TAMPINES JUNIOR COLLEGE

Thermal Physics (1)

JC1 LECTURE NOTES 2008

Content

- Temperature, Heat & Internal Energy
- Temperature Scales
- Specific Heat Capacity
- Specific Latent Heat
- Worked Examples

Learning Outcomes

Candidates should be able to:

(a) show an understanding that internal energy is determined by the state of the system and that it can be expressed as the sum of a random distribution of kinetic and potential energies associated with the molecules of a system.

(b) relate a rise in temperature of a body to an increase in internal energy.

(c) show an understanding that regions of equal temperature are in thermal equilibrium.

(d) show an understanding that there is an absolute scale of temperature which does not depend on the property of a particular substance, i.e. the thermodynamic scale

(e) apply the concept that, on the thermodynamic (Kelvin) scale, absolute zero is the temperature at which all substances have a minimum internal energy.

(f) Convert temperatures in Kelvin to degrees Celsius: T/K = t/ºC + 273.15.

(g) Define and use the concept of specific heat capacity, and to identify the main principles of its determination by electrical methods.

(h) Define and use the concept of specific latent heat, and identify the main principles of its determination by electrical methods.

REFERENCES

1.	Physics	Robert Hutchings
2.	Fundamentals of Physics	Halliday and Resnick
2.	Advanced Physics	Tom Duncan
3.	Advanced Level Physics	Nelkon and Parker
4.	Physics	Giancoli
5.	Comprehensive Physics	Chan KF, Charles Chew

1 Temperature, Heat, Thermal Equilibrium and Internal Energy

1.1 Temperature

Temperature is the physical property which determines the direction of **net** flow of heat. It is also the scientific quantity which corresponds to primary sensations—hotness or coldness. These sensations according to our sense of touch, are qualitative, subjective and inconsistent. They are unreliable for scientific work because they depend on contrast.

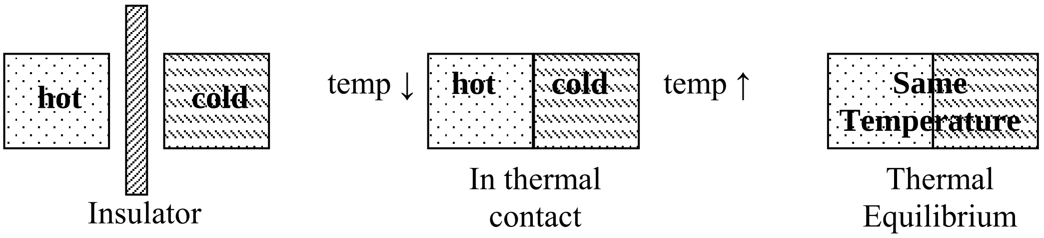
Temperature, is a measure of the degree of hotness (or coldness) expressed in terms of some arbitrary or absolute scale to indicate the direction in which thermal energy will spontaneously flow, i.e. from a hotter (higher temperature) region to a colder (lower temperature) region.

1.2 Heat

Heat is the thermal energy that is transferred from one object to another due to temperature difference between the two objects in thermal contact. When two bodies are in thermal contact with each other, heat is able to flow between them. Therefore, since heat flow is a two-way process, the rate of heat flow from a body of higher temperature will be greater than the rate of heat flow from another body of lower temperature. Therefore, there is a net flow of heat from a body of higher temperature to a body of lower temperature.

1.3 Thermal Equilibrium

When two bodies are in thermal contact and there is no net flow of heat between them, they are said to be in thermal equilibrium. At thermal equilibrium, the rate at which heat is transferred from one body to the other and vice versa is the same. The property which they all have in common at thermal equilibrium is said to be their temperature.



Two or more regions or bodies are of **equal temperature** if they are in **thermal equilibrium**.

(This is a simplified version of the Zeroth Law of Thermodynamics, which states that if two systems are in thermal equilibrium with a third system, then the first two systems are in thermal equilibrium with each other and share the same temperature. See Appendix A for more info.)

Quick Quiz 1
What is heat?

- **A** Thermal energy
- **B** Kinetic energies of all the molecules
- **C** Inter-molecular energies of all the molecules
- **D** Thermal energy flowing from one body to another

Answer: **D**

Quick Quiz 2
Thermometers M_1 and M_2 are placed inside an evacuated enclosure X with opaque walls maintained at temperature T. The thermometers are identical except that the bulb of M_1 is blackened. If T_1 and T_2 are the temperature indicated by M_1 and M_2 respectively after thermal equilibrium has been established.

A $T_1>T_2>T$ **B** $T_1>T>T_2$ **C** $T_1=T_2=T$ **D** $T_1=T>T_2$
Answer: **C**

1.4 Internal Energy

Internal energy of a system is determined by the state of the system and is the sum of the kinetic and potential energies of the randomly moving molecules."

The internal potential energy is the total energy of all the **atoms and molecules** due to **intermolecular forces**; depending on their **separation**.

The internal kinetic energy is the total energy of all the **atoms and molecules** due to their **motion**; depending on the **temperature**.

When a body absorbs heat/thermal energy, energy separates the atoms or molecules further thus the intermolecular potential energy increases. The random motion of the atoms or molecules may be increased. Macroscopically, this is seen as an increase in temperature of the body. **Thus, when the temperature of a body rises, we can infer that the total microscopic kinetic energy and potential energy of the body have increased and similarly the internal energy of the body has increased.**

Quick Quiz 3
The energies of the air in a moving aircraft are as follows:

8 MJ of kinetic energy as a result of the motion of the aircraft,
30 MJ of kinetic energy as a result of the random movement of the air molecules,
75 MJ of potential energy as a result of the altitude of the aircraft,
-3 MJ of potential energy as a result of intermolecular attraction between the air molecules.

Which of the following is the internal energy of the air in the aircraft?
A 27 MJ **B** 33 MJ **C** 35 MJ **D** 110 MJ

Ans: **A** 27 MJ

2 Temperature Scales

2.1 Thermometric Properties

So far, many of you have only come across liquid-in-glass thermometers like the alcohol and mercury thermometers. These thermometers have a scale which is marked (**calibrated**) according to the expansion of the liquid with temperature change. Hence, the **thermometric property** used in this case is the length of mercury or alcohol in the capillary tube.

Thermometric properties are physical properties of a substance that varies in a regular way with temperature.

A good thermometric property should have the following attributes:

- It must be sensitive to temperature change.
- It should respond quickly to temperature change.
- It must vary continuously and uniquely, but not necessarily linearly with temperature

Some examples of thermometers and the thermometric properties used are listed below:

Thermometer	Thermometric Property
Liquid-in-glass	Length of mercury or alcohol in capillary tube
Resistance	Resistance of a platinum wire
Thermocouple	e.m.f. of a copper-constantan thermocouple
Constant volume gas	Pressure of a fixed mass of gas at constant volume

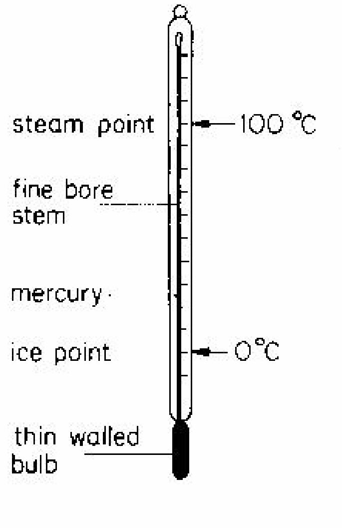
Each choice of thermometric substance and property – along with the assumed relation between property and temperature – leads to an individual temperature scale whose measurements need not necessarily agree with measurements made on any other independently defined temperature scale.

2.2 Empirical Temperature Scale (Refer to appendix B)

Most thermometers are calibrated by selecting a thermometric property, and then performing an experiment to decide the readings to be mark on the thermometer. Such a scale is known as an **empirical scale**; a scale that is obtained through **experiment**. An example of an empirical scale would be the **centigrade scale**.

For a centigrade scale, two fixed points, the **ice point** (0 °C) and **steam point** (100 °C) are identified. Next, the range in-between is divided into one hundred divisions, which calls for the name centi (meaning hundred) – grade!

Thus, a particular temperature measured by using different properties gives different readings except at the two fixed points where they must agree by definitions.



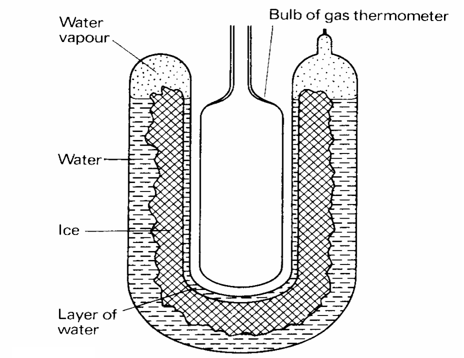
Celsius

2.3 Thermodynamic Temperature Scale

There also exists a **theoretical** scale that is **independent of any thermometric property of any particular substance**. This is known as an **Absolute Temperature Scale**, or the **Thermodynamic Temperature Scale**. Temperature for this scale is measured in **kelvin (K).**

Reasons for a Thermodynamic Temperature scale:

- Ambiguity of the empirical scale
- Thermodynamic temperature is an "absolute" scale because it is the measure of the fundamental property underlying temperature: its *null* or zero point, absolute zero, is the lowest possible temperature where nothing could be colder and minimum thermal energy remains in a substance.



triple point

The full definition of thermodynamic temperature depends on the theoretical efficiency of a perfectly reversible heat engine. The theory of reversible heat engine is **not dealt with** at A level.

The thermodynamic scale is also defined by two fixed points:

a) **The triple point of water** is the temperature at which all 3 phases of water (ice, water and water vapour) co-exist in dynamic equilibrium. The triple point is given the value of 273.16 for its temperature. This choice seems strange at first but the reason is to make the temperature difference between ice point and steam point exactly 100 on this scale as well.

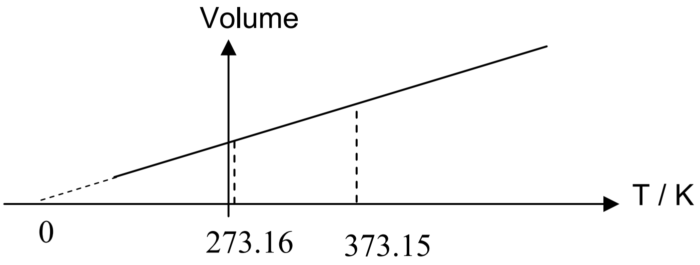
The triple point of water is chosen as a fixed point because

- It is unique, invariant and occurs at one definite temperature and pressure.
- It can be easily reproduced using a triple point cell as shown in the diagram.

b) **Absolute zero** is the coldest temperature possible; it has arbitrarily been given the value of 0 K.

How is absolute zero obtained?

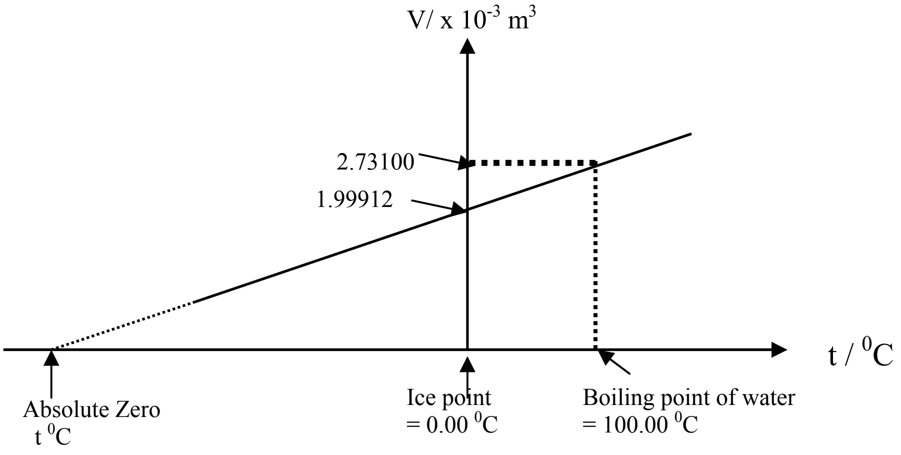
Real gases behave like ideal gases when the pressure of the gas is low. The ideal gas law (which you will learn in the later lecture topic) states that there is a linear relationship between temperature and the product of pressure and volume ($T \propto PV$), hence gases contract as the temperature is decreased. **Theoretically, at absolute zero the volume of an ideal gas would be zero** and all molecular motion would cease. Consider the volume of a gas at constant pressure undergoing a change in temperature.



The graph is extrapolated to V = 0 cuts the temperature axis; this is labeled as 0 K. It corresponds to **-273.15** ºC. The triple point of water occurs at 273.16 K, and corresponds to 0.01 ºC.

The **Kelvin is defined as to be** $\frac{1}{273.16}$ **of the thermodynamic temperature of the triple point of water.**

Example 1



The volume of a gas at constant pressure undergoing a change in temperature is given as shown above. If the volume of the gas at ice point and boiling point are 1.99912 x 10^{-3} m3 and 2.73100 x 10^{-3} m^3 respectively, Find the absolute temperature in centigrade.

$$\frac{0.00 - t}{100 - t} = \frac{1.99912 \times 10^{-3}}{2.73100 \times 10^{-3}}$$

$$t = -273.15\ ^0C$$

Quick Quiz 4

If absolute zero is taken to be 0 K and 1 degree Celsius (interval of a Celsius degree) is the same as 1 Kelvin (interval of a Kelvin), what is the the temperature in K for ice point, triple point of water and steam point of water respectively?

A 0, 0.01 and 100
B 273.00, 273.16, and 373.15
C 273.15, 273.16, and 373.15
D 373.15, 373.15, and 473.15

Quick Quiz 5

The Kelvin, the SI unit of thermodynamic temperature, is defined as

A one-hundredth of the temperature difference between the ice-point and the steam-point.
B one-hundredth of the temperature difference between the triple point of water and the steam point.
C the fraction 1/273.16 of the thermodynamic temperature of the steam-point.
D the fraction 1/273.16 of the thermodynamic temperature of the triple-point of water.

Answer: **D**

2.4 Internal Energy is at a minimum when temperature is at absolute zero.

Let's relate this to what we learnt earlier in section 1.3:

Internal Energy = Internal Potential Energy + Internal Kinetic Energy.

Furthermore, internal K.E. of a gas is dependent on the temperature. (K.E. $\propto T$), so at the lowest possible temperature (absolute zero or also known as 0 K), K.E. of the atoms and molecules must also be zero (i.e. not moving), and hence, **internal energy is at a minimum when temperature is at absolute zero**.

In actuality, all gases condense to solids or liquids well above absolute zero. Although absolute zero cannot be reached, temperatures within a few billionths of a degree above absolute zero have been achieved in the laboratory.

2.5 The Celsius Scale

The Celsius scale is a shifted thermodynamic scale. The unit for this scale is degree Celsius, (^{o}C). Between the ice point and steam points, the scale has one hundred divisions.

The Celsius scale is related to the Thermodynamic scale by the exact equation:

$$\boxed{t\,/^{o}\mathrm{C} = T/\mathrm{K} - 273.15}$$

Since the interval of one Kelvin is very nearly the same as the old centigrade degree, the effect of subtracting 273.15 is to make the **Celsius scale very nearly the same as the old centigrade scale.**

Scale	Fixed Points	Temperature
Centigrade Scale	Ice Point	0 ^{0}C / 273.15 K
	Steam Point	100 ^{0}C / 373.15 K
Thermodynamic Scale	Absolute Zero	-273.15 ^{o}C / 0 K
	Triple pt. of water	0.01 ^{o}C / 273.16 K
Celsius Scale	Absolute Zero	-273.15 ^{o}C / 0 K
	Triple pt. of water	0.01 ^{o}C / 273.16 K

Quick Quiz 6
What is 273.00 K on the Celsius scale of temperature?
A -0.15 ^{0}C **B** 0.00 ^{0}C **C** 0.15 ^{0}C **D** 546.15 ^{0}C
Answer: **A**

3 HEAT CAPACITY & SPECIFIC HEAT CAPACITY

3.1 Heat Capacity

Heat Capacity of a body is the amount of heat energy required per unit temperature change in the body.

Symbol: *C*
Units: J K^{-1}

Formula:

$$\boxed{Q = C\,\Delta\theta}$$

where Q = Heat gained or lost by the body
C = Heat capacity of the Body
$\Delta\theta$ = Temperature change

The heat capacity of a body may be regarded as the body's appetite for heat energy. It therefore depends on the material and size. It is difficult to compare which materials have higher heat capacities unless we compare *standard* masses (or sizes) of these materials.

Quick Quiz 7

Which of the following best describes the term *specific heat capacity* of a substance?

A The thermal energy required to change the state of 1 kilogram of the substance.
B The thermal energy required to change the state of the substance without change of temperature.
C The thermal energy required to raise the temperature of 1 kilogram of the substance by 1 kelvin.
D The thermal energy required to raise the temperature of the substance by I kelvin.

Answer: **C**

Quick Quiz 8

Block 1 is twice as massive as Block 2. The heat capacity of Block 1 is twice that of the heat capacity of Block 2. Both blocks are initially at the same temperature, and are then raised to the same final temperature. The amount of heat added to Block 1 is

1. four times as large
2. twice as large
3. the same
4. half as large
5. one-fourth as large

as the amount of heat added to Block 2.

Answer: 2. The amount of heat needed for a fixed temperature change is proportional to heat capacity.

3.2 Specific Heat Capacity

The Specific Heat Capacity of a substance is the amount of heat energy required **per unit temperature change per unit mass** of that substance.

Symbol: c
Units: J kg^{-1} K^{-1}

Formula: $\boxed{Q = m c \Delta\theta}$

where Q = heat gained or lost by the object
m = mass of the object
c = specific heat capacity of material
$\Delta\theta$ = change in temperature

Note: Heat capacity and specific heat capacity are related by: $\boxed{C = m c}$

Specific Heat Capacities	
Substance	**J/kg^{0}C**
Copper	390
Ethyl alcohol	2500
Gold	130
Mercury	140
Steel	480
Turpentine	1800
Water	4186

Quick Quiz 9

Block 1 is twice as massive as Block 2. Block 1 is made from a material with twice the specific heat of the material of Block 2. Both blocks are initially at the same temperature, and are then raised to the same final temperature. The amount of heat added to Block 1 is

6. four times as large
7. twice as large
8. the same
9. half as large
10. one-fourth as large

as the amount of heat added to Block 2.

Answer: 6 The amount of heat needed for a fixed temperature change is proportional to the mass and the specific heat.

Example 2
Determine the rise in temperature of a 3.6 kg block of copper when supplied with 2.8 kJ of heat. The specific heat capacity of copper is 390 J kg^{-1} K^{-1}.

Solutions:

$$Q = mc\Delta\theta$$

$$\therefore \quad 2800 = (3.6)(390)(\Delta\theta)$$

$$\Rightarrow \quad \Delta\theta = 1.99\text{K} \approx 2.0\text{K}$$

Example 3
2.0 kg of hot water at temperature 70^{o}C is poured into 3.0 kg of cold water at 20^{o}C. The final temperature of the mixture is θ. The specific heat capacity of water is 4200 J kg^{-1} K^{-1}.

1) Write down an expression for the heat lost by the hot water.

$$Q_L = mc\Delta\theta = (2)(4200)(70 - \theta)$$

2) Write down an expression for the heat gained by the cold water.

$$Q_G = (3)(4200)(\theta - 20)$$

3) Assuming no heat lost to the surroundings, find θ.

$$Q_L = Q_G$$

$$(2)(4200)(70-\theta) = (3)(4200)(\theta-20)$$
$$\theta = 40°\text{C}$$

Quick Quiz 10

If two objects have same heat capacity, are they necessarily constructed of the same material?

A No. As $C = mc$, if the products of m and c of the two objects are the same, they will have the same heat capacity.
B Yes. They must be constructed of the same material.
Answer: **A**

Quick Quiz 11
If two objects have same specific heat capacity, are they necessarily constructed of the same material?

A Yes. Specific heat capacity is the property of the material.
B No. Different materials may have the same specific heat.
Answer A

3.3 Rate of Heat Flow (Variations of the formula)

3.3.1 Fixed-mass case

If heat is supplied to a fixed-mass object at a constant rate (Q/t), and assuming that none of this heat is lost to the surroundings, then the temperature of the object would also increase at a constant rate $\Delta\theta/t$, according to the formula below:

$$\boxed{\frac{Q}{t} = mc\frac{\Delta\theta}{t}}$$

where Q/t = rate of heat gained/lost
$\Delta\theta/t$ = rate of temperature rise/fall
Note: Rate of heat gained or lost is sometimes also known as **power.** $P = Q/t$

Example 4
When heat is supplied to 5.0 kg of water at a rate of 8400 W, what is the initial rate temperature increase? The specific heat capacity of water is 4200 J kg^{-1} K^{-1}.

$$\frac{Q}{t} = mc\frac{\Delta\theta}{t}$$

$$8400 = (5)(4200)\frac{\Delta\theta}{t}$$

$$\frac{\Delta\theta}{t} = 0.4\text{Ks}^{-1}$$

3.3.2 Variable-Mass (Continuous Flow of Liquid)

If heat is constantly being supplied to a continuous flow of liquid (*m/t*), the increase in temperature $\Delta\theta$ is given by:

$$\frac{Q}{t} = \frac{m}{t}c\Delta\theta$$

where *m/t* = rate of flow of liquid

Quick Quiz 12

Why is water used as coolant in the radiator of a car engine?

A Water has high specific heat capacity. It can absorb more thermal energy per unit kg per degree rise in temperature.
B Water is high boiling point
C Water has high freezing point
D Water is volatile

Answer A

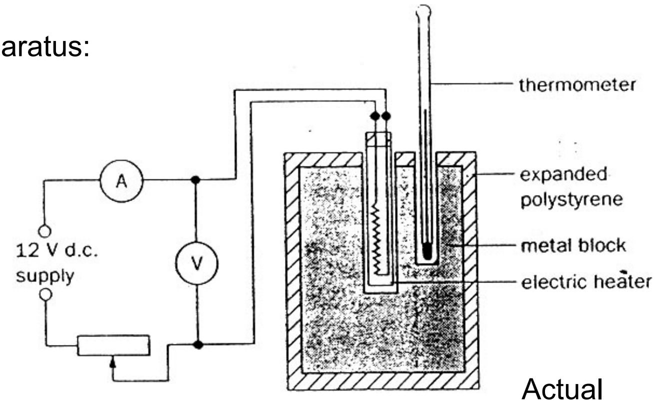
3.4 Electrical Methods to Determine Specific Heat Capacity, *c*

The principle for solids and liquids is identical. We need:
Heat supplied at the rate *Q/t* (otherwise known as the power)

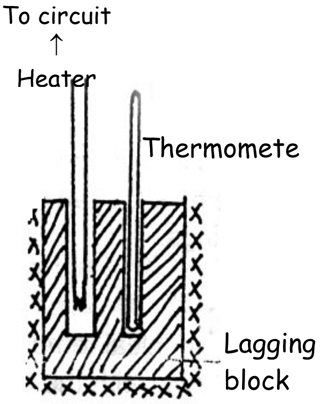
1. A specimen of mass m
2. A thermometer and a timing device (like a stopwatch) to measure $\Delta\theta$ and *t* respectively
3. To use the formula $(Q/t) = mc(\Delta\theta/t)$

3.4.1 Measuring Specific Heat Capacity of Solid

Apparatus:



Actual



Simplified

- The solid is shaped in the form of a thick cylindrical block with two deep holes.
- The electric heater is completely inside one hole.
- The thermometer is inside the other hole.
- Both the thermometer and heater must make good thermal contact with the material of the block. This is ensured by filling the holes with oil (which conducts heat well).
- The block is lagged with an insulating jacket (e.g. felt) to reduce heat loss to the surroundings.

Procedure

1 Measure the initial temperature θ_1 of the block.
2 Pass a current through the heater to heat the block for a known time t_1.
3 Measure the final temperature θ_2 of the block.
4 Record I = current flowing through the heater (from ammeter)
V = potential difference across heater (from voltmeter)
t = heating time
m = mass of block
θ_1 = initial temperature
θ_2 = final temperature
C = specific heat capacity of the block

5 Calculations: Ignoring heat loss to surroundings,
Heat energy supplied = Heat energy absorbed by solid
(Principle of Conservation of Energy)

$$P = IV = \frac{Q}{t} = \frac{mc\,\Delta\theta}{t}$$

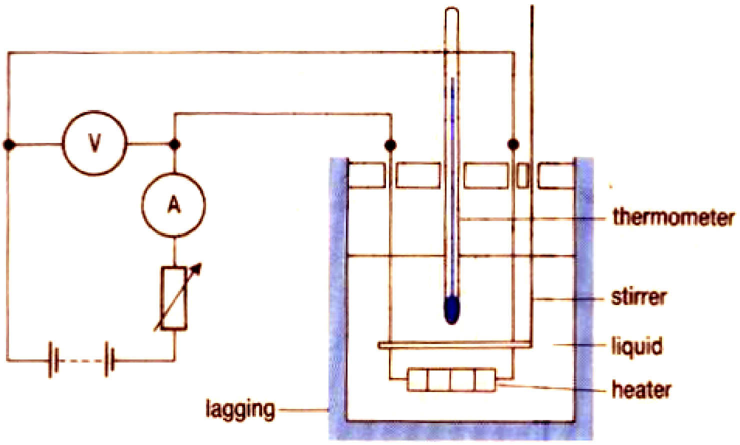
$$\Rightarrow IV = \frac{mc\,(\theta_2 - \theta_1)}{t}$$

$$\Rightarrow IVt = mc\,(\theta_2 - \theta_1)$$

Given all other measurements, the specific heat capacity of the block can be determine.

3.4.2.1 Measuring Specific Heat Capacity Liquids (fixed mass method)

Apparatus:



- The liquid is placed in a calorimeter.
- The calorimeter is lagged with an insulating jacket (e.g. felt) to reduce heat loss to the surroundings.

Procedure

1 Measure the initial temperature θ_1 of the liquid.
2 Heat the liquid with the heater for a known time t, stirring the liquid to distribute the heat evenly.

3 Measure the final temperature θ_2 of the liquid.

4 Record
I = current in the heater (from ammeter)
V = potential difference across heater (from voltmeter)
t = heating time
m = mass of liquid
θ_1 = initial temperature
θ_2 = final temperature
m_c = mass of calorimeter + stirrer
c_c = specific heat capacity of calorimeter + stirrer (can be found from books)
c_L = specific heat capacity of liquid

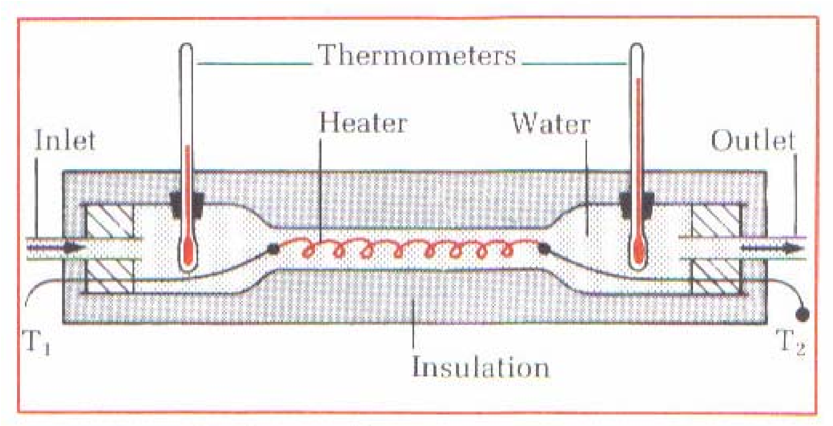
5 Calculations:
By conservation of energy,

Energy supplied = Energy received by liquid + Energy received by calorimeter and stirrer.

$$IVt = mc_L(\theta_2 - \theta_1) + m_c c_c(\theta_2 - \theta_1)$$
$$= (mc_L + m_c c_c)(\theta_2 - \theta_1)$$

The equation may be used to calculate c_L, given a value for c_c and all the necessary measurements.

3.4.2.2 Measuring Specific Heat Capacity Liquids (Continuous Flow of Liquid)



Continuous flow

Procedure

1 A steady flow of the liquid is passed along a pipe containing an electric heater.
2 The inlet and outlet temperature is measured for a known flow rate and heater power.

3 The flow rate is determined by measuring the mass of liquid collected in a measured time.

4 θ_1 and θ_2 are measured only when they are steady.

Record I = current in the heater (from ammeter)
V = potential difference across heater (from voltmeter)
t = heating time
m = mass of liquid collected over time t
θ_1 = temperature of liquid at inlet

θ_2 = temperature of liquid at outlet
c = specific heat capacity of liquid
H = heat loss to surrounding

We have $IVt = mc(\theta_2 - \theta_1) + H$

To calculate *c, H* must be eliminated from the above equation. The measurements are repeated at a different flow rate and the heater power($I'V'$) is adjusted to maintain θ_1 and θ_2 at the same value.

$$I'V't = m'c(\theta_2 - \theta_1) + H$$

Where m' is the mass of liquid collected at the outlet in the same time as before. Subtracting one equation from the other

$$IVt - I'V't = mc(\theta_2 - \theta_1) - m'c(\theta_2 - \theta_1)$$

The only unknown c can be calculated from the equation

4 LATENT HEAT

When a solid is heated, its temperature rises until it reaches its melting point. During the melting process, the temperature of the solid is constant until all the solid has melted. The heat supplied to the solid at its melting point thus only causes it to change its state, and does **NOT** raise its temperature. This heat required to **change a substance's state without changing its temperature**, is called **LATENT HEAT.**

The origins of the word “Latent” is derived from the latin word “Lateo”, which means to hide.
So latent heat is hidden heat!

4.1 Specific Latent Heats

The **Specific Latent Heat of Fusion** of a substance is the heat energy required to change per **unit** mass of the substance from solid to liquid (or vice-versa) *without any temperature change.*

The **Specific Latent Heat of Vaporisation** of a substance is the heat energy required to change per **unit** mass of the substance from liquid to vapour (or vice-versa) *without any temperature change.*

Symbol: l
Units: Jkg^{-1}

Formula: $Q = m\,l$

where Q = heat gained (or lost) by the substance
m = mass of the substance whose state has changed
l = specific latent heat

Quick Quiz 13
An open pot of water is boiling on a gas stove when someone raises the flame. The result will be

A a substantial increases in the temperature of the water
B a tiny decrease in the rate of evaporation
C an increase in the rate of boiling
D an appreciable increase in both the rate of boiling and in the temperature of the water.

Answer: C

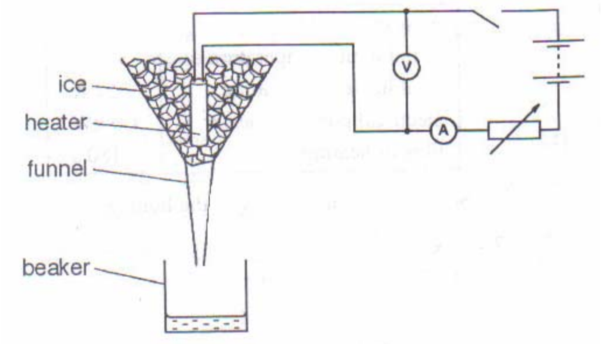
4.2 Electrical Methods for Determining Latent Heat

Again, the principle for fusion and vaporisation is identical. We need:

1. Heat supplied at the rate Q/t (otherwise known as the power)
2. A known mass of liquid or solid at its boiling or melting point, respectively.
3. A timing device, like a stopwatch, to measure time elapsed.

4.2.1 Specific Latent Heat of Fusion

Apparatus:



- The solid (say, ice) is in a funnel.
- A thermometer may be put among the ice chips to ensure the temperature is constant as the ice melts.

Procedure

1 Heat the ice with the heater for a known time t.
2 Measure the final mass, m_1 of the liquid collected.
3 Repeat the experiment without the heater, allowing the same initial mass of ice to melt naturally in the same time t in the environment. This is to compensate for `natural heating'. Measure the final mass, m_2 of the liquid collected.
4 Record
I = current in the heater (from ammeter)
V = potential difference across heater (from voltmeter)
t = heating time
m_1 = mass of liquid with heater
m_2 = mass of liquid without heater

5 Calculations:

Actual mass melted due to heater alone, $m = m_1 - m_2$

$$\frac{Q}{t} = \frac{ml_f}{t}$$

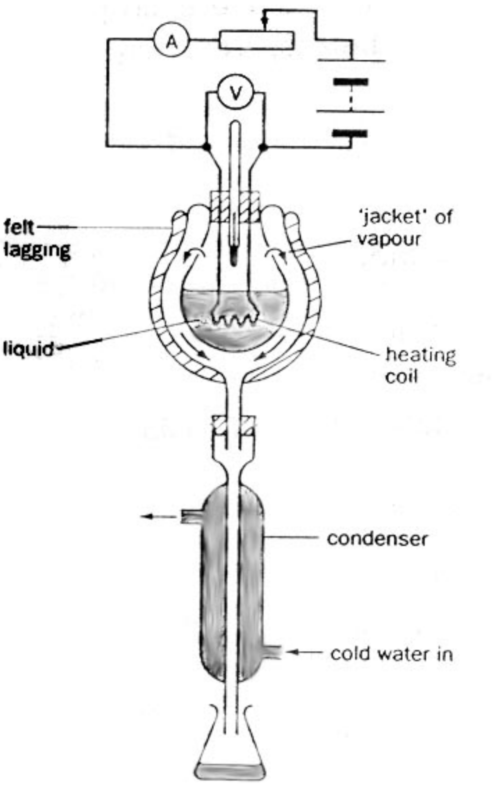
$$\Rightarrow IV = \frac{(m_1 - m_2)l_f}{t}$$

The only unknown l_f, the latent heat of fusion can be calculated from the equation

4.2.2 Specific Latent Heat of Vaporisation

Apparatus:

- The liquid (say, water) is in the U-shaped vessel.
- A heater heats the liquid, which vaporises.
- The vapour escapes through holes at the top of the vessel, condenses in the vapour jacket and slides down the condenser, ending up as liquid in the beaker.
- Once steady state (the liquid drops into the beaker at a constant rate) is reached, a time *t* can be set and the amount of liquid collected in that time measured.



If *I* and *V* are the current through the coil, and the potential difference across it, the electrical energy supplied in *t* seconds is *IVt.* And if *h* is he heat lost from the vessel per second, and *m* the mass of liquid collected in *t* second, and *m* the mass of liquid collected in *t* seconds, then

$$IVt = ml + ht \qquad .... (1)$$

The heat losses h are determined by the temperature of the vessel, which is fixed at the boiling point of liquid. If *I'V'* are the new current and potential difference, and if *m'* kg are evaporated in *t* seconds,

$$I'V't = m'l + ht$$

.

Hence by subtracting from equation (1)

$$l = \frac{(IV - I'V')}{(m-m')}$$

The latent heat of vaporisation of the liquid, *l* can be determined.

WORKED EXAMPLES

Example 5

An electric kettle with a 2.0 kW heating element has a heat capacity of 400 JK^{-1}. 1.0 kg of water of temperature 20^oC is placed in the kettle. The kettle is switched on and it is found that 13 minutes later, the mass of water in it is 0.5 kg. Ignoring heat losses, calculate a value for the specific latent heat of vaporization of water. The specific heat capacity of water is 4200 $Jkg^{-1}K^{-1}$.

Solution: Given

$P = \frac{Q}{t}$ = 2000W

m_i = 1 kg

θ_i = 20°C

θ_i (boil) = 100°C

t_{total} = 13×60s

m_f = 0.5kg

c = 4200 $Jkg^{-1}K^{-1}$

C_{kettle} = 400 JK^{-1}

Stage 1: raising temp

time taken = t_1

$$\frac{Q}{t} = \frac{(m_i)(c)(\theta_f - \theta_i)}{t_1} + \frac{C_{kettle}(\theta_f - \theta_i)}{t_1}$$

$$2000 = \frac{(1)(4200)(100-20)}{t_1} + \frac{(400)(100-20)}{t_1}$$

$$\therefore t_1 = 184s - - - - - - - - - - -(1)$$

Stage 2: Boiling

time taken = t_2 = t_{total} - t_1 = (13×60) – 184 = 596s

$$\frac{Q}{t} = \frac{m_f l}{t_2}$$

$$2000 = \frac{(1-0.5)l}{596}$$

$$\therefore l = 2.38 \times 10^6 \, Jkg^{-1}$$

∴***l*** = $2.38 \times 10^6 Jkg^{-1}$

Appendix A

Zeroth Law of Thermodynamics

The number 'zero' was used because this law logically precedes the 'first' and 'second' laws of thermodynamics and, in fact, is assumed in the two laws.

Zeroth law of thermodynamics states that if bodies A and B are separately in thermal equilibrium with a third body C, then A and B are in thermal equilibrium with each other.

The importance of this law is in the usage in temperature measurements. To determine whether two bodies A and B are in thermal equilibrium, a third body, in this case, a thermometer is used. A is first brought into thermal contact with the thermometer and the reading of the thermometer is noted. B is then placed in thermal contact with the thermometer and the reading taken. If the two readings are the same, it can be deduced that if A and B are in thermal contact, then A and B would be in thermal equilibrium.

Appendix B

Empirical Temperature Scale

An empirical temperature scale is a temperature scale based on experimental results.

An example of an empirical scale is the Centigrade Scale. The following three steps show how the scale is set up and how they are used.

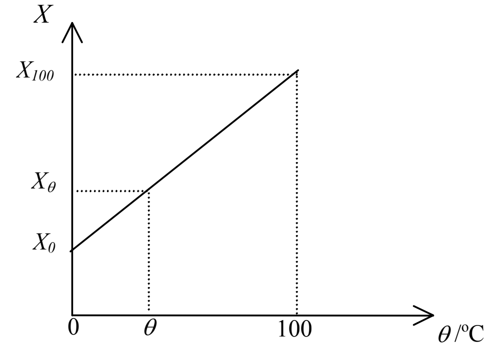
Step 1:
A thermometric substance whose thermometric property varies continuously in one direction with temperature is selected. The choice depends on the temperature range and the type of material whose temperature is to be measured.

Step 2:
Two fixed points are chosen and values are assigned to them. In the Centigrade scale of temperature, the lower fixed point is the ice point while the upper fixed point is the steam point. The ***ice point*** is the temperature at which pure ice exists in equilibrium with air-saturated water at standard atmospheric pressure and is assigned at 0 ^{o}C. The ***steam point*** is the temperature at which pure water exists in equilibrium with its vapour at standard atmospheric pressure and is assigned as 100 ^{o}C.

Step 3:
If X is the thermometric property chosen, then,

X_0 : the value at ice point

X_θ: the value at unknown temperature θ



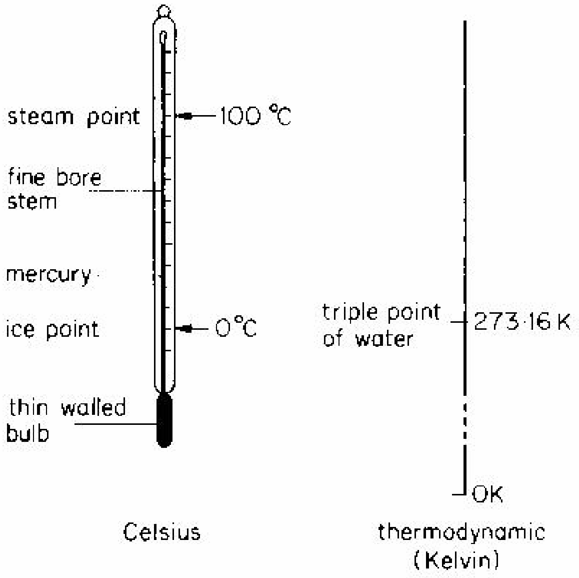
X_{100} : the value at steam point

The fundamental interval of the scale is given by (X_{100} - X_0). The calibration graph can be plotted as shown on the right:

The temperature interval between the ice point and the steam point is known as the fundamental interval. In the Centigrade scale, the fundamental temperature is divided into 100 equal divisions. Each division is known as one degree Centigrade.

If X_θ is the value of the property at some temperature θ which we wish to know, then the value of θ in ^{o}C is given by the equation:

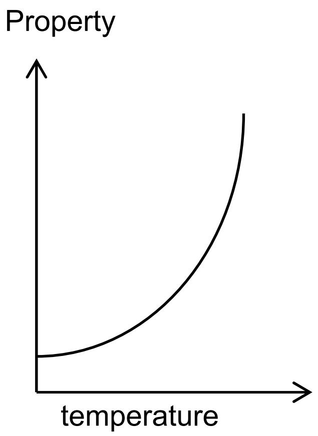
$$\boxed{\frac{X_\theta - X_0}{X_{100} - X_0} = \frac{\theta}{100}}$$



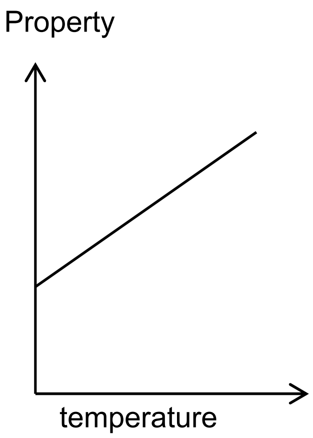
Notes:

The equation above is obtained by assuming that the thermometric property X varies linearly with temperature, i.e. equal increase in the value of the property represent equal increase of temperature. But most thermometric properties do no vary linearly with respect to temperature. In fact, the thermometric properties ***respond differently to temperature change***. Thus a particular temperature measured by different types of thermometers give different readings except at the fixed points where they must agree by definitions.

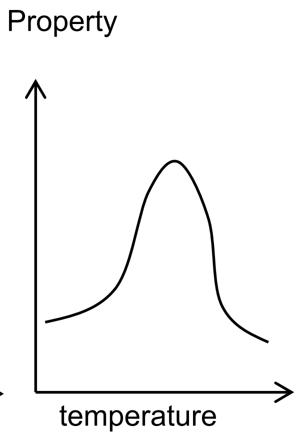
** To find out more about the different thermometers and how their thermometric properties work, you may look up Tom Duncan, Advanced Physics, 4th Edition, pg 76 – 77.*



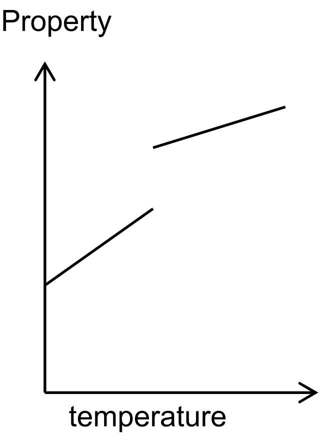
Non-linear,
continuous,



Linear, continuous,
unique



Non-linear,
continuous,
non-unique



Linear, non-continuous, unique

TAMPINES JUNIOR COLLEGE

Thermal Physics (1)

JC1 Tutorial 2008

Basic Questions

1. By reference to thermal energy transfer, explain what is meant by
   a) two bodies having the same temperature,
   b) body H having a higher temperature than body C.

2. Body A of temperature 80 ^{o}C is brought into thermal contact with body B of temperature 20 ^{o}C.
   a) What will happen to the temperatures of A and B?
   b) What term is given to the final stage reached, where there is no net exchange of heat?
   c) Would the temperature change of A be equal to the temperature change of B?

3. What is meant by the *internal energy* of a system?
   a) State 2 physical quantities which affect the internal energy of a system.
   b) State a physical quantity which does not affect the internal energy of a system.

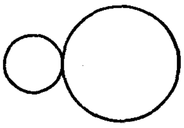
4. a) What thermodynamic temperature is equivalent to 40 ºC?
   b) Comment on the statement ‘Today the temperature is 40 ºC and yesterday it was 20 ºC, so it is twice as hot today as it was yesterday’.

5. a) What is the difference between heat capacity and specific heat capacity?
   b) Which one is a characteristic of a material and which one is a characteristic of a body?
   c) Rewrite their definitions in equation form.

Problems

Internal Energy, Heat and Thermal Equilibrium

6. The given diagram shows two metal spheres in thermal contact in a vacuum. The spheres, of different radii, are at the same temperature. Which one of the following statement is certainly correct?



A Each sphere has the same internal energy.
B There is no net transfer of thermal energy between the spheres.
C Both spheres radiate electromagnetic energy at the same rate.
D The larger sphere has a greater mean internal energy per atom than the smaller sphere.

7*. The internal energy of a fixed mass of an ideal gas depends on

A pressure, but not volume or temperature.
B temperature, but not pressure or volume.
C volume, but not pressure or temperature.
D pressure and temperature, but not volume.

Temperature scales
Formula (t /°C = T/K – 273.15)

8. A thermometer depends on the variation with temperature of a particular physical property. What is a necessary characteristic of this property?

A The property must give a linear temperature scale that agrees with the absolute scale of temperature over the whole range of the thermometer.
B The property must have a different value at each temperature, over the whole range of the thermometer.
C The property must have zero value at the absolute zero of temperature.
D The property must vary over a very wide range of temperatures.

9. What is the thermodynamic temperature that is equivalent to 501.85 °C?
A 775.00 K **B** 774.85 K **C** 228.85 K **D** 228.70 K

10. The triple point of water has been chosen as the fixed point for the establishment of the Kelvin Scale, rather than melting point of ice. Which one the following statements best accounts for this? The triple point

A is closer to the defining temperature of 273.16 K.
B ensures a more linear scale for gas thermometers.
C is shown to be better if very accurate gas thermometers are used.
D is more precisely reproducible.

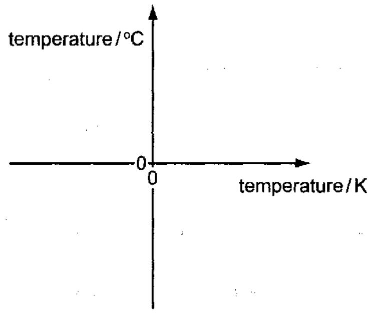
11.

	Centigrade	Celsius	Kelvin
Absolute zero	-273.15	-273.15	0.00

Freezing point of water	0.00	0.00	273.15
Triple point of water	0.01	0.01	273.16
Boiling point of water	100.00	100.00	373.15

The above table gives the numerical values of the temperature, to 2 decimal places, of four reference points on three different temperature scales. In each column, two of the values are exact by definition and two are found by experiment. Which, for each scale, are the exact temperatures?

12.*



A student draws a linear graph on the axes shown in order to convert temperatures in kelvin to temperatures in degrees Celsius.

What is the intercept on the vertical axis and the gradient of the line?

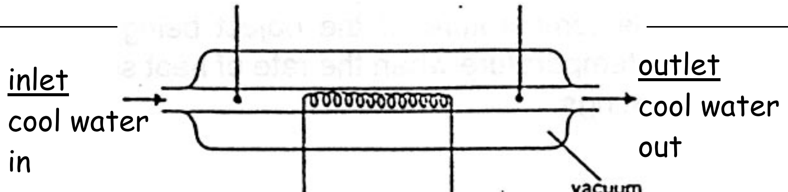
	intercept	gradient
A	0	1/273
B	-273	1
C	+273	1
D	0	273

13 The temperature of a body at 100 °C is increased by $\Delta\theta$ as measured on the Celsius scale. What is the temperature change expressed on the Kelvin scale?

A $\Delta\theta + 373$
B $\Delta\theta + 273$
C $\Delta\theta + 100$
D $\Delta\theta$

Specific Heat Capacity

Work Example A
In a water heater as shown in the diagram, water flows in through an inlet pipe and gets heated up. This hot water then leaves through the outlet pipe, flowing at a constant rate of 2.0 kg per minute. The temperature of the water at the inlet is 27 °C and 42° C at the outlet. The specific heat capacity of the water is 4200 J kg^{-1}K^{-1}. (Ignore heat loss)



(a) Find the power of the heating element / coil.

$$P = \frac{Q}{t} = \frac{m}{t} c\,\Delta\theta \quad = \frac{2}{60}(4200)(42 - 27) \quad = 2100\text{ W}$$

(b) If the rate of flow of water is increased to 2.5 kg per minute while the power of the heating element remains unchanged, what is the new temperature of the water at the outlet?

$$\frac{Q}{t} = \frac{m}{t} c\,\Delta\theta$$

$$2100 = \frac{2.5}{60}(4200)(\theta - 27)$$

$$\theta = 39^\circ\text{C}$$

(c) At this new rate of flow of water at 2.5 kg per minute, if we want the temperature of the water at the outlet to be maintained at 42° C, what should be the power of the heating element?

$$P = \frac{Q}{t} = \frac{m}{t} c\,\Delta\theta = 2625\text{ W} \approx 2630\text{ W (3sf)}$$

Work Example B

A thermally insulated tube through which a gas may be passed at constant pressure contains an electric heater and thermometers for measuring the temperature of the gas as it enters and leaves the tube. 0.003 m^3 of gas of density 1.8 kgm^{-3} flows into the tube in 90 s and when electrical power is applied to the heater at a rate of 0.16 W, the temperature difference between the outlet and inlet is 2.5 K. Find c.

$P = 0.16$ W, $\Delta\theta = 2.5$ K, $t = 90$ s, $V = 0.003\ m^3$

$\rho = 1.8 kgm^{-3}$ ➔ $m = \rho V$

$$\frac{Q}{t} = P = \frac{m}{t} c\Delta\theta$$

$$\Rightarrow c = \frac{Pt}{m\Delta\theta} = \frac{(0.16)(90)}{(0.003)(1.8)(2.5)} = 1.07\times10^3\ \text{Jkg}^{-1}\text{K}^{-1}$$

14. A solar furnace has a concave mirror of collecting area 0.8 m^2. The average thermal radiation from the sun reaching the earth is about 750 Wm^{-2}. A 0.5 kg small mass with specific heat capacity 2000 $Jkg^{-1}K^{-1}$ is heated by the furnace from 10 °C to 40 °C. Find the time taken in seconds for heating.

15. Cooling water enters the heat exchanger in the turbine hall of a nuclear power plant at 6 ^{o}C and leaves at 14 ^{o}C. The specific heat capacity of water is 4200 $Jkg^{-1}K^{-1}$. If the rate at which heat is removed from the water is 6.05×10^{9} $Jmin^{-1}$, what is the rate of water flow?

Work Example C

A metal of mass 0.2 kg at 100 ^{0}C is dropped into 0.08 kg of water at 15 ^{0}C contained in a calorimeter of mss 0.12 kg and specific heat capacity 400 J kg^{-1} K^{-1}. The specific heat capacity of water is 4200 $Jkg^{-1}K^{-1}$. The final temperature reached is 35^{0}C. Assuming negligible heat losses, find the specific heat capacity of the metal.

Heat lost by hot metal = Heat gained by water and calorimeter
$M_m c_m \Delta\theta = m_w c_w \Delta\theta + m_c c_c \Delta\theta = (m_w c_w + m_c c_c) \Delta\theta$
$0.2 \times c_m (100 - 35) = (0.08 \times 4200 + 0.12 \times 400)(35 - 15)$
$c_m = 590$ J kg^{-1} K^{-1}

16. A piece of copper of mass 100 g is heated to 100 ^{o}C and transferred to a well-lagged copper can of mass 50 g containing 200 g of water at 10 ^{o}C . Neglecting heat loss to the surroundings, calculate the final steady temperature of the water after it has been stirred.

Specific heat capacity of copper = 400 J kg^{-1} K^{-1}
Specific heat capacity of water = 4200 J kg^{-1} K^{-1}

Work Example D

Water flows at the rate of 0.1500 kg min^{-1} through a tube and is heated by a heater dissipating 25.2 W. The inflow and outflow water temperatures are 15.2 ^{0}C and 17.4^{0}C respectively. When the rate of flow is increased to 0.2318 kg min^{-1} and the rate of heating to 37.8 W, the inflow and outflow temperatures are unaltered. Find the specific heat capacity of water and the rate of loss of heat, *h* from the tube.

$IV = m/t\, c_w (\theta_2 - \theta_1) + h$
$25.2 = (0.1500/60)\, c_w (17.4 - 15.2) + h$ ……(1)
$37.8 = (0.2318/60)\, c_w (17.4 - 15.2) + h$ ……(2)

Subtracting (1) from (2),
$c_w = 4200$ J kg^{-1} K^{-1}
Substituting c_w into (1), h = 2.1 W

17* In a water heater, water at 27 °C flows in through an inlet pipe and get heated up. The hot water then flows though the outlet pipe at 45 °C. The rate of water flow is 4.0 kg per minute and the heat lost to the surrounding is 25 kW. The specific heat capacity of water is 4200 J kg^{-1} K^{-1}. What is the power of the heater?

A 5 kW

B 20 kW
C 30 kW
D 277 kW

18. Oil at 15.6 ^{0}C enters a long glass tube containing an electrically heated platinum wire and leaves it at 17.4 ^{0}C, the rate of flow being 25 cm^{3} per min and rate of supply of energy 1.34 watts. On changing the rate of flow to 15 cm^{3} per min and the power to 0.76 watt the temperature again rises from 15.6^{0} to 17.4^{0}C. Calculate the mean specific heat capacity of the oil between these temperatures and the rate of heat lost.
Assuming that the density of he oil is 870 kg m^{-3}.

19. In a domestic water heater, the heating element produces heat at a constant rate of 2000 W. If the water which enters the heater has a temperature of 24^{0}C, what should the maximum rate of water flow be if the user does not want the temperature of the water to be less than 35^{0}C ? [Specific heat capacity of water is 4200 J kg^{-1} K^{-1}]

<u>Specific Latent Heat</u>

Work Example E

One 50-g ice cube is dropped into 200g of water in a glass. If the water was initially at a temperature of 25°C, and the ice came directly from a freezer at -15°C, what will be the final temperature of the drink? The specific heat capacity of ice is 2.23 kJ kg^{-1} K^{-1}, the specific heat capacity of water is 4.2 kJ kg^{-1} K^{-1}, and the specific latent heat of ice is 334 kJ kg^{-1}. Neglect the heat capacity of the glass.

Assumption 1: Heat loss to surroundings is negligible.
To solve such problems, we use the principle of conservation of energy, i.e. heat gained = heat loss

So, what gained heat? ICE!

1. Amount of heat required to raise the temperature of ice from -15°C to 0°C
$= mc\Delta\theta = 0.050 \times 2.23 \times 10^{3} \times 15 = 1\,672.5$ J

2. Amount of heat required to melt all the ice
$= ml = 0.050 \times 3.34 \times 10^{5} = 16\,700$ J

3. Amount of heat required to raise the temperature of ice from 0°C to θ°C (final temp)
$= mc\Delta\theta = 0.050 \times 4.2 \times 10^{3} \times \theta = 210\,\theta$ J

What lost heat? WATER!

4. Amt of heat required to bring the temperature of water from 25°C to θ °C
$= mc\Delta\theta$
$= 0.200 \times 4.2 \times 10^{3} \times (25 - \theta) = 840\,(25 - \theta)$ J

5. Heat gained = Heat Loss
➔ $1\,672.5 + 16\,700 + 210\theta = 840\,(25 - \theta)$
➔ $\theta = 2.5$ °C

20. An electrical heater of 2 kW is used to heat 0.5 kg of water with initial temperature 20 °C. The specific heat capacity of water = 4200 $Jkg^{-1}K^{-1}$ and its specific latent heat of vaporisation = 2 x 10^6 Jkg^{-1}. Neglecting heat losses,

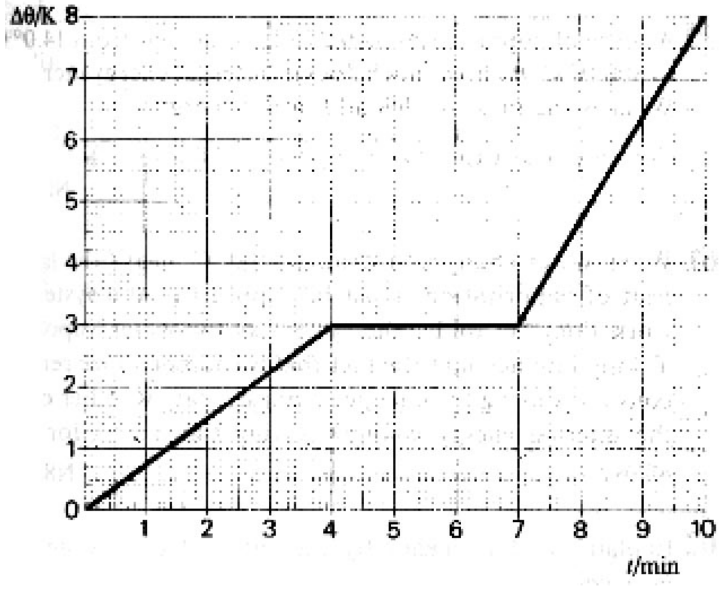
(i) how long will it take to heat the water to its boiling point, 100 °C?
(ii) starting from 20 °C, what mass of water is boiled away in 5 minutes?

21. In a heating experiment, it was noted that the temperature of a liquid in a beaker rose at 4.0 K per minute just before it began to boil, and that 40 minutes later, all the liquid had boiled away. For this liquid, what is the numerical ratio of

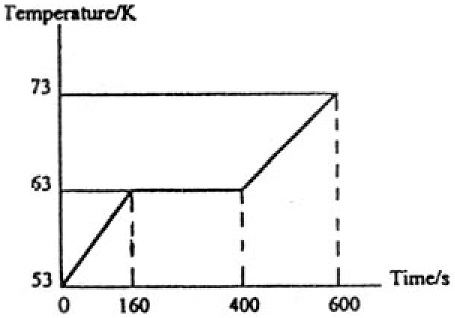
$$\frac{\text{specific heat capacity}}{\text{specific latent heat of vaporization}} \quad ?$$

22**. A thermally insulated vessel containing liquid water and water vapour is connected to a vacuum pump which removes water vapour continuously. When the temperature reaches 0 °C the vessel contains 110g of liquid water. What mass of ice has been formed when no liquid remains?
Specific latent heat of vaporisation of water = 2.52 x 10^6 Jkg^{-1}
Specific latent heat of fusion of ice = 3.40 x 10^5 Jkg^{-1}

23. The graph shows the variation of temperature *change* $\Delta\theta$ with time *t* for 1 kg of a substance, initially solid at room temperature. The substance receives heat at a uniform rate of 2000 J per minute. Determine
(i) the specific heat capacity of the substance in solid form and in liquid form,
(ii) the specific latent heat of fusion.



24*The graph below refers to an experiment in which an initially solid specimen of nitrogen absorbs heat at a constant rate. Nitrogen melts at 63 K, and the specific heat capacity of solid nitrogen is 1.6 × 10^3 J kg^{-1} K^{-1}.



What is the specific latent heat of fusion of nitrogen?

A 2.0 × 10^4 J kg^{-1}	C 2.0 × 10^3 J kg^{-1}
B 2.4 × 10^4 J kg^{-1}	D 2.4 × 10^3 J kg^{-1}

25.** If 4 g of steam at 100 ^{0}C are mixed with 20 g of ice at -5 ^{0}C, find the final temperature of the mixture.

Specific latent heat of vaporisation of water = 2.26 x 10^6 Jkg^{-1}
Specific latent heat of fusion of ice = 3.34 x 10^5 Jkg^{-1}
Specific heat capacity of water = 4.19 kJ $kg^{-1}K^{-1}$
Specific heat capacity of ice = 2.09 kJ $kg^{-1}K^{-1}$

26.*** Equal masses of ice at 0 ^{0}C, water at 50 ^{0}C, and steam at 100 ^{0}C are mixed and allowed to reach equilibrium. Will all the steam condense? What will be the temperature of the final mixture? What percentage of the final mixture will be water, and what percentage will be steam?

Specific latent heat of vaporisation of water = 2.26 x 10^6 Jkg^{-1}
Specific latent heat of fusion of ice = 3.34 x 10^5 Jkg^{-1}
Specific heat capacity of water = 4.19 kJ $kg^{-1}K^{-1}$
Specific heat capacity of ice = 2.09 kJ $kg^{-1}K^{-1}$

11) (centigrade : 0.00 and 100.00; Celsius: -273.15 and 0.01 Kelvin: 0.00 and 273.16,

14) 50s, 15) 3.0 x10^3 kgs^{-1} 16) 14^{0}C 17) C 18) 2.22 kJ Kg^{-1} K^{-1}, -0.109 W
19) 0.043 kg s^{-1} 20) 84 s, 0.2 kg 21) 1/160 22) 97 g
23) 2.67 x 10^3 $Jkg^{-1}K^{-1}$, 1.20 x 10^3 $Jkg^{-1}K^{-1}$, 6000Jkg^{-1} 25) 38.1 ^{0}C
26) no, 100 ^{0}C, 19.1 % steam and 80.9 % water