Past-paper walk-through

Thermal Energy Transfer and Equilibrium ▪ 9.3

eXercise

Questions in this set

- 2026 Q1
- 2025 Q2
- 2021 Q1
- 2019 Q3

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 1

2026 ▪ Q1

Part A

A sample of n moles of a monatomic, ideal gas is in a large, sealed, thermally conducting container with fixed volume. A small sphere of mass m_S is in the container. The volume of the sphere is much less than the volume of the container.

The gas is initially in State X with pressure P and volume V, as shown in Figure 1.

[Figure 1: A sealed square container labelled "Gas n, P, V" with a small sphere labelled "Sphere m_S" inside near the bottom, connected by an arrow from the "Sphere" label to a dot inside the container. Caption below the figure: "State X". Note: Figure not drawn to scale.]

The sphere is initially in thermal equilibrium with the gas. The gas undergoes a heating process until the gas is in State Y with pressure $3P$ and the sphere is again in

Question 1

thermal equilibrium with the gas. The total energy transferred to the sphere during the heating process is Q_S.

(i) The graph in Figure 2 represents the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State X. On Figure 3, **sketch** a curve that could represent the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State Y.

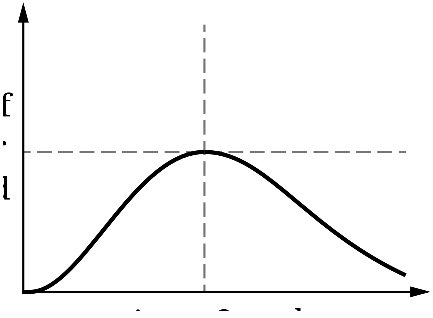
[Figure 2: Axes labelled “Number of Atoms per Unit Speed” (vertical) vs. “Atom Speed” (horizontal), captioned “State X”. A Maxwell-Boltzmann-type curve starts at the origin, rises to a single rounded peak (marked with a dashed horizontal line to the peak height and a dashed vertical line to the corresponding atom speed), then decreases back toward the horizontal axis at higher speeds.]

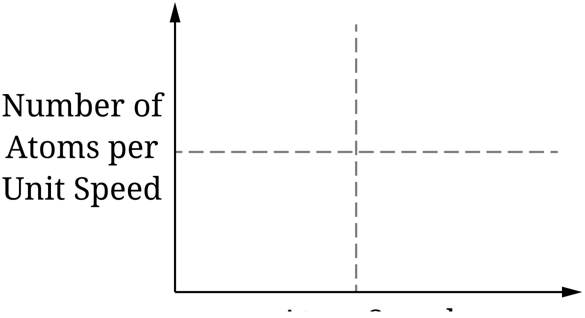
[Figure 3: Blank axes labelled “Number of Atoms per Unit Speed” (vertical) vs. “Atom Speed” (horizontal), captioned “State Y”, with the same dashed reference lines

Question 1

(horizontal at the State X peak height, vertical at the State X peak speed) shown for reference, but no curve drawn — to be sketched by the student.]
(ii) **Derive** an expression for the change ΔT in temperature of the gas for the heating process that the gas undergoes as the gas changes from State X to State Y. Express your answer in terms of n, P, V, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.
(iii) **Derive** an expression for the specific heat c_S of the sphere. Express your answer in terms of n, m_S, P, V, Q_S, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 1





Question 1

2026 ▪ Q1

Part A

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The sphere is initially in thermal equilibrium with the gas. The gas undergoes a heating process until the gas is in State Y with pressure $3P$ and the sphere is again in thermal equilibrium with the gas. The total energy transferred to the sphere during the heating process is Q_S.

(b) Part B

Question 1

An insulated container is filled with a liquid of mass m_L and specific heat c_L. The original sphere is submerged in the liquid. The sphere has mass m_S, where $m_S < m_L$, and specific heat c_S, where $c_S < c_L$. The initial temperature of the sphere is greater than the initial temperature of the liquid. Later, the liquid and the sphere reach thermal equilibrium. The absolute values of the changes in the temperatures of the liquid and the sphere are $|\Delta T_L|$ and $|\Delta T_S|$, respectively.
Indicate whether $|\Delta T_S|$ is greater than, less than, or equal to $|\Delta T_L|$. Include one of the following relationships in your response.
- $|\Delta T_S| > |\Delta T_L|$ - $|\Delta T_S| < |\Delta T_L|$ - $|\Delta T_S| = |\Delta T_L|$
Justify your answer. Your justification may include expressions/equations but must include conceptual reasoning beyond algebraic solutions.

Question 2

2025 ▪ Q2

A sample of a monatomic ideal gas is sealed in a thermally conducting container by a movable piston of mass M and area A. The container is in a large water bath that is held at a constant temperature T_0. The piston is free to move with negligible friction. At the instant shown, the gas is in thermal equilibrium with the water bath, the piston is at rest, and the gas occupies volume V_0. The pressure of the air above the piston is P_{atm}.

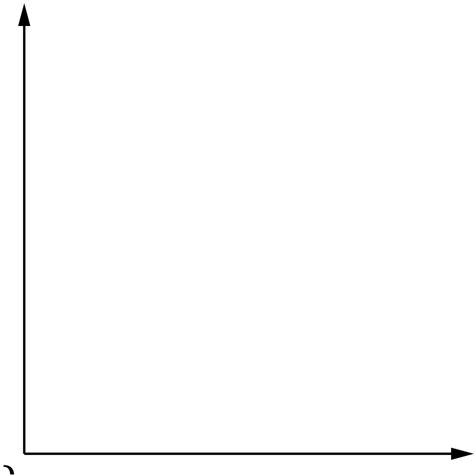
[Figure: Side View. A container (open at the top) sits inside a larger tank labeled "Water Bath". Inside the container, a horizontal bar labeled "Piston" sits partway up, with the region below it labeled "Gas" and the region above it open to the air. The tank surrounding the container is filled with the water bath.]

Note: Figure not drawn to scale.

Question 2

(a) On the dot shown, representing the piston, **draw** and **label** the forces that are exerted on the piston. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.
[Figure: a single dot representing the piston, for the student to draw force vectors from.]

Question 2



Question 2

2025 ▪ Q2

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Note: Figure not drawn to scale.

(b) Derive an expression for the internal energy of the gas in terms of M, A, V_0, P_{atm}, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 2

2025 ▪ Q2

A sample of a monatomic ideal gas is sealed in a thermally conducting container by a movable piston of mass M and area A. The container is in a large water bath that is held at a constant temperature T_0. The piston is free to move with negligible friction. At the instant shown, the gas is in thermal equilibrium with the water bath, the piston is at rest, and the gas occupies volume V_0. The pressure of the air above the piston is P_{atm}.
[Figure: Side View. A container (open at the top) sits inside a larger tank labeled "Water Bath". Inside the container, a horizontal bar labeled "Piston" sits partway up, with the region below it labeled "Gas" and the region above it open to the air. The tank surrounding the container is filled with the water bath.]

Note: Figure not drawn to scale.

(c) A block, also of mass M, is placed on the piston at time $t = t_0$ and is slowly lowered. The piston comes to rest at $t = t_f$ when the block is completely released.

Question 2

On the axes provided, **sketch** the expected relationship between the pressure P and volume V of the gas for the thermodynamic process that the gas undergoes during time interval $t_0 \leq t \leq t_f$. **Draw** an arrow on your sketch to represent the direction of the thermodynamic process.
[Graph: axes with vertical axis P (origin labeled O) and horizontal axis V; both axes unlabeled with values — a blank grid for the student to sketch the P-V process and direction arrow.]

Question 2

2025 ▪ Q2

A sample of a monatomic ideal gas is sealed in a thermally conducting container by a movable piston of mass M and area A. The container is in a large water bath that is held at a constant temperature T_0. The piston is free to move with negligible friction. At the instant shown, the gas is in thermal equilibrium with the water bath, the piston is at rest, and the gas occupies volume V_0. The pressure of the air above the piston is P_{atm}.
[Figure: Side View. A container (open at the top) sits inside a larger tank labeled “Water Bath”. Inside the container, a horizontal bar labeled “Piston” sits partway up, with the region below it labeled “Gas” and the region above it open to the air. The tank surrounding the container is filled with the water bath.]

Note: Figure not drawn to scale.

(d) With the block still on the piston, the temperature of the water bath is changed to a new constant temperature T_{new}. The gas occupies the original volume V_0 when the sample of gas and the water bath come to thermal equilibrium.

Question 2

Indicate whether T_{new} is greater than, less than, or equal to T_0.

________ $T_{new} > T_0$

________ $T_{new} < T_0$

________ $T_{new} = T_0$

Briefly **justify** your answer by referencing at least one feature of your answers to parts A, B, or C.

Solution 2

(a)

Mark scheme

- Three forces act on the piston, each drawn as a distinct arrow starting on the dot: F_g (gravity/weight of the piston) points downward; F_atm (force of the atmosphere pushing down on the top of the piston) points downward; F_gas (force of the gas pushing up on the bottom of the piston) points upward. All three arrows must be correctly labeled with the correct direction (F_g down, F_atm down, F_gas up) to earn full credit – one point per correctly drawn/labeled force.

Solution 2

(b) Mark scheme

- Derive U starting from Newton's second law for the piston in equilibrium and the ideal gas law. $a_{sys} = sum(F)/m_{sys} = F_{net}/m_{sys}$, and since the piston is in equilibrium sum(F) = 0. Using $P = F_{perp}/A$ on the piston: $P*A - P_{atm}*A - F_g = 0$, i.e. $P*A - P_{atm}*A - Mg = 0$, so $P - P_{atm} - Mg/A = 0$, giving $P = P_{atm} + Mg/A$. Then using $U = (3/2)nRT$ together with $PV = nRT$ gives $U = (3/2)PV$. Substituting the pressure found above and the original volume V0: $U = (3/2)*(P_{atm} + Mg/A)*V0$. Full credit requires: (1) a multistep derivation that includes $U=(3/2)nRT$ (or $U=(3/2)N*kB*T$), $PV=nRT$ (or $PV=N*kB*T$), and Newton's second law / $P=F_{perp}/A$, or equivalent relevant equations; (2) correctly relating U to PV, e.g. $U=(3/2)PV$; (3) a correct expression for the

Solution 2

absolute pressure P = P_atm + Mg/A (or consistent with an incorrect force diagram from part A); (4) the final expression for U consistent with that pressure, e.g. U = (3/2)(P_atm + Mg/A)*V0. A correct isolated final expression alone earns the last three points.

Solution 2

(c) Mark scheme

- On the P-V axes, sketch a curve/line connecting a point in the lower-right region of the diagram (larger V, smaller P – the initial state before the block's weight is fully added) to a point in the upper-left region (smaller V, larger P – the final state once the block is completely resting on the piston), i.e. the gas is compressed as pressure increases. The curve should be concave up. Draw an arrow on the curve pointing from the larger-volume/lower-pressure point toward the smaller-volume/higher-pressure point (i.e., from lower-right to upper-left), showing volume decreasing (or pressure increasing) as the process proceeds. Full credit requires: (1) a line/curve connecting lower-right to upper-left; (2) the curve

Solution 2

is concave up; (3) an arrow indicating volume decreasing / pressure increasing along the curve.

Solution 2

(d) Mark scheme

- $T\_new > T0$ (or an indication consistent with incorrect features of parts A, B, or C). Justification: with the block's weight now supported by the gas but the gas back at the original volume V0, the pressure of the gas must be greater than the original pressure (to support the added weight of the block in equilibrium) – e.g. using the part B derivation, since $U = (3/2)*P*V$ and $V = V0$ is unchanged while P has increased (due to the block's added weight, $P = P\_atm + Mg/A$ becomes larger with the extra weight), the internal energy – and hence temperature – increases. Therefore $T\_new > T0$. (Any justification consistent with the student's own diagram in part A, derivation in part B, or graph in part C that correctly relates a pressure increase at equal volume, or a volume increase at equal

Solution 2

pressure, to a temperature increase earns full credit; a justification consistent with an incorrect earlier part is also accepted for the reasoning point.)

Question 1

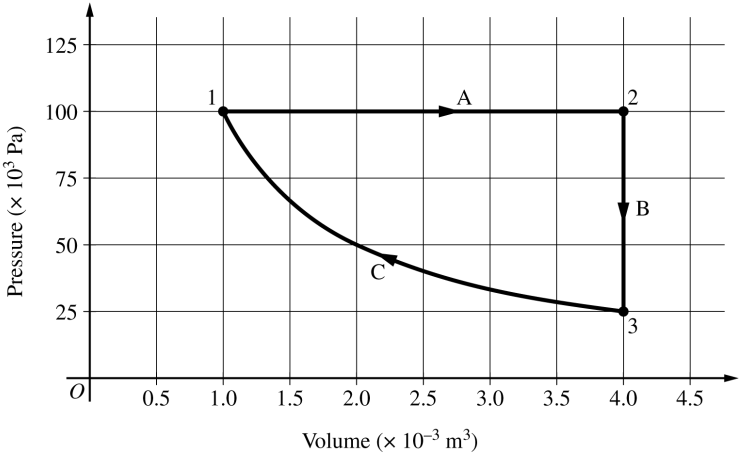
2021 ▪ Q1

A sample of ideal gas is taken through the thermodynamic cycle shown above. Process C is isothermal.
[Graph: Pressure ($\times 10^3$ Pa) on the y-axis (gridlines at 25, 50, 75, 100, 125) vs. Volume ($\times 10^{-3}$ m^3) on the x-axis (gridlines at 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5). State 1 is at approximately $(1.0, 100)$. Process A is a horizontal arrow from state 1 at $(1.0, 100)$ to state 2 at $(4.0, 100)$, pointing right. Process B is a vertical arrow from state 2 at $(4.0, 100)$ down to state 3 at $(4.0, 25)$, pointing down. Process C is a curve from state 3 at $(4.0, 25)$ back to state 1 at $(1.0, 100)$, passing through a labeled point near $(2.1, 42)$, with an arrow pointing up and to the left toward state 1.]
(a) Consider the portion of the cycle that takes the gas from state 1 to state 3 by processes A and B. Calculate the magnitude of the following and indicate the sign of any nonzero quantities.

Question 1

- The net change in internal energy ΔU of the gas - The net work W done on the gas - The net energy Q transferred to the gas by heating

Question 1



125
100
75
50
25
Pressure (× 10³ Pa)
O
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Volume (× 10⁻³ m³)
1
2
3
A
B
C

Question 1

Sample 2 State 2	Sample 3 State 3

Question 1

2021 ▪ Q1

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(b)(i) Consider isothermal process C.

Question 1

Compare the magnitude and sign of the work W done on the gas in process C to the magnitude and sign of the work in the portion of the cycle in part (a). Support your answer using features of the graph.

(b)(ii) Explain how the microscopic behavior of the gas particles and changes in the size of the container affect interactions on the microscopic level and produce the observed pressure difference between the beginning and end of process C.

Question 1

2021 ▪ Q1

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(c) Consider two samples of the gas, each with the same number of gas particles. Sample 2 is in state 2 shown in the graph, and sample 3 is in state 3 shown in the graph. The samples are put into thermal contact, as shown above.

Question 1

[Diagram: two adjacent boxes labeled "Sample 2 State 2" and "Sample 3 State 3", placed in contact with each other.]
Indicate the direction, if any, of energy transfer between the samples. Support your answer using macroscopic thermodynamic principles.

Solution 1

(a) Mark scheme

- $\Delta U = 0$ J (temperatures at states 1 and 3 are equal, so internal energy is unchanged). Net work done ON the gas: $W = -P\Delta V = -(100\times10\hat{}3$ Pa)($3\times10\hat{}$-3 m^3) $= -300$ J (volume increases from $1\times10\hat{}$-3 m^3 to $4\times10\hat{}$-3 m^3 at constant pressure $100\times10\hat{}3$ Pa; answer must show the negative sign or state the work is done BY the gas). Applying the first law $\Delta U = Q + W$ with $\Delta U=0$ and $W=-300$ J gives $Q = +300$ J transferred TO the gas by heating (or equivalently, showing $|Q|=|W|$ with opposite sign). Award 1 point each for: $\Delta U=0$; $W=-300$ J with correct sign/units; correctly using the first law to obtain Q.

Solution 1

(b)(i)

Mark scheme

- The magnitude of the work in isothermal process C is LESS than in part (a) ($|W\_C| < 300$ J), because there is less area under the P–V curve for process C than for the combined processes A+B (1 point, must reference area under the curve). The sign is OPPOSITE that of part (a): in part (a) the volume increased so W (on gas) was negative; in process C the volume decreases (shown by the arrow direction on the graph), so the work done ON the gas is POSITIVE (1 point, must reference the sign of ΔV or the direction of the process on the graph).

Solution 1

(b)(ii) Mark scheme

- Process C is isothermal, so temperature is constant and the average kinetic energy/average speed of the gas molecules does NOT change (1 point). The volume of the container decreases, which changes something relevant to the collision rate — acceptable references include volume, surface area, or time to traverse the container (1 point). With unchanged molecular speed but decreased volume, molecules collide with the container walls more frequently, producing more net force per unit area on the walls — the response must explicitly refer to collisions with the walls (1 point). Example: temperature (and thus molecular speed) is unchanged; smaller volume increases the density of gas molecules, so they collide with the walls more often, giving more net force due to wall collisions

Solution 1

(and the smaller volume also means less wall surface area), producing higher pressure.

Solution 1

(c)

Mark scheme

- The temperature of the gas in state 2 (sample 2) is HIGHER than the temperature in state 3 (sample 3), as read from their positions on the P–V diagram/isotherms (1 point). When placed in thermal contact, energy spontaneously flows from the hotter sample to the cooler sample, so energy transfers from sample 2 to sample 3 (1 point, must reference the macroscopic principle that heat flows hot$\rightarrow$cold).

Question 3

2019 ▪ Q3

[Figure: A diagram of an apparatus. From top to bottom: a block labeled "Ice" sits on top of a layer labeled "Slab of Plastic"; below that is a dark rectangle labeled "Hot Plate" on the left with "Container of Boiling Water" labeled to its left; a small container to the right labeled "Water Collected" catches a drip from the slab, shown with a shaded region at the bottom of that container.]

A group of students use the apparatus shown above to determine the thermal conductivity of a certain type of plastic. A hot plate is used to keep water in a container boiling at a temperature of $100°$C. They place a slab of the plastic with area 0.025 m^2 and thickness 0.010 m above the container so that the bottom surface of the slab is at a temperature of $100°$C. They put a large block of ice with temperature $0°$C on top of the plastic slab. Some of the ice melts, and the students measure the amount of water collected during a time Δt. The students correctly calculate the

Question 3

amount of energy Q delivered to the ice and thus determine $Q/\Delta t$. They repeat this experiment several times, each time adding an identical slab to increase the total thickness L of plastic. Their results are shown in the table below.

Energy flow rate $Q/\Delta t$ (J/s)	97	53	31	27	18
Total thickness of plastic L (m)	0.010	0.020	0.030	0.040	0.050

(a)(i) The students want to create a graph to yield a straight line whose slope could be used to calculate the thermal conductivity of the plastic.

Label the axes below to indicate a pair of quantities that could be graphed to yield a straight line. Include units for the quantities.

[Figure: A blank grid with axes to be labeled by the student, gridlines shown but no data plotted, no axis labels or scale provided.]

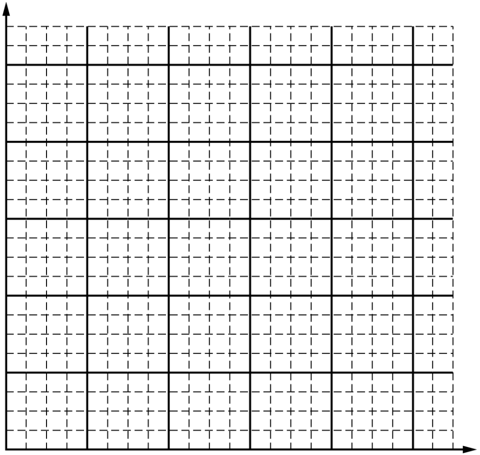
(a)(ii) On the grid on the previous page, create a linear graph using the values for the quantities indicated in part (a)(i). Be sure to do the following.

Question 3

- Add to the data table the values of any quantities to be plotted that are not already given.
- Scale the axes.
- Plot the data from the table.
- Draw a line that best represents the data.

(a)(iii) Use the graph to calculate the thermal conductivity of the plastic.

Question 3



Question 3

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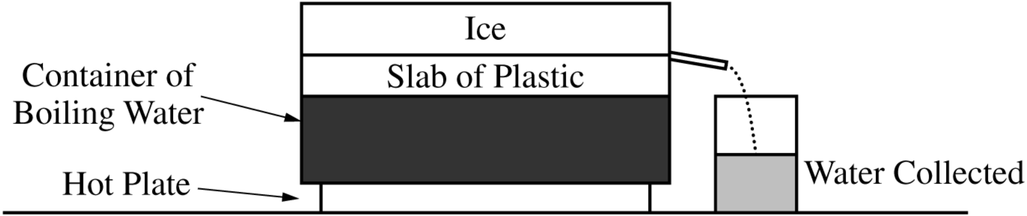
Question 3


Ice
Slab of Plastic
Container of
Boiling Water
Hot Plate
Water Collected

Question 3

2019 ▪ Q3

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Question 3

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(b) Indicate one potential problem with the setup that could lead to an experimental value for the thermal conductivity that is different from the actual value. Use physics principles to explain the effect this problem could have on the experimental value.

Question 3

2019 ▪ Q3

[Figure: A diagram of an apparatus. From top to bottom: a block labeled "Ice" sits on top of a layer labeled "Slab of Plastic"; below that is a dark rectangle labeled "Hot Plate" on the left with "Container of Boiling Water" labeled to its left; a small container to the right labeled "Water Collected" catches a drip from the slab, shown with a shaded region at the bottom of that container.]

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(c) The rectangle below represents a side view of the plastic slab. Draw a single arrow on the diagram representing the direction of the net flow of energy through the plastic. [Figure: A blank rectangle labeled "Plastic Slab" at the bottom right, representing a side view of the slab, with no arrow drawn.]

Question 3

2019 ▪ Q3

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(d) Describe what occurs in the plastic at the microscopic level that explains the energy flow you indicated in part (c).

Question 3

2019 ▪ Q3

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Question 3

$Q/\Delta t$. They repeat this experiment several times, each time adding an identical slab to increase the total thickness L of plastic. Their results are shown in the table below.

Energy flow rate $Q/\Delta t$ (J/s)	97	53	31	27	18
Total thickness of plastic L (m)	0.010	0.020	0.030	0.040	0.050

(e) An extra plastic slab sits on a wood surface, with both the plastic slab and the wood surface at room temperature. A student touches each and finds that the plastic slab feels cooler than the wood surface. Explain what causes this observation.

Solution 3

(a)(i)

Mark scheme

- From $\dfrac{Q}{\Delta t} = \dfrac{kA\Delta T}{L}$, plotting $Q/\Delta t$ (J/s) on the vertical axis against $1/$thickness (units 1/m) on the horizontal axis yields a straight line through the origin with slope $kA\Delta T$. (1 pt for labeling the axes with two quantities that produce a linear graph, including units.)

Solution 3

(a)(ii) Mark scheme

- Complete the table with $1/$thickness values (100, 50, 33.3, 25, 20 m^{-1} for thicknesses 0.01–0.05 m, already shown), then plot $Q/\Delta t$ (97, 53, 31, 27, 18 J/s) against $1/$thickness: points at (100,97), (50,53), (33.3,31), (25,27), (20,18). Scale both axes linearly so the data spans at least half of each axis, plot the points accurately, and draw a best-fit straight line through the data (passing close to the origin, e.g., through approximately (20,20) and (100,100)). Points: 1 pt for scaling the axes linearly so the data extends over at least half of each axis; 1 pt for accurately plotting the data; 1 pt for a best-fit line/curve that fits the trend in the data.

Solution 3

(a)(iii)

Mark scheme

- Using two points on the best-fit line, e.g., (20,20) and (100,100): slope $= \dfrac{(80-20)\ \mathsf{J/s}}{(80-20)\ \mathsf{m}^{-1}} = 1.0\ \mathsf{J\cdot m/s}$ (1 pt for a correct method of calculating the slope using points on the best-fit line). Since slope $= kA\Delta T$, $k = \text{slope}/(A\Delta T) = 1.0\ \mathsf{J\cdot m/s}/\left[(0.025\ \mathsf{m}^2)(100°\mathsf{C})\right] = 0.40\ \mathsf{J/(s\cdot m\cdot °C)}$ (1 pt for determining the thermal conductivity k, with or without units, using the slope found above).

Solution 3

(b) Mark scheme

- Example 1: The setup allows energy to be transferred to the ice from the surrounding air (not solely through the plastic slab from below), so the measured $Q/\Delta t$ includes extra energy that did not pass through the plastic, making the experimental value of k too large. Example 2 (also accepted): The setup allows energy to be lost out the sides of the plastic slab, so the measured $Q/\Delta t$ does not include all the energy that actually passed through the slab, making the experimental value of k too small. Points: 1 pt for any valid indication of an additional thermal interaction with the environment; 1 pt for a reasonable physics explanation of how the added/lost energy changes the experimental conductivity value.

Solution 3

(c)

Mark scheme

- A single arrow drawn pointing toward the top of the page — energy flows by conduction from the hot (100°C) bottom surface, in contact with the boiling water, up through the plastic slab to the cooler (0°C) ice on top. (1 pt for drawing an arrow toward the top of the page.)

Solution 3

(d)

Mark scheme

- At the bottom (hot) surface of the plastic, particles have a higher temperature and thus greater average kinetic energy, so they vibrate faster (1 pt). These faster-vibrating particles collide with neighboring particles above them, transferring kinetic energy from faster to slower particles; this particle-to-particle energy transfer propagates upward through the slab until it reaches the cooler top surface, e.g., "Energy absorbed at the lower surface makes particles jiggle faster; they jiggle particles above them, and so forth until energy reaches the other side" (1 pt).

Solution 3

(e) Mark scheme

- Even though the plastic slab and the wood surface are both at room temperature, they have different thermal conductivities (or: energy is transferred into the plastic and into the wood from the hand at different rates). The plastic (higher thermal conductivity) conducts heat away from the warmer hand faster than the wood (lower thermal conductivity) does, so the plastic feels cooler to the touch even though both objects are actually at the same temperature. (1 pt for indicating the slab and wood have different thermal conductivities or that energy is transferred at different rates, with no incorrect statements.)