

Example: A gas occupies a volume of 100 cm^3 (cubic centimeters) at 30 psi of pressure. What new volume will the gas occupy if the pressure is increased to 50 psi?

The old volume (V) is 100 cm^3. The old pressure (P) is 30 psi. The new pressure (P_1) is 50 psi. We are looking for the new volume (V_1).

$$V_1 = \frac{V \times P}{P_1}$$

$$V_1 = \frac{100cm^3 \times 30}{50}$$

$$V_1 = 60\ cm^3$$

The gas, which originally occupied a volume of 100 cm^3, now occupies 60 cm^3 at the new, increased pressure.

Volume varies inversely with pressure. As pressure increases, the volume decreases. Remember that this relationship only holds if the gas is in a container that can be compressed.

Example: The pressure in a gas tank reads 10 psi. If the gas is compressed to 1/3 its volume, what will its pressure be, assuming the temperature remains the same?

The volume of a gas is inversely proportional to the pressure. If the volume is decreased so the gas only occupies 1/3 of its original volume, it *decreases* by a factor of 3. Therefore, the pressure *increases* by a factor of 3.

10 psi x 3 = 30 psi

The new pressure reading will be 30 psi.

CHARLES' LAW

Boyle's Law specifies that the temperature must remain the same if his observations are to be accurate. We have to keep the temperature of the gas constant as we observe the effect of the changing pressure on the volume of the gas.

This is because temperature also has an effect on the volume of a gas. But we use gases at all kinds of temperatures. We need to know what will happen if the temperature changes. A scientist named Charles studied how a change in temperature changes the volume of a gas.

Charles found that as the temperature of a gas increased, assuming the pressure stayed the same, its volume also increased. *The volume of a gas increases proportionally as the temperature increases.*

The reason for this is connected to the kinetic motion of gas molecules.

- If a gas confined in a flexible container experiences an increase in temperature, the molecules of the gas will move with more energy. (Temperature is the measurement of the amount of heat in a substance; the more heat a substance has, the more kinetic energy or motion its molecules have.)
- This more rapid motion causes the molecules to collide with the walls of the container with more force.
- The force of these collisions causes the flexible walls to expand, increasing the volume of the gas.
- The gas now occupies a larger volume.

In Charles' experiment, the outside pressure exerted on the gas remains the same. See Figure 3.

- The outside pressure is the weight of the mercury on the gas molecules.
- No mercury is added or taken away, so the outside pressure does not change.
- Provided the pressure remains the same, a rise in temperature results in the same number of gas molecules occupying a larger volume.
- As the gas molecules are heated, they push the mercury back and occupy more space.

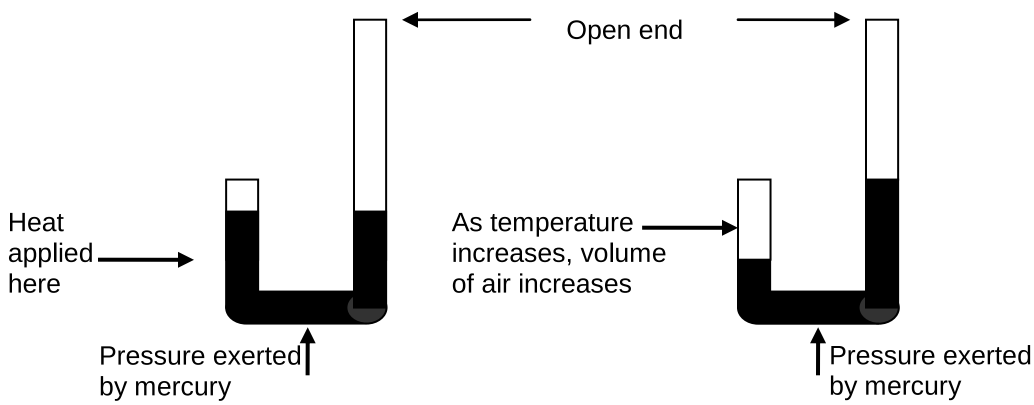

FIGURE 3: Volume of Gas Increases as Temperature Increases

If you measured the pressure of the gas in the larger volume, you would find it was the same as before the rise in temperature. In a flexible container, the increase in temperature results in a greater volume, not an increase of pressure. It is the increased force of the gas molecules pushing on the walls of the container that causes the expansion in volume. But, because the walls are free to expand, the measured pressure doesn't increase.

Throughout this experiment, the outside pressure exerted on the gas remains the same. In Figure 3, the outside pressure is the weight of the mercury on the gas molecules. Provided the outside pressure stays the same, a rise in temperature results in the same number of gas molecules occupying a larger volume. So if the gas in the tube is heated, it pushes back the mercury and it occupies more space.

If the gas was in a rigid container such as a steel cylinder, increasing the temperature would increase the pressure instead of the volume. The gas molecules are confined, so their more rapid movement causes an increase in pressure, not an increase in volume.

Charles Law states this relationship as follows: *The volume of a gas is **directly proportional** to the absolute temperature, provided the outside pressure remains constant.*

- As the temperature increases or gets larger, the volume of the gas also increases.
- In the same way, if the temperature decreases, the volume gets smaller.
- You can see this happening if you take a balloon outside on a cold day. The balloon shrinks when it is in the cold and expands again when it is brought back into a warm room.

Calculations Using Charles' Law

The formula expressing Charles' Law is:

$$\frac{V}{T} = \frac{V_1}{T_1}$$

where V is the original volume, T is the original temperature, V_1 is the new volume and T_1 is the new temperature.

We use the Kelvin temperature scale to do these calculations. This means we have to convert the temperature in degrees Celsius (°C) to degrees Kelvin (°K). We know that Absolute 0°K is the same as −273°C. To convert from C to K we have to add 273° to the number of degrees C.

Example: At 25°C, a gas occupies 500 cc (cubic centimeters). If the temperature is increased to 50° and the pressure remains constant, what is the new volume?

Change temperatures to ° Kelvin.

25° C = 273 + 25 = 298°K
50° C = 273° + 50° = 323°K

Rearrange the formula:

$$\frac{V}{T} = \frac{V_1}{T_1}$$

$$V_1 = \frac{V \times T_1}{T}$$

And solve:

$$V_1 = \frac{500cc \times 323\,°K}{298\,°K}$$

$$V_1 = 542cc$$

Example: A gas occupies 500 cc (cubic centimeters) at a certain temperature. If the temperature is doubled and the pressure remains constant, what is the new volume?

If the temperature is doubled, the volume will also be doubled.

500 cc x 2 = 1000 cc

The new volume will be 1000 cc.

COMBINED GAS LAWS

Boyle's Law and Charles' Law can be combined to create the ***Combined Gas Law***. The Combined Gas Law describes the change in volume of a gas when both the temperature and pressure change. The combined gas law states: *The volume of a gas is directly proportional to the temperature, **and** varies inversely with pressure.*

The combined gas law is expressed by the formula:

$$\frac{\mathrm{P} \times \mathrm{V}}{\mathrm{T}} = \frac{\mathrm{P_1} \times \mathrm{V_1}}{\mathrm{T_1}}$$

Example: At 25°C, a gas occupies 500 cc and 730 mm pressure. If the temperature is increased to 50°C and the pressure is increased to 760 mm, what is the new volume?

Change temperatures to °Kelvin
.
25°C = 298°K
50° C = 323°K

Rearrange the formula.

$$\frac{P \times V}{T} = \frac{P_1 \times V_1}{T_1}$$

$$V_1 = \frac{P \times V \times T_1}{P_1 \times T}$$

And solve.

$$V_1 = \frac{730\text{mm} \times 500\text{cc} \times 323°\text{K}}{760\text{mm} \times 298°\text{K}}$$

$V_1 = 520.5\ \text{cc}^3$

CONCLUSION

Volume, pressure and temperature of a gas are closely related to one another. If you make a change to the volume, pressure or temperature of gas molecules, you also affect the other two quantities.

A gas will occupy a certain volume if it is put in a container. Because they are contained, the rapidly moving gas molecules, which have mass, will bounce off the walls of the container in every direction, exerting pressure on them. The walls in turn exert a certain amount of pressure back on the gas molecules.

The temperature of the gas molecules determines how much energy they move with. If the temperature is increased, the gas molecules move with more energy, exerting more pressure. If the container is flexible, it will expand, increasing the volume. If it is rigid, the pressure will increase, causing an explosion of the container if the temperature gets too high.

The important concepts from the gas laws, assuming the gas is in a flexible container, are:

- As the pressure on a gas increases, the volume of the gas decreases if the temperature stays the same.
- Similarly, as the pressure decreases, the volume increases if the temperature remains the same.
- As the temperature increases, the volume of the gas increases if the outside pressure stays the same.
- Similarly, as the temperature decreases, the volume decreases if the outside pressure stays the same.

Answer the following questions on the effects of changing pressure and temperature on the volume of a gas. Answers are on the last page.

Fill in the blanks with true or false:

1. When a substance absorbs more heat energy, it increases its kinetic energy. ____________
2. The volume of a gas does not vary with changes in pressure. ____________
3. The pressure, volume and temperature of a gas are all related. ____________
4. Gases have no definite shape or volume but expand to fill the container they are in __________
5. When gas molecules are compressed into a smaller space, their volume decreases. __________
6. If a gas in a flexible container is heated, the volume occupied by the gas decreases. ____________
7. When more gas molecules are put into a container using a compressor, the pressure of the gas inside increases. ____________

Fill in the blanks with the correct words:

8. If one quantity varies inversely with another quantity, it means that as one changes, the other changes in the _____________ way.
9. When quantities are directly_________________ to each other, it means that if one quantity gets larger, the other also gets larger.
10. As pressure increases (if the temperature remains the same), the volume of a gas in a flexible container will ______________ .
11. The volume of a gas is 6 L at 100 mm pressure. If the pressure is doubled, what is the new volume? ______________
12. As temperature increases (if outside pressure remains the same), the volume of a gas will _______________ .
13. As temperature decreases, (if outside pressure remains the same), the volume of a gaswill _______________ .

Answer page

1. true
2. false
3. true
4. true
5. true
6. false
7. true
8. opposite
9. proportional
10. decreases
11. Use Boyle's Law
    Pressure is increased by a factor of 2; so volume is decreased by a factor of 2 or by ½ .
    ½ x 6 = 3 L
12. increases
13. decreases