EDEXCEL NATIONAL CERTIFICATE/DIPLOMA
SCIENCE FOR TECHNICIANS

OUTCOME 3 - ENERGY

TUTORIAL 2 – HEAT

3. Energy

Mechanical work, energy and power: work - energy relationship, gravitational potential energy, kinetic energy, conservation of energy, work done and energy transfer, work done against friction

Heat energy: elementary molecular definition of solids, liquids and gases; gas laws, transfer of heat energy, temperature, temperature scales, change of state, expansion of solids and liquids

You should judge your progress by completing the self assessment exercises. These may be sent for marking at a cost (see home page).

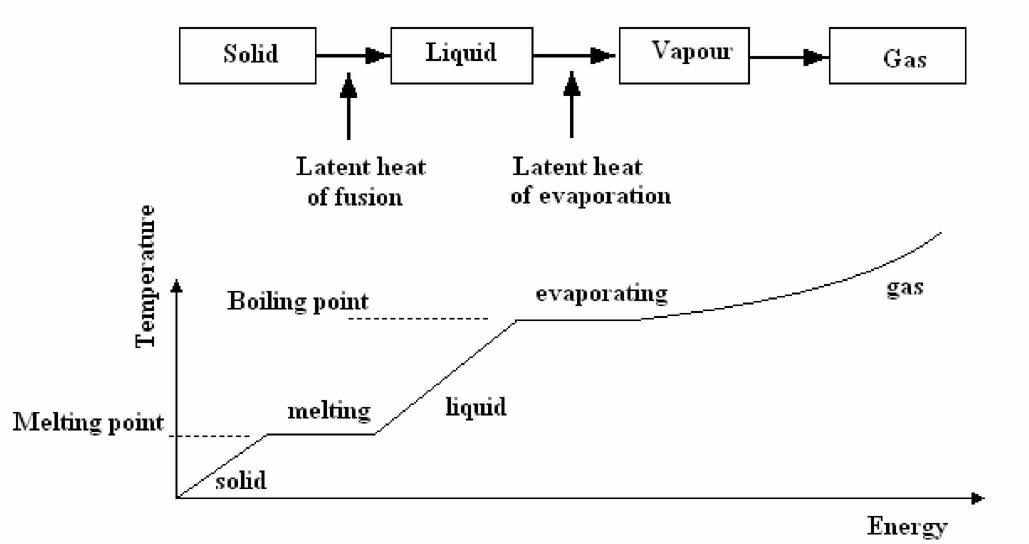
It is not clear from the syllabus content what depth of knowledge is required for this section. The topic is one of those that require a lot of additional science to fully appreciate it. It is likely that the content of this tutorial exceeds that required.

It should be pointed out from the beginning that heat is not a form of energy as the syllabus suggests but it is the name used for energy being transferred by virtue of temperature difference.

The energy stored within a body by virtue of its temperature is correctly called the internal energy.

1. INTRODUCTION

If we heat a solid material, it gets hotter and at some temperature called the melting point it melts and changes to a liquid. More heating will make the liquid hotter and when it reaches the boiling point it evaporates to form gas. When it has only just been evaporated it is called a vapour and it needs to be made hotter before it behaves like a true gas. The diagram illustrates this process. Note that melting and evaporating does not occur instantly. Energy is added to change the state of the substance without raising the temperature.

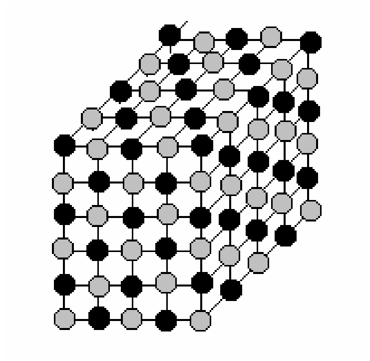


We should study what happens to the atoms and molecules to explain this process.

2. SOLIDS, LIQUIDS AND GASES

All substances are made up from atoms. A substance made from only one type of atom is called an element (for example copper Cu). There are 92 different elements occurring naturally. The smallest and simplest is the hydrogen atom and the largest is uranium.

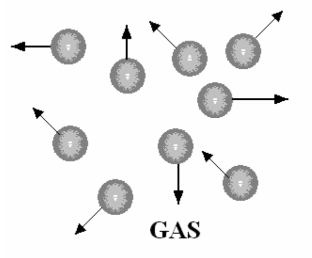
Atoms may join with more atoms of the same material to form a molecule. For example, Oxygen normally exists as O_2 meaning a single molecule has two atoms. The same goes for Hydrogen (H_2) and Nitrogen (N_2) and other substances. Atoms may also join with atoms of a different substance to form molecules of a new substance such as water (H_2O) which is a single atom of oxygen joined with two atoms of hydrogen. The way that atoms and molecules join together is called **BONDING**. The theory of bonding is not given here but it is basically a force that pulls them together (like magnets).



In a solid material, the atoms and molecules are bonded together very strongly (perhaps in a regular pattern as shown) and this makes it rigid. The molecules cannot wander about but as the temperature is raised, they vibrate and so obtain kinetic energy. If the temperature is raised enough, this vibration becomes so severe that the bonds break and the molecules are no longer able to maintain a rigid structure. In other words the substance melts and becomes a liquid.

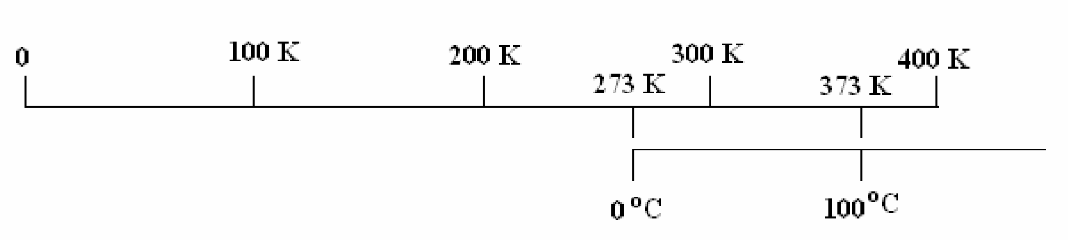
We may define a liquid as a substance that has bonds strong enough to hold the molecules together but also weak enough that the substance will flow and can be poured into a vessel of any shape. You might think of the molecules as small sticky balls.

If the temperature of a liquid is raised the weak bonds get even weaker and the molecules move around with increased kinetic energy. The liquid normally becomes more fluid. At some point the molecules will break free all together and unless constrained in a vessel, they will fly off. This is evaporation. The substance has become a gas. An ideal gas is defined as a substance with no bonding forces at all. In reality there are very weak bonding forces in gas.



3. TEMPERATURE

We commonly use the Celsius scale of temperature with units of degrees Celsius or ^oC. The freezing point of water is 0^oC and the boiling point 100^oC (at specified conditions). If we had a negative temperature, the internal energy would be negative. Although this is commonly used, in relative terms there is no such thing as negative energy. If a substance was cooled down until it contained no energy at all, the temperature would be a true or absolute zero. This occurs at -273^oC (rounded off to the nearest degree). If we made this the true zero, then the freezing point of water would be + 273 degrees. This scale is called the Kelvin scale and the unit is the Kelvin symbol K. To convert ^oC into K just add on 273. A temperature in ^oC is usually denoted θ and absolute temperatures by T.



4. INTERNAL ENERGY

The molecules of a substance possess kinetic energy. There may be elements of other energy involved but basically it is the kinetic energy of the molecules inside the substance that gives us the internal energy. We might think of internal energy as the energy due to the temperature (but it is really much more complicated than this because the substance melts and evaporates).

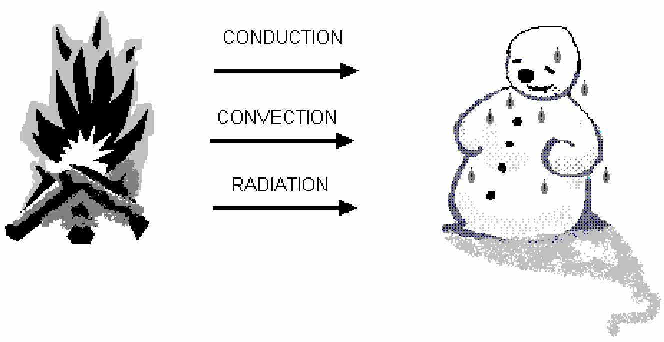
If a substance changes temperature by ΔT and does not change state (melting or evaporating), the change in internal energy is directly proportional to ΔT and the mass m.

$$\Delta U = m\,c\,\Delta T = m\,c\,\Delta\theta$$

Note that a change in absolute temperature ΔT is the same as a change in degrees Celsius $\Delta\theta$. The units of temperature change may be stated in ^oC or K. The constant of proportionality is c and this is called the specific heat capacity. This is different for different materials. The units of c are J/kg K or kJ/kg K. The symbol for internal energy is U kJ or u kJ/kg.

5. HEAT TRANSFER

Heat transfer occurs because one place is hotter than another. Under normal circumstances, heat will only flow from a hot body to a cold body by virtue of the temperature difference. There are 3 mechanisms for this, ***Conduction, convection and radiation.***
You do not need to study the laws governing conduction, convection and radiation in this module.



A quantity of energy transferred as heat is given the symbol Q and it's basic unit is the Joule. The quantity transferred in one second is the heat transfer rate and this has the symbol Φ and the unit is the Watt.

An example of this is when heat passes from the furnace of a steam boiler through the walls separating the combustion chamber from the water and steam. In this case, conduction, convection and radiation all occur together. In many problems, the heat transfer is the same as the change in internal energy so we often use the formula

$$\mathbf{Q = \Delta U = m\ c\ \Delta T}$$

WORKED EXAMPLE No.1

Calculate the energy needed to heat up 50 kg of aluminium from 20°C to 300°C. The specific heat capacity is 913 J/kg K.

SOLUTION

$\Delta U = m\ c\ \Delta T = 50 \times 913 \times (300 - 20) = 12.782 \times 10^6$ J or 12.782MJ

5. CHANGE OF STATE

When a solid is heated, a temperature is eventually reached when it cannot absorb any more energy and it melts. Whilst it is melting, its temperature stays constant. The energy absorbed by melting is called the latent energy of fusion. The values of latent energy may be looked up in tables. The figures are always given for 1 kg so it is called the specific latent energy of fusion. The change in specific internal energy is denoted as u_i. If this is entirely due to a heat transfer Q then :

$$\mathbf{Q = \Delta U = m\ u_i}$$

Once a solid has melted, the addition of more energy will make the temperature rise again. The specific heat capacity is different to that of the solid but the change in internal energy is again given by $\Delta U = m\ c\ \Delta T$

There is also a maximum amount of energy that the liquid can absorb. When this point is reached, it is said to be saturated with heat and the temperature and pressure of the liquid is the saturation temperature t_S and saturation pressure p_S. The liquid starts to evaporate at this point and turns into vapour. The temperature is more commonly called the boiling point.

We all should know that water boils at 100°C but we should also know that this is only true if the pressure is standard atmospheric pressure of 1.01325 bar. Water boils at higher temperatures if it is at a higher pressure.

WORKED EXAMPLE No. 2

80 kg of copper at 20°C is heated up to its melting point of 932°C and then just exactly melted. Calculate the energy needed. The latent heat of fusion is 210 kJ/kg and the specific heat capacity is 385 J/kg K

SOLUTION

$Q = \Delta U = m\ c\ \Delta T + m\ u_i = m\ \{c\ \Delta T + u_i\} = 80\ \{385 \times (932 - 20) + 210\ 000\}$

Note we have to use consistent units J or kJ

$Q = 44.89 \times 10^6$ J or 44.89 MJ

Whilst liquid is evaporating, the temperature stays constant and energy is absorbed. This energy is called the latent energy of evaporation. Because the liquid changes volume as it turns into vapour, the energy transfer may be more than the change in internal energy. The change in internal energy during the evaporation process is denoted u_{fg} but here the story gets more complicated and it is doubtful that we should go into this in this module. The values of these latent energies must be found in tables at the pressure and temperature required.

After the liquid has evaporated it becomes vapour. If this is heated, its temperature rises again. A vapour does not accurately behave as a gas because of the tendency to turn back into liquid if cooled. When it is heated well above the boiling it becomes a gas and obeys gas laws. Steam and other vapours are also called superheated vapours when heated above the boiling point. The internal energy of vapours is found from charts and tables. Specific heats may be used with gases with care.

WORKED EXAMPLE No. 3

A boiler heats up 2.5 kg of water per second from 20°C to 100°C and then evaporates it without raising the temperature. The specific heat capacity is 4.86 kJ/kg K and the latent heat u_{fg} is 2090 kJ/kg. Calculate the change in internal energy. (Note this is not the same as the heat transfer).

SOLUTION

$\Delta U = m\,c\,\Delta T + m\,u_{fg} = m\,\{c\,\Delta T + u_{fg}\} = 2.5\,\{4.186 \times (100 - 20) + 2090\}$
$\Delta U = 6062.2$ kJ/s or 6.062 MW

SELF ASSESSMENT EXERCISE No.1

1. Calculate the energy needed to heat up 2 kg of copper from 100°C to 250°C. The specific heat capacity is 386 J/kg K. (115.8 kJ)

2. Calculate the change in internal energy when 30 kg of water is heated from 20°C to 80°C. Take c = 4186 J/kg K. (7.54 MJ)

3. 5 kg of lead at 20°C is heated up to its melting point of 600°C and then just exactly melted. Calculate the energy needed.
The specific heat capacity of solid lead is 126 J/kg K and the latent energy of fusion u_l is 26 kJ/kg. (495.4 MJ)

4. A boiler heats high pressure water from 80°C to 152°C and then evaporates it without raising the temperature. The specific heat capacity is 4.86 kJ/kg K and the latent heat u_{fg} is 1923 kJ/kg. Calculate the change in internal energy of 1 kg. (2.27 MJ)

6. GAS LAW AND PROPERTIES

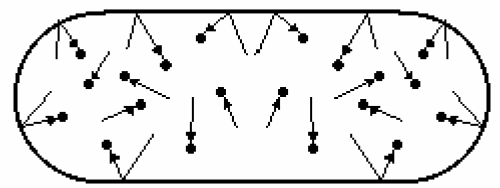
THEORY

A gas is made of molecules which move around with random motion. In a perfect gas, the molecules may collide but they have no tendency at all to stick together or repel each other: in other words a perfect gas in completely inviscid. In reality there is a slight force of attraction between gas molecules but this is so small that gas laws formulated for an ideal gas work quite well for real gas.

Each molecule in the gas has an instantaneous velocity and hence has kinetic energy. The sum of this energy is the internal energy U. The velocity of the molecules depends upon the temperature. When the temperature changes, so does the internal energy. The internal energy is for all intents and purposes zero at - 273^{o} C. This is the absolute zero of temperature. Remember that to convert from Celsius to absolute, add on 273. For example 40^{o}C is 40 + 273 = 313 Kelvins.

PRESSURE

If a gas is compressed it obtains pressure. This is best explained by considering a gas inside a vessel as shown.



The molecules bombard the inside of the container. Each produces a momentum force when it bounces. The force per unit area is the pressure of the gas. Remember that pressure = Force/area

p = F/A N/m^2 or Pascals

Note that 10^3 Pa = 1 kPa 10^6 Pa = 1 MPa 10^5 Pa = 1 bar

CONSTANT VOLUME LAW

When a gas is heated the molecular velocity increases. If the container is rigid, then the molecules will hit the surface more often and with greater force so we expect the pressure to rise proportionally to temperature. (Note strictly absolute temperature)

p = c T when V is constant.

WORKED EXAMPLE No. 4

A mass of gas has a pressure of 500 kPa and temperature of 150^{o}C. The pressure is changed to 900 kPa but the volume is unchanged. Determine the new temperature.

SOLUTION

Using constant volume law find p_1/T_1 =c = p_2/T_2 where

T_1 =150 + 273 = 423 K

p_1 = 500 000 p_2 =900 000

$T_2 = p_2T_1/p_1$ = 900 000 x 423/500 000 T_2 = 761.4 K

CHARLES'S LAW

If we kept the pressure constant and increased the temperature, then we would have to make the volume bigger in order to stop the pressure rising. This gives us Charles's Law:

$$V = c\,T \quad \text{when } p \text{ is constant}$$

WORKED EXAMPLE No. 5

A mass of gas has a temperature of 250°C and volume of 0.2 m^3. The temperature is changed to 50°C but the pressure is unchanged. Determine the new volume.

SOLUTION

Using Charle's law we find $V_1/T_1 = c = V_2/T_2$ where

$T_1 = 250 + 273 = 523$ K

$V_1 = 0.2$

$T_2 = 50 + 273 = 323$ K

$V_2 = T_2V_1/T_1 = 323 \times 0.2/523$

$V_2 = 0.123\ m^3$

BOYLE'S LAW

If we keep the temperature constant and increase the volume, then the molecules will hit the surface less often so the pressure goes down. This gives Boyle's Law:

$$p = c/V \quad \text{when } T \text{ is constant.}$$

WORKED EXAMPLE No. 6

A mass of gas has a pressure of 800 kPa and volume of 0.3 m^3. The pressure is changed to 100 kPa but the temperature is unchanged. Determine the new volume.

SOLUTION

Using Boyle's law we find $p_1V_1 = c = p_2\,V_2$ where

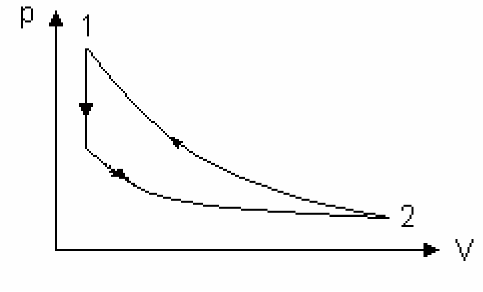
$p_1 = 800 \times 10^3$ $\quad$ $V1 = 0.3$ $\quad$ $p_2 = 100 \times 10^3$

$V_2 = p_1V_1/p_2 = 800 \times 10^3 \times 0.3/100 \times 10^3$

$V_2 = 2.4 m^3$.

GENERAL GAS LAW

The general gas law states $\frac{p_1V_1}{T_1}=\frac{p_2V_2}{T_2}$ and it may be used to solve any of the previous problems.



Here is the derivation for those who want it.

Consider a gas which undergoes a change in pV and T from point (1) to point (2) as shown. It could have gone from (1) to (A) and then from (A)to (2) as shown.

Process (1) to (A) is constant volume so $p_A/T_A = p_1/T_1$

Process (A) to (2) is constant temperature so $T_2 = T_A$

Hence $p_A/T_2 = p_1/T_1$ and $p_A = p_1T_2/T_1$ ....(1)

For the process (A) to (2) Boyle's Law applies so

$p_AV_A = p_2V_2$

Since $V_A = V_1$ then we can write : $p_AV_1 = p_2V_2$

So $p_A = p_2V_2/V_1$............(2)

Equating (1) and (2) we get $\frac{p_1V_1}{T_1}=\frac{p_2V_2}{T_2}$ **= constant**

This is the GENERAL GAS LAW and it is used to calculate one unknown when a gas changes from one condition to another.

WORKED EXAMPLE No. 7

A mass of gas has a pressure of 1.2 MPa, volume of 0.03 m^3 and temperature of 100^oC. The pressure is changed to 400 kPa and the volume is changed to 0.06 m^3. Determine the new temperature.

SOLUTION

Using the general gas law we find $p_1V_1/T_1 = p_2V_2/T_2$ where

$p_1 = 1.2 \times 10^6$

$V_1 = 0.03$

$p_2 = 400 \times 10^3$

$T_1 = 100 + 273 = 373$ k

$T_2 = p_2V_2 T_1/p_1V_1 = 400 \times 10^3 \times 0.06 \times 373/(1.2 \times 10^6 \times 0.03)$

$T_2 = 248.7$ K

CHARACTERISTIC GAS LAW

The general gas law tells us that when a gas changes from one pressure, volume and temperature to another, then

$$pV/T = \text{constant}$$

Thinking of the gas in the rigid vessel again, if the number of molecules was doubled, keeping the volume and temperature the same, then there would be twice as many impacts with the surface and hence twice the pressure. To keep the pressure the same, the volume would have to be doubled or the temperature halved. It follows that the constant must contain the mass of the gas in order to reflect the number of molecules.

The gas law can then be written as $pV/T = mR$

m is the mass in kg and R is the remaining constant which must be unique for each gas and is called the CHARACTERISTIC GAS CONSTANT.

If we examine the units of R they are J/kg K.

The equation is usually written as $\mathbf{pV = mRT}$

Since m/V is the density ρ, it follows that $\boldsymbol{\rho = p/RT}$

Since V/m is the specific volume '*v*' then $\boldsymbol{v = RT/p}$

WORKED EXAMPLE No. 8

A mass of gas has a pressure of 1.2 MPa, volume of 0.03 m^3 and temperature of 100°C. Given the characteristic gas constant is 300 J/kg K find the mass.

SOLUTION

From the characteristic gas law we have pV = mRT where

$p = 1.2 \times 10^6$

$V = 0.03$

$T = 100 + 273 = 373$

$m = pV/RT = 1.2 \times 10^6 \times 0.03/300 \times 373 = 0.322$ kg

SELF ASSESSMENT EXERCISE No. 2

All pressures are absolute.

1. Calculate the density of air at 1.013 bar and 15 ^oC if R = 287 J/kg K. (1.226 kg/m^3)

2. Air in a vessel has a pressure of 25 bar, volume 0.2 m^3 and temperature 20^{o}C. It is connected to another empty vessel so that the volume increases to 0.5 m^3 but the temperature stays the same. Taking R = 287 J/kg K. Calculate

   i. the final pressure. (10 bar)
   ii. the final density. (11.892 kg/m^3)

3. 1 dm^3 of air at 20^{o}C is heated at constant pressure of 300 kPa until the volume is doubled. Calculate

   i. the final temperature. (586 K)
   ii. the mass. (3.56 g)

4. Air is heated from 20^{o}C and 400 kPa in a fixed volume of 1 m^3. The final pressure is 900 kPa. Calculate

   i. the final temperature.(659 K)
   ii. the mass. (4.747 kg)

5. 1.2 dm^3 of gas is compressed from 1 bar and 20^{o}C to 7 bar and 90^{o}C . Calculate

   i. the new volume. (212 cm^3)
   ii. the mass. (1.427 g)

7. THERMAL EXPANSION

When solids and liquids are heated, the molecules vibrate more and take up more space so the material expands. Consider first the expansion in one direction.

If a bar of material of length L_o has its temperature increased by $\Delta\theta$ degrees, the increase of length is ΔL.

This is directly proportional to the original length L and to the temperature change $\Delta\theta$. It follows that :-

$$\Delta L = \text{constant} \times L_o \Delta\theta$$

The constant of proportionality is called the coefficient of linear expansion (α).

$$\Delta L = \alpha L_o \Delta\theta$$

WORKED EXAMPLE No. 9

A thin steel band 850 mm diameter must be expanded to fit around a disc 851 mm diameter. Calculate the temperature change needed. The coefficient of linear expansion is 15×10^{-6} per ^oC

SOLUTION

Initial circumference of ring = $\pi D = \pi \times 850 = 2670.35$ mm
Required circumference = $\pi \times 851 = 2673.50$ mm
$\Delta L = 2673.50 - 2670.35 = 3.15$ mm
$\Delta L = \alpha L \Delta\theta$
$3.15 = 15 \times 10^{-6} \times 2670.35 \times \Delta\theta$
$\Delta\theta = 3.15/(15 \times 10^{-6} \times 2670.35) = 78.6$ Kelvin

SUPERFICIAL EXPANSION

This is about the change in area of a flat shape. Consider a flat plate of metal with area A_o. The change in area is ΔA and this is directly proportional to the temperature change so:-

$$\Delta A = \text{constant} \times A_o \Delta\theta$$

The constant is the coefficient of superficial expansion β

$$\Delta A = \beta A_o \Delta\theta$$

Note $\beta = 2\alpha$

WORKED EXAMPLE No. 10

A steel sheet has an area of 500 cm^2 at 20^oC. Calculate the area when it is heated to 300 ^oC. The coefficient of superficial expansion is 30×10^{-6} per ^oC

SOLUTION

$\Delta A = \beta L \Delta\theta = 30 \times 10^{-6} \times 500 \times (300 - 20) = 4.2\ cm^3$
The new area is 504.2 cm^2

CUBICAL EXPANSION

Since a material expands in all direction the volume changes. The change in volume is ΔV.

This is directly proportional to the original volume V_o and to the temperature change $\Delta\theta$. It follows that :-

$$\Delta V = \text{constant x } V_o \Delta\theta$$

The constant of proportionality is called the coefficient of cubical expansion expansion (γ).

$$\Delta L = \gamma L \Delta\theta$$

Note that $\gamma = 2\alpha$

WORKED EXAMPLE No. 11

Calculate the change in volume of 1 m^3 of water when it is heated from 10 ^oC to 80 ^oC. The coefficient of cubical expansion is 210 x 10^{-6} per ^oC

SOLUTION

$\Delta V = 210 \times 10^{-6} \times 1 \times (80 - 10) = 14.7 \times 10^{-3}$ m^3 or 14.7 dm^3 or 14.7 litre

SELF ASSESSMENT EXERCISE No. 3

1. A brass bar is 600 mm long and 100 mm diameter. It is heated from 20 ^oC to 95^oC. Calculate the change in length. α is 18 x 10^{-6} per ^oC. (Answer 0.81 mm)

2. A steel ring is 50 mm diameter and 2 mm thick. It must be fitted onto a shaft 50.1 mm diameter. Calculate the temperature to which it must be heated in order to fit on the shaft. The initial temperature is 20 ^oC and the coefficient of linear expansion is 15 x 10^{-6} per ^oC.
(Answer 133.3 K)

3. A stub shaft 85.2 mm diameter must be shrunk to 85 mm diameter in order to insert it into a housing. By how much must the temperature be reduced? Take the coefficient of linear expansion is 12 x 10^{-6} per ^oC. (Answer -195.6 K)

4. A tank contains 40 m^3 of oil at 10^oC. Calculate the volume at 40^oC given γ = 700 x 10^{-6} per ^oC
(0.84 m^3)

5. Copper sheet covers a wall and has an area of 20 m^2 at 15^oC. What is the change in area when it is heated to 80^oC? β = 34 x 10^{-6} per ^oC. (44.2 x 10^{-3} m^2)