

IB Topic 3: Thermal Physics

Part I: Summer Assignment

How to complete this assignment:

1. The entire assignment is not meant to take more than 8 hours; most find that it takes about 5 hours.
2. Please note that there are links to simulations and other internet sources embedded in the documents, and so you may wish to download the documents.
3. Keep your notes in a notebook. You may type them if you desire, but studies have shown that it is easier to remember written notes compared to typed notes.
4. A list of objectives directly from the IB curriculum guide, two PowerPoints and lecture notes, with some links to websites (so you can actually learn this stuff!) are included, as well as a brief assignment (so you can practice it and see what types of questions IB expects you to be able to answer!).
 - a. Read the objectives so you know what you're about to learn about!
 - b. Read through and study the two PowerPoints and the Lecture Notes making sure to visit the websites to see simulations, etc. when necessary.
 - c. Read Chapter 13 and Chapter 14 of Giancoli.
 - d. TAKE NOTES on the objectives. Answer all the conceptual questions in a notebook.
 - e. Do the IB Homework set.
5. When we return in August, you will be asked to:
 - a. show your notes, which should be hand-written or printed out and in your notebook for your IB 2 class,
 - b. submit all assignments in a stapled packet with your NAME and appropriate headings,
 - c. demonstrate your knowledge of the essential concepts through an ASSESSMENT during the second week of school (following a brief review in class).

Part II: Internal Assessment

The internal assessment is required both for part of your IB score and for taking this class. As you learned from the science fair process, coming up with a “good” topic can be the most challenging part! Use some time you have over the summer to come up with 2-3 potential ideas for your Internal Assessment. Your ideas should include a solid research question, a quantifiable independent and dependent variable (at least 5 levels), and an outline of your procedure including a labelled diagram of your experimental setup AND all necessary safety requirements (if applicable). It is better to completely explain a simple experiment than partially explain a more complex setup. Remember to consider the types of sensors available to you, either by borrowing them from school (motion detector, speed sensor, force probe, temperature probes, etc.) or by purchasing them yourself (various Apps, etc.). Additionally, your topic MUST fit into the IB Physics curriculum.

Topic 3: Thermal physics (11 hours)

Essential idea: Thermal physics deftly demonstrates the links between the macroscopic measurements essential to many scientific models with the microscopic properties that underlie these models.

3.1 – Thermal concepts

Nature of science:

Evidence through experimentation: Scientists from the 17th and 18th centuries were working without the knowledge of atomic structure and sometimes developed theories that were later found to be incorrect, such as phlogiston and perpetual motion capabilities. Our current understanding relies on statistical mechanics providing a basis for our use and understanding of energy transfer in science.

Understandings:

- Molecular theory of solids, liquids and gases
- Temperature and absolute temperature
- Internal energy
- Specific heat capacity
- Phase change
- Specific latent heat

Applications and skills:

- Describing temperature change in terms of internal energy
- Using Kelvin and Celsius temperature scales and converting between them
- Applying the calorimetric techniques of specific heat capacity or specific latent heat experimentally
- Describing phase change in terms of molecular behaviour
- Sketching and interpreting phase change graphs
- Calculating energy changes involving specific heat capacity and specific latent heat of fusion and vaporization

Guidance:

- Internal energy is taken to be the total intermolecular potential energy + the total random kinetic energy of the molecules
- Phase change graphs may have axes of temperature versus time or temperature versus energy
- The effects of cooling should be understood qualitatively but cooling correction calculations are not required

International-mindedness:

- The topic of thermal physics is a good example of the use of international systems of measurement that allow scientists to collaborate effectively

Theory of knowledge:

- Observation through sense perception plays a key role in making measurements. Does sense perception play different roles in different areas of knowledge?

Utilization:

- Pressure gauges, barometers and manometers are a good way to present aspects of this sub-topic
- Higher level students, especially those studying option B, can be shown links to thermodynamics (see *Physics* topic 9 and option sub-topic B.4)
- Particulate nature of matter (see *Chemistry* sub-topic 1.3) and measuring energy changes (see *Chemistry* sub-topic 5.1)
- Water (see *Biology* sub-topic 2.2)

Aims:

- **Aim 3:** an understanding of thermal concepts is a fundamental aspect of many areas of science
- **Aim 6:** experiments could include (but are not limited to): transfer of energy due to temperature difference; calorimetric investigations; energy involved in phase changes

Data booklet reference: $Q = m c \Delta T$

$$Q = m L$$

Essential idea: The properties of ideal gases allow scientists to make predictions of the behaviour of real gases.

3.2 – Modelling a gas

Nature of science:

Collaboration: Scientists in the 19th century made valuable progress on the modern theories that form the basis of thermodynamics, making important links with other sciences, especially chemistry. The scientific method was in evidence with contrasting but complementary statements of some laws derived by different scientists. Empirical and theoretical thinking both have their place in science and this is evident in the comparison between the unattainable ideal gas and real gases.

Theory of knowledge:

Understandings:

- Pressure
- Equation of state for an ideal gas
- Kinetic model of an ideal gas
- Mole, molar mass and the Avogadro constant
- Differences between real and ideal gases

Applications and skills:

- Solving problems using the equation of state for an ideal gas and gas laws
- Sketching and interpreting changes of state of an ideal gas on pressure–volume, pressure–temperature and volume–temperature diagrams
- Investigating at least one gas law experimentally

Guidance:

- Students should be aware of the assumptions that underpin the molecular kinetic theory of ideal gases
- Gas laws are limited to constant volume, constant temperature, constant pressure and the ideal gas law
- Students should understand that a real gas approximates to an ideal gas at conditions of low pressure, moderate temperature and low density

Data booklet reference:

Utilization:

- Transport of gases in liquid form or at high pressures/densities is common practice across the globe. Behaviour of real gases under extreme conditions needs to be carefully considered in these situations.
- Consideration of thermodynamic processes is essential to many areas of chemistry (see *Chemistry* sub-topic 1.3)
- Respiration processes (see *Biology* sub-topic D.6)

Aims:

- **Aim 3:** this is a good topic to make comparisons between empirical and theoretical thinking in science
- **Aim 6:** experiments could include (but are not limited to): verification of gas laws; calculation of the Avogadro constant; virtual investigation of gas law parameters not possible within a school laboratory setting

$$\begin{aligned} \bullet & \quad p = \frac{F}{A} \\ \bullet & \quad n = \frac{N}{N_A} \\ \bullet & \quad pV = nRT \end{aligned}$$

$$\bullet \quad \bar{E}_K = \frac{3}{2} k_B T = \frac{3}{2} \frac{R}{N_A} T$$

Part 1 Definitions, Thermometers, and How Energy Transfers

1. A circular hole is cut through a flat aluminum plate. A circular disk of aluminum has a diameter slightly smaller than the diameter of the hole. The plate and the ball have the same temperature at all times. Should the plate and disk both be heated or both be cooled to prevent the disk from falling through the hole? Explain your reasoning.
2. When the bulb of a mercury-in-glass thermometer is inserted into boiling water, the mercury column first drops slightly before it begins to rise. Account for this phenomenon.
3. Sea breezes are often encountered on sunny days at the shore of a large body of water. Explain in light of the fact that the temperature of the land rises more rapidly than that of the nearby water. Can you explain which way the breezes are most likely to blow during the morning? What about the evening?
4. Why is the liner of a thermos bottle silvered, and why does it have a vacuum between its two walls?
5. Explain why air-temperature readings are always taken in the shade.
6. People often ask: Which will cool the coffee faster, adding cold milk immediately after pouring the coffee into a mug or waiting a few minutes until you are ready to drink the coffee? Explain your choice.

Part 2 Kinetic Theory of Gases and the Ideal Gas Law

1. Why doesn't the size of different molecules enter into the gas laws?
2. When a gas is rapidly compressed (say, by pushing down a piston) its temperature increases. When a gas expands against a piston it cools. Explain these changes in temperature using the kinetic theory, in particular noting what happens to the momentum of molecules when they strike the moving piston.
3. Explain why a hot humid day is far more uncomfortable than a hot dry day at the same temperature.
4. Is it possible to boil water at room temperature without heating it? Explain.
5. When you climb a mountain, your eardrums "pop" outward, and when you come down, they "pop" inward, because of changes in pressure. At the sea coast, there is a cave that can be entered only by swimming through a completely submerged passage and emerging into a pocket of air within the cave. The cave is not vented to the external atmosphere. As the tide comes in, the water level in the cave rises, and your eardrums "pop". Is this popping analogous to what happens when you climb up or down a mountain? Give your reasoning.
6. A commonly used packing material consists of "bubbles" of air trapped between bonded layers of plastic. Using the ideal gas law, explain whether the packing material offers more protection on warm or cold days, and why.
7. Explain how much the average translational kinetic energy of each particle in an ideal gas changes, when the temperature of the gas goes from 50 to 100 °C.

Part 3 Thermal Energy Transfer, Specific and Latent Heats

1. In warm zones the temperature may drop below freezing a few times in the winter, the destruction of sensitive plants due to freezing can be reduced by watering them in the evening. Explain.
2. Explain why burns caused by steam on the skin are often more severe than burns caused by boiling hot water.
3. Will potatoes cook faster if the water is boiling faster?
4. Why do cooks add salt to the water when they cook potatoes?

IB PHYSICS 2: Topic 3

ESSENTIAL UNDERSTANDING: Heat as energy transfer.

- **Objectives:** Students should understand the "mechanical equivalent of heat" so they can calculate how much a substance will be heated by the performance of a specified quantity of mechanical work.
- Students should understand the concepts of specific heat, specific latent heat of fusion, and specific latent heat of vaporization so they can;
 1. Identify, given a graph relating the quantity of heat added to a substance and its temperature, the melting point and boiling point and determine the heats of fusion and vaporization and the specific heat of each phase.
 2. Determine how much heat must be added to a sample of a substance to raise its temperature from one specified value to another, or to cause it to melt or vaporize.
- Students should understand heat transfer and thermal expansion so they can:
 1. Determine the final temperature achieved when substances, all at different temperatures, are mixed and allowed to come to thermal equilibrium.
 2. Calculate how the flow of heat through a slab of material is affected by changes in the thickness or area of the slab, or the temperature difference between the two faces of the slab.
 3. Analyze qualitatively what happens to the size and shape of a body when it is heated.

TOPIC	Essential knowledge	Resources
Thermal Physics	<p>Temperature measure of an object's kinetic energy; temperature measures how hot or how cold an object is with respect to a standard. Temperature is a property of a system that determines whether the system will be in thermal equilibrium with other systems. Objects are in thermal equilibrium when they are at the same temperature.</p> <p>Temperature Scales. The most common scale is the Celsius (or Centigrade, though in the United States the Fahrenheit scale is common). Both of these scales use the freezing point and boiling point of water at atmospheric pressure as fixed points. On the Celcius scale, the freezing point of water corresponds to 0°C and the boiling point of water corresponds to 100°C. On the Farenheit scale, the freezing point of water is defined to be 32°F and the boiling point 212°F. It is easy to convert between these two scales by remembering that 0°C = 32°F and that 5°C = 9°F. The Kelvin scale is based upon absolute zero (-273.15 °C), or 0 K.</p> <p>Molecular Interpretation of Temperature The concept that matter is made up of atoms in continual random motion is called the kinetic theory. In an ideal gas, there are a large number of molecules moving in random directions at different speeds, the gas molecules are far apart, the molecules interact with one another only when they collide, and collisions between gas molecules and the wall of the container are assumed to be perfectly elastic. The average translational kinetic energy of molecules in a gas is directly proportional to the absolute temperature</p> $KE_{av} = 1/2 mv_{av}^2 = 3/2 kT$ <p>where T is the temperature in Kelvin and k is Boltzmann's constant</p> $k = 1.38 \times 10^{-23} \text{ J/K}$ <p>The relationship between Boltzmann's constant (k), Avogadro's number (N), and the gas constant (R) is given by:</p> $k = R/N$	<p>Particle speed and temp.</p> <p>Thermo. Equilibrium</p> <p>Ideal Gas laws</p> <p>Sources of radiation</p> <p>PV=nRT</p>

<p>Internal or Thermal Energy(symbol is U; unit is J)</p> <p>sum of all the energy an object possesses; it cannot be measured; only changes in internal energy can be determined</p> <p>The kinetic theory can be used to clearly distinguish between temperature and thermal energy. Temperature is a measure of the average kinetic energy of individual molecules. Thermal energy refers to the total energy of all the molecules in an object.</p> <p>Heat(symbol is Q; SI unit is Joule)</p> <p>amount of thermal energy transferred from one object to another due to temperature differences (heat flows from a hot to a cold body).</p> $Q = m c \Delta T$ <p>where m is mass in kg ; c is specific heat of the material</p> $\Delta T = T_f - T_i \text{ in } ^\circ\text{C}$ <p>Specific heat (c) (also referred to as heat capacity): a characteristic of a material; the amount of energy (measured in Joules) that must be added to raise the temperature of one kilogram of the material one degree Celcius or one Kelvin</p> <p>Specific of heat of water: $c = 4180 \text{ J/kg K}$ (at a temperature of 15°C and a pressure of 1 atmosphere). Please note, the units J/kg K are the same as $\text{J/kg } ^\circ\text{C}$.</p> <p>Mesurement of heat capacity (c): In an experiment, a substance of known mass (m) is heated over a period of time such that the total amount of heat added (Q) is measured along with the known difference in temperature (ΔT), the specific heat capacity can then be found by:</p> $c = \frac{\Delta Q}{m \Delta T}$ <p>Energy transfer mechanisms:</p> <ol style="list-style-type: none"> 1. conduction (solids)-KE transfer due to collisions of particles; heat transfer occurs only when there is a difference in temperature Thermal Conductivity It is found experimentally that the heat flow per unit of time ($\Delta Q/\Delta t$)is proportional to the corss-sectional area of the object (A), the distance (d) between the two ends of the object, the temperatures of each end of the object (T_1 and T_2), and a proportionality constant, k, called the thermal conductivity of the substance. $\Delta Q/\Delta t = kA(T_1 - T_2)/d$. Substances that have large values for k are good thermal conductors. Those with low values for k are good insulators. 2. convection (fluids)-KE transfer due to movements of fluids over large distances caused by different densities at different temperatures 3. radiation-energy transfer through a vacuum. Conduction and convection require the presence of matter. Radiation consists of electromagnetic waves. <p>When different parts of an isolated system are at different temperatures, heat will flow from the part at a higher temperature to that at the lower temperature until they are at thermal equilibrium</p>		
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Law of heat exchange $Q_{\text{loss}} + Q_{\text{gain}} = 0$

the sum of heat losses and gains in a closed system is zero. When two bodies of unequal temperature are mixed, the cold body absorbs heat (raising its temperature) and the hot body loses heat (lowering its temperature) until an equilibrium temperature is reached. Thermal equilibrium exists when two objects that are in thermal contact with one another no longer affect each other's temperature.

Calorimeter : device used to measure changes in thermal energy.

Changes of State: The three most common states of matter are solid, liquid, and gas. When heat is added to a substance, one of two things can occur. The temperature can increase or the material can change to a different state. There is a fourth state of matter - plasma. A plasma is a state of matter in which atoms are stripped of their electrons. In a plasma, atoms are separated into their electrons and bare nuclei.

When a material changes phases from solid to liquid or from liquid to gas, a certain amount of energy is absorbed (in the reverse process, the heat is given off). Let's look at ice (a solid) at a temperature of -5° . When heat is added to ice, its temperature increases until it reaches 0° . At this point, ice begins to melt--it changes its state from a solid to a liquid. The temperature remains constant at 0° until all the ice has melted. Now we have water at 0° . As heat is added to the water, its temperature increases until it reaches 100° . At this point, the water begins to boil, changing its state from liquid to gas. The temperature remains constant at 100° until all the water boils, turning into steam. Now we have steam at 100° . If you continue to add heat, the temperature of the steam begins to increase.

Latent heat of fusion, (H_f or L_f)

amount of energy needed to change 1 kg of a substance from a solid to a liquid.

for water, $H_f = 333,000 \text{ J/kg}$ ($333 \times 10^3 \text{ J/kg}$) or $3.33 \times 10^5 \text{ J/kg}$

Latent heat of vaporization,(H_v or L_v)

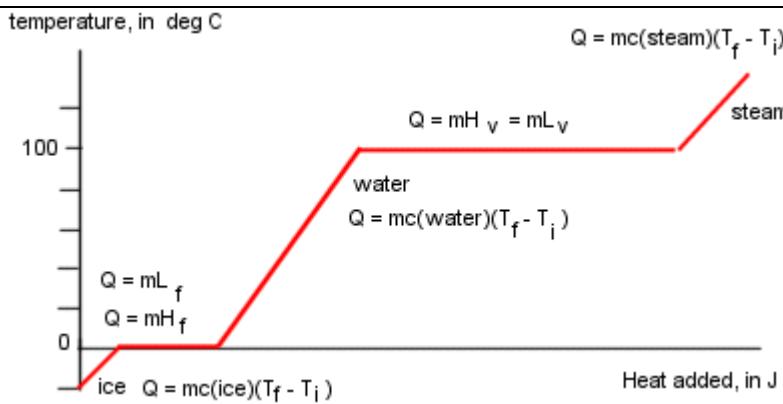
amount of energy needed to change 1 kg of a substance from a liquid to a gas.

for water, $H_v = 2,260,000 \text{ J/kg}$ K (or $2.26 \times 10^6 \text{ J/kg}$) or $22.6 \times 10^5 \text{ J/kg}$

If energy is added to a system heating it and causing an increase in temperature, energy is positive; if energy is removed from a system cooling it and causing a decrease in temperature, energy is negative. If energy is added to a system causing a change in the state of matter from a solid to a liquid or from a liquid to a solid, that energy is positive. If energy is removed from a system causing a change in the state of matter from a gas to a liquid or from a liquid to a solid, that energy is negative. At a phase change, the amount of heat given off or absorbed is found using:

$$Q = m H \text{ or } Q = mL \text{ (where L is the latent heat)}$$

where m is mass in kg and H is heat of transformation. No temperature change occurs at a phase change.



Example: How much heat is added to 10 kg of ice at -20°C to convert it to steam at 120°C?

Evaporation can be explained in terms of the kinetic theory. The fastest moving molecules in a liquid escape from the surface, decreasing the average speed of those remaining. When the average speed is less, the absolute temperature is less. Thus evaporation, the escaping of the fastest moving molecules from the surface of a liquid, is a **cooling process**.

Ideal Gas Law The volume of a gas is proportional to the number of moles of the gas, n . The volume varies inversely with the pressure. The pressure is proportional to the absolute temperature of the gas. Combining these relationships yields the following equation of state for an ideal gas,

$$PV = nRT = (m/M)RT$$

Where T is measured in Kelvin and R is the ideal gas constant, $R = 8.314 \text{ J/mol K}$
Characteristics of an Ideal Gas:

1. An ideal gas consists of a large number of gas molecules occupying a negligible volume.
2. Ideal gas molecules have random motion.
3. Ideal gas molecules undergo elastic collisions with the walls of the container and with other gas molecules.
4. The temperature of an ideal gas is proportional to the kinetic energy of the gas molecules.

IB Problem Set

1. Thermal energy is transferred through the glass windows of a house mainly by
- A. conduction.
 - B. radiation.
 - C. conduction and convection.
 - D. radiation and convection.

(1)

2. Which of the following correctly describes the changes in the kinetic energy of the molecules and the potential energy of the molecules as a liquid changes phase to a gas?

	kinetic energy of the molecules	potential energy of the molecules
A.	no change	increases
B.	no change	no change
C.	increases	increases
D.	increases	no change

(1)

3. Temperature is the **only** property that determines

- A. the total internal energy of a substance.
- B. the phase (state) of a substance.
- C. the direction of thermal energy transfer between two bodies in thermal contact.
- D. the process by which a body loses thermal energy to the surroundings.

(1)

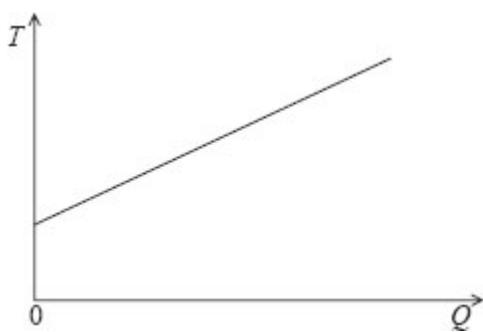
4. A solid is at an initial temperature of 500 K. The solid is heated so that its temperature rises by 50 K.

What are the initial temperature and the temperature rise of the solid, as measured on the Celsius scale of temperature?

	initial temperature	temperature rise
A.	227°C	50°C
B.	227°C	323°C
C.	773°C	50°C
D.	773°C	323°C

(1)

5. The specific heat capacity c of a solid block of mass m is determined by heating the block and measuring its temperature. The graph below shows the variation of the temperature T of the block with the thermal energy Q transferred to the block.



The gradient of the line is equal to

A. $\frac{c}{m}$.

B. $\frac{m}{c}$.

C. mc .

D. $\frac{1}{mc}$.

(1)

6. When the volume of a fixed mass of an ideal gas is reduced at constant temperature, the pressure of the gas increases.

This pressure increase occurs because the atoms of the gas

A. collide more frequently with each other.

B. collide more frequently with the walls of the containing vessel.

C. are spending more time in contact with the walls of the containing vessel.

D. are moving with a higher mean speed.

(1)

7. The kelvin temperature of an object is a measure of

A. the total energy of the molecules of the object.

B. the total kinetic energy of the molecules of the object.

C. the maximum energy of the molecules of the object.

D. the average kinetic energy of the molecules of the object.

(1)

8. (a) A small lump of ice (a hailstone) at 0°C falls to the Earth's surface. When the hailstone hits the surface, all of the kinetic energy of the hailstone is transferred to thermal energy in the ice. Calculate the minimum speed of the hailstone so that it just melts when it hits the surface. The specific latent heat of fusion of ice is 340 kJ kg^{-1} .

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(3)

- (b) By reference to your answer in (a), suggest whether hailstones are likely to melt on hitting the Earth's surface.

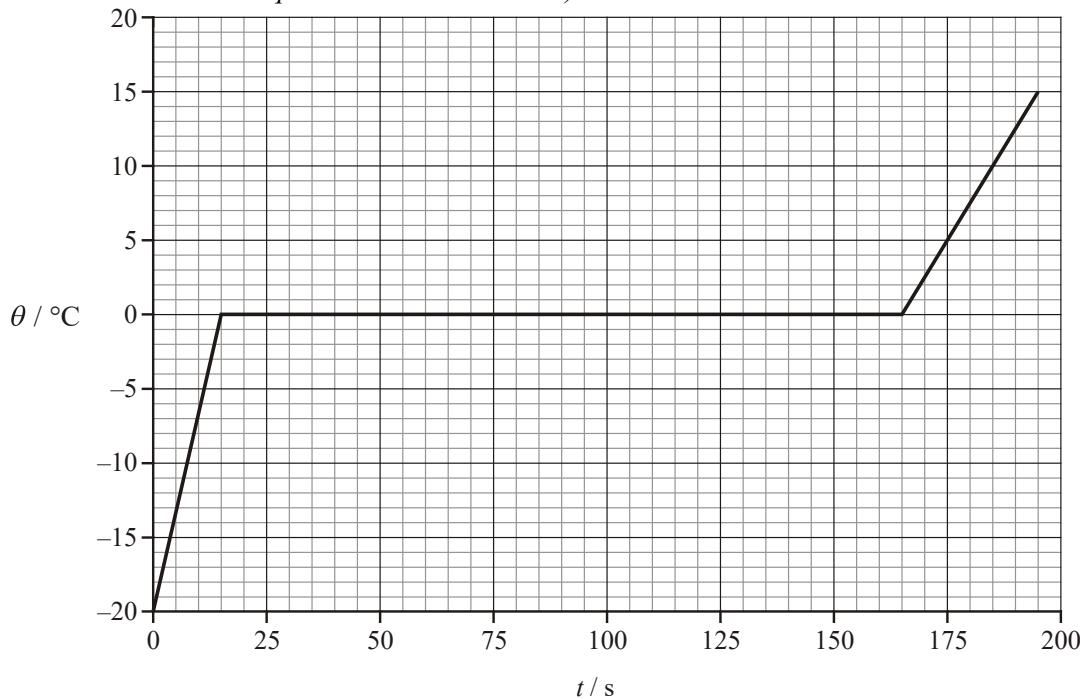
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(2)

(Total 5 marks)

9. A quantity of crushed ice is removed from a freezer and placed in a calorimeter. Thermal energy is supplied to the ice at a constant rate. To ensure that all the ice is at the same temperature, it is continually stirred. The temperature of the contents of the calorimeter is recorded every 15 seconds.

The graph below shows the variation with time t of the temperature θ of the contents of the calorimeter.
(Uncertainties in the measured quantities are not shown.)



- (a) On the graph above, mark with an X, the data point on the graph at which all the ice has just melted.
(b) Explain, with reference to the energy of the molecules, the constant temperature region of the graph.

(1)

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(3)

The mass of the ice is 0.25 kg and the specific heat capacity of water is $4200 \text{ J kg}^{-1} \text{ K}^{-1}$.

- (c) Use these data and data from the graph to
(i) deduce that energy is supplied to the ice at the rate of about 530 W.

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(3)

- (ii) determine the specific heat capacity of ice.

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(3)

- (iii) determine the specific latent heat of fusion of ice.

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(2)
(Total 12 marks)

10. Temperature and thermal energy

- (a) Outline how a temperature scale is constructed.

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(2)

- (b) Discuss why even an accurate thermometer may affect the reliability of a temperature reading.

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(2)

- (c) (i) Define *specific heat capacity*.

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(2)

- (ii) The table below gives data for water and ice.

specific heat capacity of water	4.2 kJ kg ⁻¹ K ⁻¹
specific latent heat of fusion of ice	330 kJ kg ⁻¹

A beaker contains 450 g of water at a temperature of 24°C. The thermal (heat) capacity of the beaker is negligible and no heat is gained by, or lost to, the atmosphere. Calculate the mass of ice, initially at 0°C, that must be mixed with the water so that the final temperature of the contents of the beaker is 8.0°C.

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(4)

- (d) (i) Distinguish between evaporation and boiling.

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(2)

- (ii) Explain, in terms of molecular behaviour, why boiling involves a transfer of thermal energy with no change in temperature.

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(3)
(Total 15 marks)