

THERMODYNAMICS

Faculty of Applied Design and Engineering

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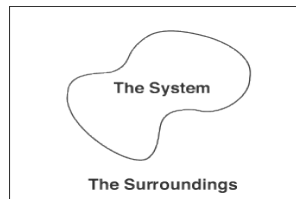


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Definitions:

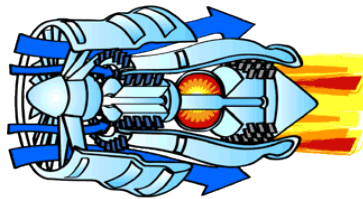
System:

A system is defined as a collection of matter with prescribed and identifiable boundaries and surroundings.



Open System:

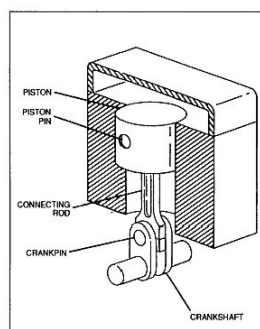
An open system has a transfer of mass across a boundary.
For example, a jet turbine engine



Closed System:

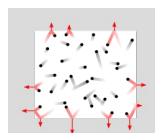
A closed system has no transfer of mass across a boundary, all the mass remains in the system

For example – A piston in a cylinder (with no valves)



What is Pressure?

The pressure in a system is the 'force per unit area' acting on the system boundaries (N/m^2). This pressure is a result of the interaction of the moving atoms or molecules in the system colliding with the system boundary.



Work:

- is defined as the product of a force and the distance moved in the direction of the force.
- Is an energy in transition – it is not possible to 'store' work
- If the boundary of a system moves outwards, then work is done by the system on its surroundings
- If the boundary of a closed system moves in the direction of the force acting on it, then work is said to have been done on the system by the surroundings
- Work has the units of ... Joules = N.m

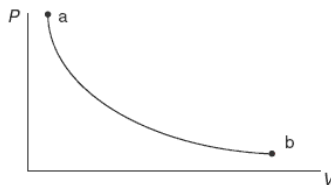
Sign Conventions:

ALL EXTERNAL INPUTS TO A SYSTEM ARE POSITIVE

- i.e. HEAT supplied to the system, Q , is positive
Work input to a system, W , is positive

Reversibility:

The state of a fluid can be represented on a diagram using two properties to specify the coordinate of the state



At point 'a', the fluid has a certain pressure and volume and is said to be in one STATE. At point 'b', it is at a different state (at a different pressure and volume).

The path between points 'a' and 'b' is called a PROCESS (in this case it can be seen that it is an expansion process)

IF THE PROCESS IS **REVERSABLE** BOTH THE FLUID AND ITS SURROUNDINGS CAN ALWAYS BE RESTORED TO THEIR ORIGINAL STATE.

Criteria for Reversibility:

- a) Process must be friction-less, there must be no internal friction from the fluid and no mechanical friction.
- b) The difference in pressure between the fluid and the surroundings must be infinitely small.
- c) The difference in temperature between the fluid and the surroundings must be infinitely small.

An Interesting Aside:

SI Units and their origin...

metre [m]

The metre is the basic unit of length. It is the distance light travels, in a vacuum, in $1/299792458^{th}$ of a second.

kilogram [kg]

The kilogram is the basic unit of mass. It is the mass of an international prototype in the form of a platinum-iridium cylinder kept at Sevres in France. *It is now the only basic unit still defined in terms of a material object, and also the only one with a prefix[kilo] already in place.*

second [s]

The second is the basic unit of time. It is the length of time taken for 9.19×10^9 periods of vibration of the caesium-133 atom to occur.

kelvin [K]

The kelvin is the basic unit of temperature. It is $1/273.16^{th}$ of the thermodynamic temperature of the triple point of water. *It is named after the Scottish mathematician and physicist William Thomson 1st Lord Kelvin (1824-1907).*

mole [mol]

The mole is the basic unit of substance. It is the amount of substance that contains as many elementary units as there are atoms in 0.012 kg of carbon-12.

hertz [Hz]

The hertz is the SI unit of the frequency of a periodic phenomenon. One hertz indicates that 1 cycle of the phenomenon occurs every **second**. For most work much higher frequencies are needed such as the kilohertz [kHz] and megahertz [MHz]. *It is named after the German physicist Heinrich Rudolph Hertz (1857-94).*

joule [J]

The joule is the SI unit of work or energy. One joule is the amount of work done when an applied force of 1 **newton** moves through a distance of 1 **metre** in the direction of the force. *It is named after the English physicist James Prescott Joule (1818-89).*

newton [N]

The newton is the SI unit of force. One newton is the force required to give a mass of 1 **kilogram** an acceleration of 1 **metre** per **second** per **second**. *It is named after the English mathematician and physicist Sir Isaac Newton (1642-1727).*

watt [W]

The watt is used to measure power or the rate of doing work. One watt is a power of 1 **joule** per **second**. *It is named after the Scottish engineer James Watt (1736-1819).*

Sidenote...

So if energy is the Joule... is $1\text{N} \times 1\text{m}...$
And one newton is $1\text{kg} \times 1\text{m/s}^2...$

Energy is really $1\text{kg} \times 1\text{m/s}^2 \times 1\text{m}$ or more easily $\frac{\text{kg.m}^2}{\text{s}^2}$

Kinetic Energy is $\frac{1}{2} mv^2$ which is $kg \times (m/s)^2$..

$$\text{Which is } \frac{kg.m^2}{s^2}$$

Potential Energy is mgh ... $1kg \times m/s^2 \times m$

$$\text{Which is } \frac{kg.m^2}{s^2}$$

Other popular units of measuring energy can also be measured in joules...

1 electron volt = $1eV = 1.602\,176 \times 10^{-19}$ Joules

1 calorie = $1\,cal = 4.1855$ J

The units of power can be looked in the same way....

Power is measured in 'watts'... which is the same as 'joules per second'

$$\text{So the units are.... } \frac{kg.m^2}{s^3}$$

1 horsepower = $1hp = 735.498\,75$ W

These are the basic units needed for thermodynamics...

We'll introduce others when required...

BOYLE'S LAW EXPERIMENT - VERIFICATION OF BOYLE'S LAW

Apparatus:

One type of Boyle's law apparatus (shown here) consists of a thick walled glass tube that is closed at one end. It contains a volume of air trapped by a column of oil. A pressure gauge attached to the oil pipe is used in measuring the pressure of this volume of air

Procedure:

1. Using the pump, increase the pressure on the air in the tube. Make sure not to exceed the safety limit indicated on the pressure gauge. Close the valve and wait 20 s to allow the temperature of the enclosed air to reach equilibrium. Read the volume V of the air column from the scale.
2. Take the corresponding pressure reading from the gauge and record the pressure P of the trapped air.
3. Reduce the pressure by opening the valve slightly, this causes an increase the volume of the trapped air column. Again let the temperature of the enclosed air reach equilibrium.
4. Record the corresponding values for the volume V and pressure P .
5. Repeat steps two to five to get at least six pairs of readings

Plot a graph of P against V .

Plot a graph of P against $1/V$.

A straight line graph through the origin will verify that, for a fixed mass of gas at constant temperature, the pressure is inversely proportional to the volume, i.e. Boyle's law.

$$P \propto \frac{1}{V}$$

This means that:

$$\begin{aligned}\text{Pressure} \times \text{Volume} &= \text{Constant} \\ PV &= C\end{aligned}$$

Note:

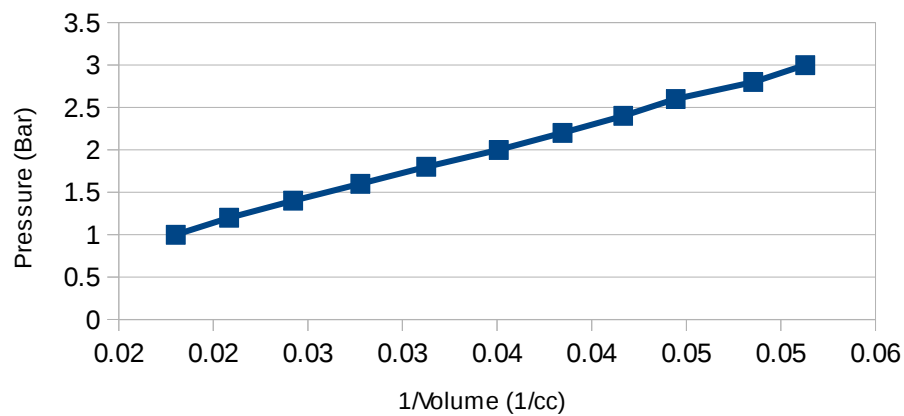
Before starting the experiment, the pressure gauge reading must be checked. Open the valve fully. If the pressure gauge reads 0, then the value of atmospheric pressure (1×10^5 Pa) must be added to the pressure reading on the gauge to get the pressure of the air in the tube. If the gauge reads atmospheric pressure (1×10^5 Pa) with the valve opened, then the pressure of the air in the tube is obtained directly from the gauge.

RESULTS:

Boyles Law Experiment

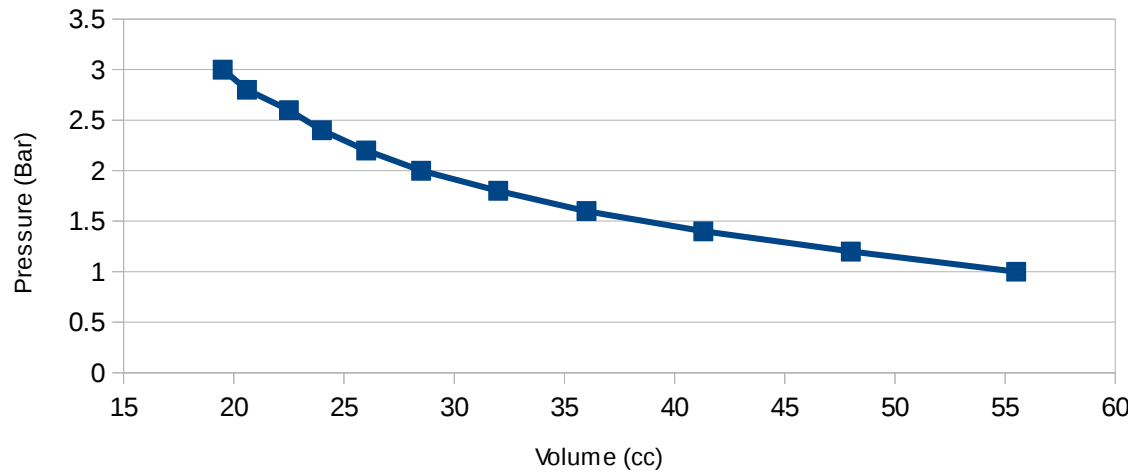
<i>Abs Pressure</i>	<i>Volume</i>	<i>1 / Vol</i>	<i>PV = Constant</i>
3	19.5	0.051	58.5
2.8	20.6	0.049	57.68
2.6	22.5	0.044	58.5
2.4	24	0.042	57.6
2.2	26	0.038	57.2
2	28.5	0.035	57
1.8	32	0.031	57.6
1.6	36	0.028	57.6
1.4	41.3	0.024	57.82
1.2	48	0.021	57.6

Pressure against 1/Volume



Pressure Volume Diagram

Boyle's Law Experiment



Hyman Fire Piston:

This device shows that when the pressure and volume are changed very quickly, there is a much greater rise in pressure and temperature than Boyle's law predicts.... Why is this?

Hyman Fire Piston

Start Pressure	Start Volume
1	1.132E-05
End Pressure	End Volume
76.96	5.089E-07
1030.74 Kelvin - C	757.74

PV ^ n = C	Exp
	1.4

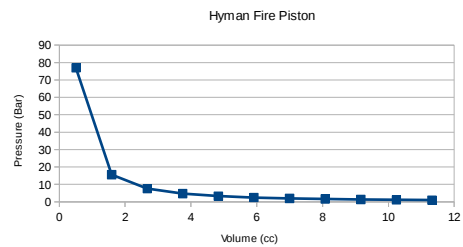
PV = C
or
PV^n = C

Bore	9.00mm
Stroke	170.00mm
Deck	8.00mm
Area	6.362E-05
Clearance Vol	5.089E-07
Swept Vol	1.081E-05
CR	22.25

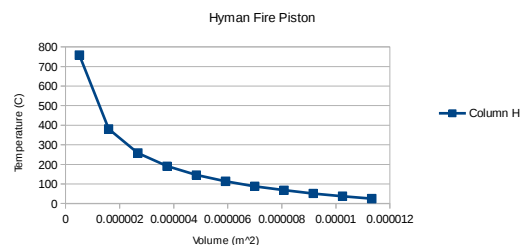
Step	Start Pressure	Start Volume	Start Vol (cc)	PV = Constant
0	1.00	0.0000113	11.324	0.0000113
1	1.15	0.0000102	10.242	0.0000118
2	1.35	0.0000092	9.161	0.0000123
3	1.60	0.0000081	8.079	0.0000130
4	1.96	0.0000070	6.998	0.0000137
5	2.48	0.0000059	5.916	0.0000147
6	3.29	0.0000048	4.835	0.0000159
7	4.69	0.0000038	3.753	0.0000176
8	7.55	0.0000027	2.672	0.0000202
9	15.61	0.0000016	1.590	0.0000248
10	76.96	0.0000005	0.509	0.0000392

Step	Start Pressure	Start Volume	Start Temp	Deg C
0	1.000	0.00001132	298.00	25.00
1	1.151	0.00001024	310.21	37.21
2	1.345	0.00000916	324.37	51.37
3	1.604	0.00000808	341.09	68.09
4	1.962	0.00000700	361.27	88.27
5	2.481	0.00000592	386.36	113.36
6	3.292	0.00000483	418.85	145.85
7	4.692	0.00000375	463.49	190.49
8	7.552	0.00000267	530.99	257.99
9	15.612	0.00000159	653.44	380.44
10	76.959	0.00000051	1030.74	757.74

Pressure Volume Diagram



Temperature Volume Diagram



This Shows that for faster processes, the equation

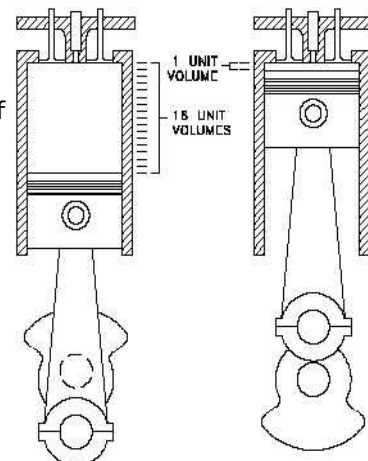
$$PV^n = \text{Constant}$$

This is a very important result!

Notes on Compression Ratio and Clearance Volume:

Clearance volume (V_c) is the volume remaining in the cylinder when the piston is at TDC. Because of the irregular shape of the combustion chamber (volume in the head) the clearance volume is calculated empirically by filling the chamber with a measured amount of fluid while the piston is at TDC. This volume is then added to the swept volume (V_s) in the cylinder to obtain the cylinders total volume. An engine's compression ratio is determined by taking the volume of the cylinder with piston at TDC (highest point of travel) and dividing the volume of the cylinder when the piston is at BDC (lowest point of travel), as shown in Figure 15. This can be calculated by using the following formula:

$$\text{Compression Ratio} = \frac{(V_s + V_c)}{V_c}$$



Heat and Heat Transfer (Basic Introduction)

Heating an object is when you are transferring thermal energy to the object from another object that is at a higher temperature. Heat is often defined as energy in transit or the flow of energy. Thermal energy is the energy itself.

Thermal energy is the amount of internal kinetic energy and potential energy of an object. Temperature is a measure of the average kinetic energy of the particles in an object.

An object feels warm or hot if its temperature is higher than your skin. To say something is hot means its temperature is relatively high.

Cooling an object is when you are transferring thermal energy from the object to another object that is at a lower temperature. You could say you are removing thermal energy from your object.

An object feels cool or cold if its temperature is lower than your skin. To say something is cold means its temperature is relatively low.



Whether heating or cooling, the end result is that the two objects become the same temperature after a period of time. This is called thermal equilibrium.

Heat transfer

Thermal energy is transferred from an object of high temperature to one of lower temperature by conduction, convection and radiation. This process is usually called heat transfer or heat flow, although it is the heat energy that is really being transferred. The property 'Heat' is the amount of energy transferred.

Conduction

Thermal energy can be transferred from one substance to another when they are in direct contact. The moving molecules of one material can increase the energy of the molecules of the other. Heat can also travel along a material as one molecule transfers energy to a neighboring one. This type of heat transfer is called **conduction**.



Conduction is mainly seen with solid objects, but it can happen when any materials come into contact. When you put your hand in a container of warm water, your hand is heated by conduction from the water.

Some materials are better conductors of heat than others. For example, metals are good conductors of heat, while a material like wood isn't. Metal heated on one end will soon be

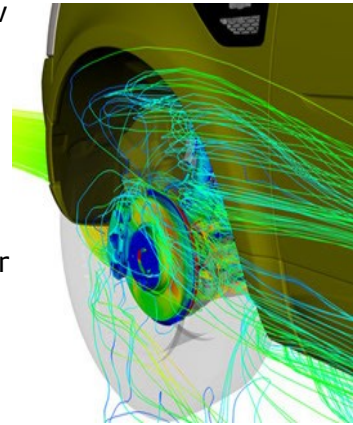
hot on the other end too, while that is not true with a piece of wood. Good conductors of electricity are often good conductors of heat.

Since the atoms are closer together, solids conduct heat better than liquids or gasses. This means that two solid materials in contact would transfer heat from one to the other better than a solid in contact with a gas or a gas with a liquid.

Convection

When a gas or a liquid is heated, hot areas of the material flow and mix with the cool areas. This type of heating is called **convection**. Forced air heating and air conditioning are examples of heating (or cooling) by convection.

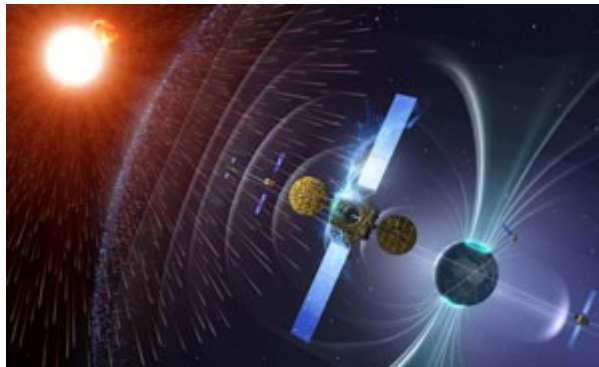
This is an effective way of bringing a hot (or cold) fluid to a different area. Convection transfers heat over a distance faster than conduction. But ultimately conduction must transfer the heat from the gas to the other object, though molecular contact.



Radiation

A third method to transfer heat is by **radiation**. A warm or hot object gives off infrared electromagnetic radiation, which can be absorbed in another object, heating it up. Electric heaters with the shiny reflector use radiation to heat. If they add a fan, they use both radiation and convection to heat an area.

Transfer of heat by radiation travels at the speed of light and goes great distances, even in a vacuum. We are heated from the Sun through radiation transfer of heat.



In conclusion

Atoms or molecules transfer kinetic energy to their neighbors through collisions. When objects are in contact this transfers heat by conduction. Liquids and gases can move high or low energy molecules to another region through convection. Atoms can radiate energy that can energize a distant atom, resulting in heat transfer by radiation.

Temperature is intensity of thermal energy

The temperature of an object is the average intensity of its thermal energy.

The thermal energy of an object is the total kinetic or moving energy of all its particles, plus their potential energy. This is different than heat, which is the *flow* of thermal energy from one object to another.

The intensity of thermal energy is the average kinetic energy of the object. That average is the energy of a typical particle in the object. Its equation is:

$$KE_a = \frac{1}{2} mv^2,$$

where:

KE_a is the average kinetic energy of all the particles

m is the mass of a single particle or molecule

v is the average velocity of all the particles

The kinetic energy is measured in joules. Since it is difficult to determine the average kinetic energy of a measure the intensity of thermal energy, temperature is used as a relative measurement of that intensity.

Temperature limits

There are upper and lower limits to temperature.

Upper limit

The highest possible temperature is limited by the greatest speed possible for a particle of matter, which is the speed of light. According to the Theory of Relativity, matter can approach that speed but never reach it.

The thermal energy is determined by Einstein's famous $E = mc^2$ equation.

Lower limit

The lowest or coldest temperature possible is called *Absolute Zero*. This absolute zero limit is the temperature of an object when all of its matter has zero energy.

Quantum Mechanics laws state that Absolute Zero can be approached but never reached, because matter cannot have zero energy.

For scientific work with the energy of molecules, it is good to have a starting point where the energy level is at a lowest possible state. This point is called *absolute zero*.

This absolute zero limit is the temperature of an object when all of its matter has zero

energy.

This limit cannot be reached because of the rules of quantum mechanics that require some motion must be present for matter to exist. Usually, absolute zero is defined as the lowest possible temperature allowed by the laws of quantum mechanics.

It is impossible for an object to be at absolute zero because of the effects of gravitation forces, which are everywhere. Gravity and electromagnetic waves provide energy that will increase the temperature of a hypothetical object at absolute zero, if only a slight amount.

Scientists have been able to cool things to a fraction of a degree above absolute zero. At such a cold temperature, matter starts to behave strangely.

The Kelvin scale was determined based on the Celsius scale, but with a starting point at absolute zero. Temperatures in the Kelvin scale are 273 degrees less than in the Celsius scale. Thus absolute zero is -273°C and the boiling point of water 100°C is 373 K or 373 kelvins.

Note that there is no degree sign when using the Kelvin scale.

There is also the Rankine scale, which also starts at absolute zero but is based on the Fahrenheit scale. Since most scientific work is done based on the Kelvin scale, the Rankine scale for absolute temperatures is seldom used.

Relationships

Kinetic energy and temperature

The relationship between the kinetic energy of the molecules or atoms in an ideal gas is:

$$KE = 3kT/2$$

where

KE = the kinetic energy of particles in an ideal gas

k = Boltzmann's constant (a number that relates energy and temperature)

T = temperature in degrees Kelvin,

$$k = 1.38 \times 10^{-23} \text{ joule/kelvin}$$

Kinetic energy-temperature relationship equations for real-world gases, liquids and solids are too complex to work with at this level of study.

Kinetic energy and velocity

The kinetic energy of a moving mass of particles is:

$$KE = \frac{1}{2}mv^2$$

where:

KE = kinetic energy in joules or $\text{kg}\cdot\text{m}^2/\text{s}^2$

m = mass in kilograms

v = velocity in meters/second

Temperature and Velocity

We can find the relationship between temperature and the velocity of its particles

Since $KE = 3kT/2$ and $KE = \frac{1}{2}mv^2$:

$$3kT/2 = \frac{1}{2}mv^2$$

thus

$$T = mv^2/3k$$

where

T is measured in Kelvin

m is in kilograms

v is in meters/second

k is in joule/kelvin or $kg \cdot m^2/s^2$ -kelvin

It can easily be seen from $T = mv^2/3k$ that when $T = 0$ kelvin, the velocity of the particles $v = 0$. Thus the kinetic energy due to linear movement is zero. But the atoms still possess spin, which means they still have some energy.

Another fact is that the equation is really an approximation, since we are dealing with an ideal gas. A real-world gas would not be able to reach $T = 0$.

How fast does an air molecule move?

Mass = 5.6×10^{-26} kg

k = 1.38×10^{-23} J/K

$$v^2 = 3kT/m$$

$$v = \sqrt{\left(\frac{3kT}{m}\right)}$$

Try it...