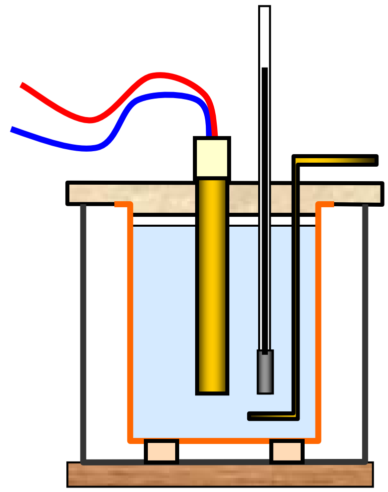
Episode 607: Specific heat capacity

Energy must be supplied (or rejected) to increase (or decrease) the temperature of a material. Here is how to calculate how much.



(resourcefulphysics.org)

Summary

Discussion: Energy and change of phase. (15 minutes)

Student experiment: Measuring specific heat capacities. (40 minutes)

Worked example: Calculation involving *c*. (10 minutes)

Student questions: Calculations. (30 minutes)

Discussion:

Energy and change of phase

Up until this point the link between ‘internal energy’ and temperature has been qualitative, except for gases. In order to extend the discussion to solids and liquids we need to get more quantitative in two ways. One is to discuss how much the temperature of a body changes when its internal energy in increased by a certain amount. The other is to ask what happens when a substance *changes phase* from a solid to a liquid or liquid to a gas.

Start by introducing the equation for specific heat capacity *c* (SHC) and defining the terms. The word *specific* is an old fashioned way of saying ‘per unit mass’. Work through a simple calculation.

Understanding this equation will help solidify ideas about temperature and energy and how they differ. A possible analogy was supplied by Richard Feynman. He suggested thinking of heat energy as being like water, and temperature as wetness. A towel can have different amounts of fluffiness, so take more or less water to make it wet. When we dry ourselves, we dry until the towel is as wet as we are (“same temperature”).

The anomalously large SHC of water should also be discussed as it is particularly important for the development and maintenance of life on Earth.

NB nomenclature: there isn’t any agreed way to name c. Some use *specific thermal capacity,* others favour *specific heating capacity* to emphasise the fact that ‘heat’ is not an entity but a short hand name for a process (heating as oppose to working). Perhaps the most common is specific heat capacity.

Another source of confusion is treating *state* and *phase* as synonyms (as in changes of state / phase). Solids, liquids and gases are three of the different phases of matter (superfluids and plasmas are two others. NB Here, by a plasma, we mean an ionised gas, not a biological fluid). Thus melting, boiling etc are changes of phase. Each phase can exist in a variety of states depending upon e.g. the temperature and pressure. Thus the Ideal Gas Equation of *State*

PV = nRT summarises the physically possible combinations of P, V and T for n moles of the ideal gas.

Student experiment:

Measuring specific heat capacities

Students should carry out an experiment to measure the specific heat capacity of a solid and/or a liquid very soon after meeting the expression. There are a number of points to note here:

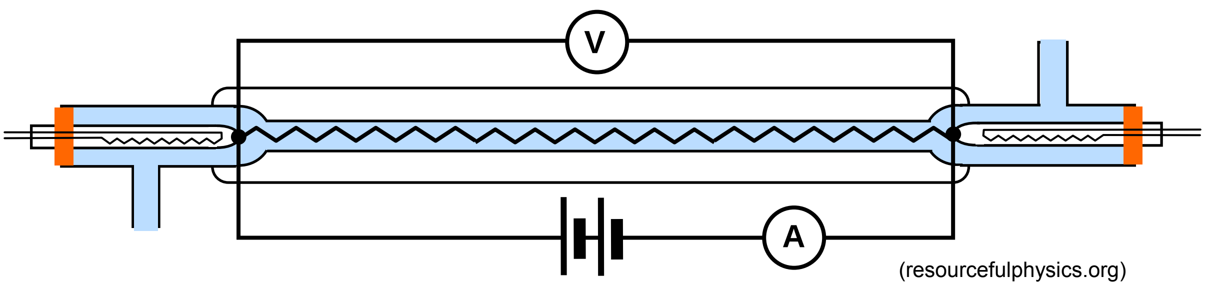
1. If specific heat capacity is constant, the temperature will rise at a uniform rate so long as the power input is constant and no energy is lost to the outside.
2. There are large potential heat losses if the substance is not well insulated. These can be accounted for but in most cases students will not do so quantitatively.
3. They should calculate their value and make a comparison with data book values. They should be able to think of a number of reasons why their value does not match that in the data book.

Several different methods of determining the SHC of liquids and solids are given in the links below. Choose those best suited to your pupils and available equipment.

TAP 607-1: Measuring the specific heat capacity of a metal

TAP 607-2: The specific heat capacity of water and aluminium

It is useful to compare electrical methods of measuring the specific heat capacity of a solid and liquid including the continuous flow calorimeter for a liquid.



TAP 607-3: Measurement of specific heat capacities

Worked example:

Calculation involving C

This example deals with the mixing of liquids at different temperatures.

1.5 l of water from a kettle at 90°C is mixed with a bucket of cold water (10 l at 10 °C) to warm it up for washing a car. Find the temperature of the mixed water, assuming no significant heat loss during the mixing. c of water = 4.2 kJ kg^{-1} $°C^{-1}$

Answer: If there is no heat loss and no work done then the total energy of the system at the end is the same as at the start. Working with temperature differences from 10°C we have:

Initial energy = m c ΔT = 1.5 $\times$ 4200 $\times$ (90-10) [as 1.5 l has mass 1.5 kg] = 504 kJ

This is the amount of energy available to raise the temperature of all 11.5 l of water. Hence:

$504 \times 10^3 = 11.5 \times 4200 \times (T-10)$ [where T is the final temperature]

T = 20.4°C.

You can invent similar problems using a mixture of substances – a hot brick in water for example. However, be careful to consider realistic situations where not too much is lost as steam.

Student questions:

Calculations

A range of questions involving specific heat capacity.

TAP 607-4: Specific heat capacity: some questions

TAP 607-5: Thermal changes

TAP 607- 1: Measuring the specific heat capacity of a metal

The value of the specific thermal capacity of a material tells us how much energy is needed to change the temperature of one kilogram of the material by 1 degree. It is an important measurement for engineers and physicists who work with any material that changes its temperature or is designed to retain thermal energy.

In this activity you will make measurements to calculate a value for specific thermal capacity and consider some of the uncertainties in the measurements you have made.

You will need

- ✓ 1 kg blocks for thermal capacity
- ✓ 12 V immersion heater (typically 60 W)
- ✓ thermometer, 0 – 100 °C
- ✓ power supply, 0 – 12 V rated to supply 6 A
- ✓ 4 mm leads
- ✓ two digital multimeters
- ✓ stopwatch

Basic experiment

1. Insert a thermometer and the immersion heater into their respective holes in the block. You may wish to drop a small amount of oil into the thermometer hole to improve the thermal contact between thermometer and block.
2. Allow the thermometer to reach thermal equilibrium and then write down the temperature.
3. Set up a suitable circuit that will enable you to measure the energy input to the heater.
4. Turn on the current, noting the time if you are measuring energy using an ammeter and a voltmeter to record power.
5. Energy = current × potential difference × time. Monitor and note the meter readings as the energy is supplied. They may change slightly as things warm up.
6. Allow the block to heat up by about 10 °C, then turn off the current and note the time again.
7. At this point, keep watching the thermometer. The temperature at the turn-off time is **not** the appropriate final temperature to record. What do you think **is** the appropriate final temperature?
8. Use $\Delta E = m\,c\,\Delta\theta$ to calculate the specific thermal capacity, c, of your block. Compare your answer with a data book value.
9. Was your calculated value of specific thermal capacity too high or too low? Which of the measurements you made is likely to be the one most in error? In which direction is it in error, and why might this be?

Slightly more sophisticated…

Energy losses are a problem in this experiment. The electrical energy measured going into the heater does not correspond exactly to the thermal energy actually delivered to the block itself (some of it goes to the immersion heater and to the surroundings) and so the temperature will increase less than you expect.

As a first improvement to the basic method, try cooling the block to about 5 °C below room temperature (stand it in cold water for a while) and then warm it to about 5 °C above room temperature.

Did this improve your value? How does this method help to reduce heat losses?

Outcomes

1. This experiment gives you a value for the specific thermal capacity of a metal. If others in your group have used different metals, compare your values. You may also have evaluated the specific thermal capacity for water. Is this value very different?
2. You have considered energy losses in this experiment and you may have worked hard to remove them. Generally, when devising your own experiments, try to be ingenious in removing or reducing unwanted effects.

Safety

Check the seals on the immersion heaters before use. Reject any that are obviously defective. In doubtful cases, any water which has entered during a precious activity can be removed by placing the heater in an oven for an hour at about 80 °C.

Practical advice

If you can provide a selection of different metals, it might be interesting to ask groups of students to use different blocks in order to compare results. The activity here assumes the use of an ammeter, voltmeter and stop-clock. Students using a joulemeter need only to take initial and final readings.

Some may still find setting up the electrical circuit demanding, and may need support.

It may be that the greatest source of error in this experiment is the lack of a smooth power supply. The meters do not read the correct average value of dc+ heavy ripple. If high current smoothing units are available they should be used. Better still would be 12 V car batteries.

Be safe

Impress on students the need to avoid running the immersion heaters outside the blocks, and not to cool them in water when hair-line cracks will draw water inside.

If 12 V car batteries are used, remember that they are often too heavy for one technician to lift.

Alternative approaches

A number of approaches may be used here depending on the abilities of the students. Certainly you should not feel constrained to use the proprietary blocks and immersion heaters if other equipment is already available. It might be possible with an able group to introduce a method of mixtures variant as a final piece of extension material but this would need careful treatment with a simpler method first.

Social and human context

The specific thermal capacity is an essential quantity to consider for any change of temperature. When materials are used for cooling purposes, for example, it is crucial to remove energy quickly and economically without the coolant changing its temperature too greatly. Water is, of course, ideal in this respect. But other materials are used too. In nuclear reactor technology, a variety of coolants are used to remove thermal energy from the reactor core, including liquid sodium. An additional property for reactor coolants is that they should not disturb the running of the reactor by absorbing neutrons. Hot water, close to boiling, when dropped on to the skin can cause great harm. It releases large quantities of energy into the tissues and, as every first-aider knows, the correct remedial treatment is to cool the affected part (i.e. to remove thermal energy from it) for a time of at least 500 s. This removes thermal energy from the underlying tissue as well. Storage heaters rely on the large mass and the high specific thermal capacity of the hot materials; the heater needs to retain the energy for a significant time for release into a room late into the day.

External reference

This activity is taken from Advancing Physics chapter 13, 220E

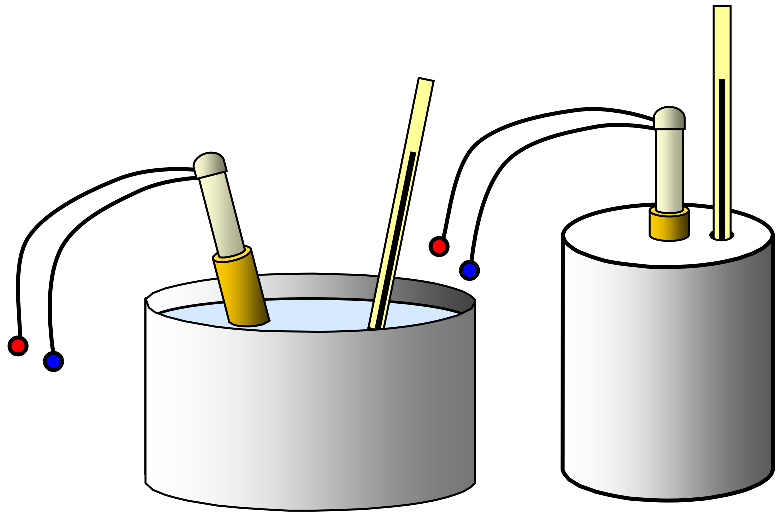
TAP 607- 2: The specific heat capacity of water and aluminium

This experiment is designed to measure the specific heat capacities of water and aluminium.

Before starting the experiment read through the instructions carefully.

You will need:

- ✓ 12 V immersion heater 60 W
- ✓ aluminium saucepan
- ✓ 1 kg block of aluminium
- ✓ thermometer
- ✓ 12 V power supply (6 A)
- ✓ stop clock
- ✓ balance
- ✓ 2 digital multimeters



What to do

1. Water

Put 1 kg of water in the saucepan and measure its temperature. Now hold the heater in your hand and switch on the power supply. When you feel the heater getting warm put it in the water and start the stop clock. After 10 minutes switch off the power supply, stir the water and take its temperature. Allow the heater to cool in air.

2. Aluminium

Put the thermometer in the small hole in the aluminium block. Switch on the heater and when it is warm put it in the large hole in the block and start the stop clock, having recorded the initial temperature of the block. After 10 minutes switch off the power supply and take the temperature of the block.

Safety

Check the seals on the immersion heaters before use. Reject any that are obviously defective. In doubtful cases, any water which has entered during a precious activity can be removed by placing the heater in an oven for an hour at about 80 °C.

Measurements to make

Mass of water (m)	=	kg
Temperature of water before heating	=	^oC
Temperature of water after heating	=	^oC
Rise in temperature of water (θ)	=	^oC
Voltage applied to heater (V)	=	V
Current through heater (I)	=	A
Electrical energy converted to heat energy in 10 minutes	=	J
Heat energy required to heat m kg by θ ^oC	=	J
Specific heat capacity of water	=	J / (kg ^oC)

Make up a similar set of results for aluminium.

Questions

1. Why do you think that you allowed the heater to warm up before putting it in the water?
2. Why will your result for either experiment not be very accurate?
3. Why should you stir the water at the end?
4. Why would it not be a good idea to get the water or aluminium too hot?

Follow up topic

Devise an experiment to measure the specific heat capacity of soil.

Practical advice

After switching off the heater make sure you take the highest temperature reached by the thermometer in the aluminium block.

External reference

This activity is taken from Resourceful Physics

TAP 607- 3: Measurement of specific heat capacities

There are several simple methods for measuring the specific heat capacities of both solids and liquids, such as the method of mixtures, but we will consider here only electrical methods. Since the specific heat capacity varies with temperature, we have seen it is important to record the mean temperature at which the measurement is made.

Electrical calorimeters

Figure 1(a) and 1(b) show possible arrangements for electrical calorimeters for a solid and a liquid specimen.

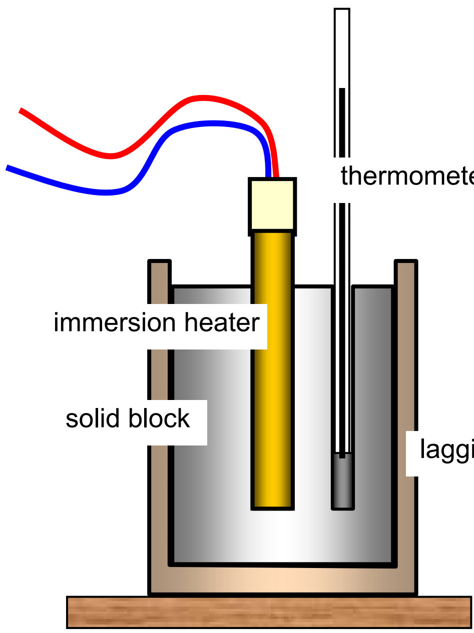


Figure 1(a)

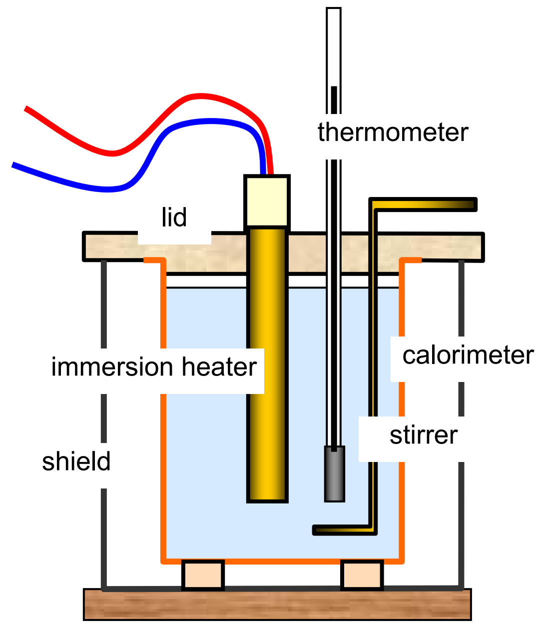


Figure 1(b)

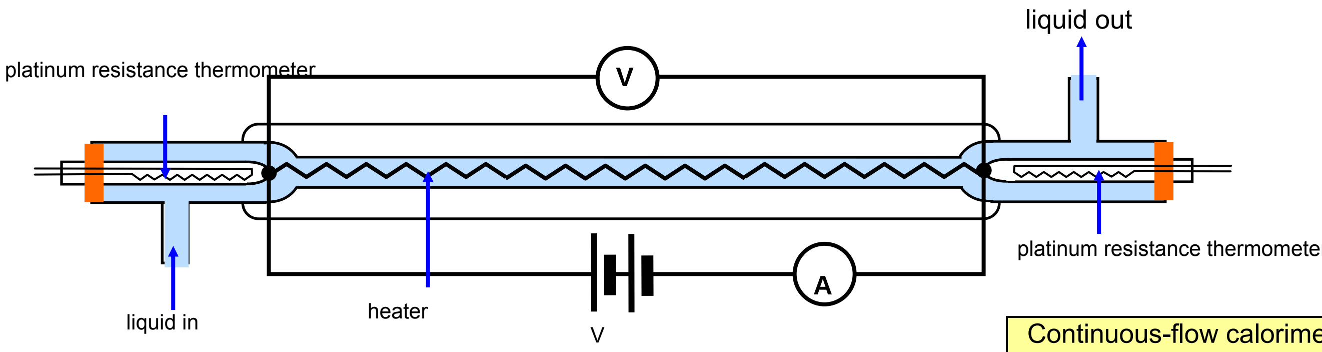
The material under investigation is heated by an electrical immersion heater and the input energy (Q) and the rise in temperature that this produces are measured. If the mass of the specimen (solid or liquid) is m and its specific heat capacity C, then:

$$\boxed{Q = m C (\theta_1 - \theta_o) + q}$$

where θ_0 and θ_1 are the initial and final temperatures of the specimen and q is the heat loss. Using the cooling correction, the value of q may be found. This simple method can be used for liquids or solids, although in the case of a liquid, allowance has to be made for the thermal capacity of the container, and the liquid should also be stirred to allow an even distribution of the heat energy throughout its volume. This is necessary since liquids are such poor thermal conductors

The continuous-flow calorimeter

This was first developed by Callender and Barnes in 1902 for the measurement of the specific heat capacity of a liquid, and is shown in diagram below. Its main advantage is that the thermal capacity of the apparatus itself need not be known.



Continuous-flow calorimeter

Liquid flows in from a constant-head apparatus at a constant rate past a thermometer (θ_0). It then flows around the heater coil and out past a second thermometer where the outlet temperature (θ_1) may be measured. When steady-state conditions have been reached (a temperature difference between inlet and outlet points of 5^0C is reasonable) the temperatures and the flow rate of the liquid (m) are measured. A vacuum jacket round the heater coil reduces heat losses.

The electrical energy supplied to the heater coil (E = V I t) may be found readily with a joulemeter or with an ammeter and voltmeter.

Two sets of measurements are carried out.

For a first experiment we have:

Electrical energy supplied (E_1) = $V_1 I_1 t_1 = m_1 C (\theta_1 - \theta_0) + q$

C is the specific heat capacity of the liquid and q the heat loss to the surroundings and to the apparatus.

The flow rate and rate of energy input are now altered to give a second set of results. However, if the inlet and outlet temperatures are the same as in the first experiment the heat loss will also be the same. Therefore:

Electrical energy supplied (E_2) = = $V_2 I_2 t_2 = m_2 C (\theta_1 - \theta_O) + q$

Eliminating the heat loss (q) gives

Specific heat capacity of the liquid (C) = $[E_2 - E_1]/ (m_2 - m_1)(\theta_1 - \theta_o)$

Practical advice

A smaller amount of water could be heated in a polystyrene cup than in a calorimeter; this reduces the heating time needed and provides insulation. *The heater must be covered by the water*. The heat absorbed by the polystyrene is also small compared to that absorbed by the calorimeter. However take care that the heater does not touch the cup or it will melt. Thermometers can also overbalance the cup. Always stir liquids before taking a temperature.

It is better to choose an immersion heater that fits all the way into the solid material rather than having part of it in the air. The top of the block should also be lagged. Take the highest temperature reached by the block after the heater has been switched off.

External reference

This activity is taken from Resourceful Physics

TAP 607- 4: Specific heat capacity: some questions

What to do

Three of these questions ask you to consider areas in which specific heat capacity is important: one domestic, one transport-based and one industrial. The remaining questions are calculations that involve the use of specific heat capacity.

The specific heat capacity of water is 4200 J kg^{-1} K^{-1}; the specific heat capacity of air is about 1000 J kg^{-1} K^{-1}.

Why does heat capacity matter?

1. Some cooks make toffee. Essentially, this is a process of boiling down a sugar solution to concentrate it and then allowing the liquid to cool until it sets. Small children are usually warned not to touch the cooling toffee for a very long time – much longer than the cooling for the same volume of pure water in the same vessel. Why is the cooling period so long?

2. Why is water commonly used in the cooling system of a motor car? Why is the system pressurised?

3. Find out which materials are used as coolants in nuclear reactors. What do these materials have in common?

Calculations

4. The Sun delivers about 1 kW of power to a square metre of the Earth when overhead at the equator. A parabolic mirror of radius 1m is used to focus this energy onto a container of water. Estimate the time taken by the mirror to raise 1 litre of water to 100 ^{o}C. Comment on whether your answer is likely to be an over or an underestimate.

5. Estimate how much energy is required to heat the air in your physics laboratory from a chilly 10 °C to a more comfortable 20 °C. Comment on the answer.

Practical advice

Students may find it more difficult to answer the qualitative questions than the quantitative questions. Answering qualitative questions provides essential practice in using the language (and concepts) of physics correctly.

Answers and worked solutions

1. There are a number of factors that determine the time it takes the toffee to cool sufficiently to eat:

   The boiling point of the sugar solution is higher than that of water so the toffee is cooling from a higher temperature.

   The sugar solution has a higher specific heat capacity than pure water. So for an equivalent temperature drop, more energy has to be lost.

   [Perhaps most significant is the amount of energy that has to be lost for the liquid toffee mixture to solidify, cooling and then changing from a liquid to a solid takes a long time. This involves the idea of latent heat capacity, rather than specific heat capacity]

2. The specific heat capacity of water is large; water is cheap and liquid, it has a reasonable temperature range before boiling. It is pressurised to elevate the boiling point – but, as important, also to retain the material.

3. Coolants used include: water, heavy water (D_2O), liquid sodium, pressurised carbon dioxide. They need a high specific heat capacity and, ideally, should not absorb neutrons.

   Area of mirror is about 3 m^2. So 3 kW is delivered. One litre has a mass of 1 kg, assume an 80 degree temperature rise.

   Minimum time taken is (4200 J kg^{-1} $°C^{-1}$ $\times$ 80 °C) / 3000 kg = 112 s but this does not allow for losses to the surroundings from the container which the Sun has to make up. This is an estimate of the energy needed to raise the temperature to 100 °C, it does not boil the water. Assuming no energy losses, it takes a further 800 s (minimum) to vaporise the liquid. An equally valid estimate – this time experimental – is to time your household kettle having read its electrical energy input from the base plate and then scale up or down its time to boiling accordingly.

5. Assume the laboratory is 3 m $\times$ 10 m $\times$ 10 m, this leads to a volume of 300 m^2. Assume further that the heating is just a question of warming up the air. The density of air is approximately 1 kg m^{-3} so energy = 300 kg $\times$ 1000 J $kg^{-1}$$°C^{-1}$ $\times$ 10°C, i.e. 3 MJ.

   A reasonable heater might deliver this in 1000 s (about 20 minutes). Most people would guess that the heating time would be much longer. This estimate ignores heating the contents of the room, etc. Our perception of temperature is affected both by the humidity of the air and by the cooling effect of any draughts. It would take much longer in reality.

External reference

This activity is taken from Advancing Physics chapter 13, 110S

TAP 607- 5: Thermal changes

Use these data to answer the questions below, showing how thermal changes apply to a wide range of phenomena:

Material	Specific heat capacity / J kg^{-1} K^{-1}
Aluminium	900
Copper	385
Expanded polystyrene	1300
Iron and steel	450
Ice	2100
Air	1000
Water	4200

A set of varied questions

For each of the following, find the internal energy difference for a 10 K change in temperature:

1. 5.0 kg of water.

2. The bit of a soldering iron, made from 3.5 g of copper.

3. An expanded polystyrene cup of mass 5.0 g.

4. A steel brake disc of mass 1.5 kg.

5. If you eat a fruit pastry fresh from a hot oven, the pastry may be harmless while the fruit filling scalds your tongue.

   Use your ideas about specific heat capacity to explain why.

6. You can put your hand in an oven at 200 °C and even touch a baking cake, without serious harm. But you must avoid touching anything in the oven made from metal.

   Why is it not so harmful unless you touch metal?

7. In Fiji, some people will walk barefoot over a bed of white-hot pumice coals as part of a religious ritual. It is meant to demonstrate supernatural powers over pain and heat. Their feet are generally not hurt.

   Pumice has a low specific heat capacity, low density and is a poor conductor of heat. Explain how each of these properties helps to make a bed of white-hot pumice coals safe to walk (quickly) over.

8. In the middle of the nineteenth century, James Joule performed a great series of experiments, which was part of the work leading to the law of conservation of energy. One of them was on his honeymoon, when he measured the temperature difference between water at the top and bottom of a waterfall.

   If the waterfall was 100 m high, what maximum temperature difference could Joule expect?

Two holes are made in a 1.0 kg block of aluminium. A 48 W electric immersion heater is placed in one hole, and a thermometer in the other. Both objects make good thermal contact with the block. The heater is switched on for exactly 3 minutes and the temperature rises from 20 °C to 29 °C.

9. Calculate the specific heat capacity of aluminium.

10. Is this likely to overestimate or underestimate the true value?

In some supermarkets the freezer compartments are upright, with front-opening doors, while in other supermarkets there are chest-type freezers, with access from the top and no lids. Some people consider the upright design wasteful, because the cold air escapes when the door is opened. The temperature inside such freezers might be – 20 °C, and the specific heat capacity of air (at constant pressure) is about 1000 J kg^{-1} K^{-1}.

11. Consider a freezer of volume 1.5 m^3 and discuss whether you agree or disagree.

A power station needs to get rid of energy at a rate of 800 MW and does so by warming up a river that flows past it.

12. If the river flow rate is 1100 m^3 s^{-1}, how much warmer is the river downstream of the power station?

Practical advice

Students may find it more difficult to answer the qualitative questions than the quantitative questions. Answering qualitative questions provides essential practice in using the language (and concepts) of physics correctly.

Answers and worked solutions

1.

$$E = mc\,\Delta\theta = 5.0\text{ kg} \times 4200\text{ J kg}^{-1}\text{ K}^{-1} \times 10\text{ K} = 210\text{ kJ}.$$

2.

$$E = mc\,\Delta\theta = 0.0035\text{ kg} \times 385\text{ J kg}^{-1}\text{ K}^{-1} \times 10\text{ K} = 13\text{ J}.$$

3.

$$E = mc\,\Delta\theta = 0.005\text{ kg} \times 1300\text{ J kg}^{-1}\text{ K}^{-1} \times 10\text{ K} = 65\text{ J}.$$

4.

$$E = mc\,\Delta\theta = 1.5\text{ kg} \times 450\text{ J kg}^{-1}\text{ K}^{-1} \times 10\text{ K} = 6.8\text{ kJ}.$$

5. The fruit, largely sugar and water, has a high heat capacity and therefore has more energy.

6. Both air and cake have low specific heat capacities and are poor conductors, so little energy is transferred; metals have higher specific thermal capacities but are good conductors, so the energy can be rapidly conducted to your hand.

7. Low specific heat capacity and density mean little energy is stored in the pumice; because it is a poor conductor, there is little energy transfer from below the surface.

8.

$$mgh = mc\Delta\theta$$

$$\begin{aligned}\Delta\theta &= \frac{mgh}{mc} \\ &= \frac{9.8\text{ N kg}^{-1} \times 100\text{ m}}{4200\text{J kg}^{-1}\text{ K}^{-1}} \\ &= 0.23\text{ K}\end{aligned}$$

9.

$$\begin{aligned}c &= \frac{Pt}{m\,\Delta\theta} \\ &= \frac{48\text{ W} \times 3 \times 60\text{ s}}{1.0\text{ kg} \times (29 - 20)\text{ K}} \\ &= 960\text{ J kg}^{-1}\text{ K}^{-1}.\end{aligned}$$

10. Overestimate. Because of thermal transfer to the surroundings, less energy goes into the aluminium than this calculation assumes.

11. Assume the freezer volume is half air (the other half is the contents of the freezer) and that all the air escapes when the door is opened. If the room temperature is 20 °C, the temperature difference is 40 K:

$$E = mc\Delta\theta$$

$$E = 1.3\,\mathrm{kg\,m^{-3}} \times \frac{1.5\,\mathrm{m^3}}{2} \times 1000\,\mathrm{J\,kg^{-1}\,K^{-1}} \times 40\,\mathrm{K}$$
$$= 39\,\mathrm{kJ}$$

If the door were opened frequently, the power demand would be significant. But perhaps this is a contribution to the air-conditioning of the supermarket?

12.

$$\Delta\theta = \frac{P}{\rho \times (V/t) \times c}$$
$$= \frac{800 \times 10^6\ \mathrm{W}}{1000\ \mathrm{kg\,m^{-1}} \times 1100\ \mathrm{m^3\ s^{-1}} \times 4200\ \mathrm{J\,kg^{-1}\,K^{-1}}}$$
$$= 0.17\ \mathrm{K}.$$

External reference

This activity is taken from Advancing Physics chapter 13, 140D