Set 3 Heat

Q1

Two different objects are in thermal equilibrium. If you remove equal amounts of heat from each, will they still be in thermal equilibrium? Explain.

No, since they have different specific heat capacities.

Q2

In each of the following, state and explain which container will have the hotter liquid in it after thirty seconds.

[a] You pour equal amounts of hot coffee into two cups from a percolator. The cups are the same general size and shape. One is made from heavy china and the other from very thin, delicate china.

[b] You pour equal amounts of hot olive oil into two urns. The urns are the same general size and shape. One is made from pewter and the other from brass.

(a)	Convection losses from the surface of each cup should be the same, however heat would flow more quickly through the thinner more delicate china so this cup would cool down quicker.
(b)	Brass has a higher specific heat capacity than pewter so the brass urn will take more heat away from the hot olive oil, meaning that the oil in the pewter urn will be hotter after 30 seconds.

Q3

Solar hot water systems convert electromagnetic energy from the Sun into thermal energy in the water in the heater. How much solar energy does a solar heater need to absorb to raise the temperature of 153 kg of water from 15.0 °C to 75.0 °C? Assume that the system converts all the solar energy to thermal energy of the water.

$$Q = m\,c\,\Delta T = 153\text{ kg} \times 4180\text{ J kg}^{-1}\text{ K}^{-1} \times (75\text{ °C} - 15\text{ °C}) = 38.4\text{ MJ}$$

Q4

A chef removes a saucepan from an electric stove element made from stainless steel. He then immediately switches off that element. How much waste heat passes from the 782 g element to the air as it cools from a temperature of 445 ºC to 20.0 ºC?

$$Q = m\,c\,\Delta T = 0.782\ \text{kg} \times 445\ \text{J kg}^{-1}\,\text{K}^{-1} \times (20\ ^{\circ}\text{C} - 445\ ^{\circ}\text{C}) = -148\ \text{kJ}$$

Q5

A gas heater produces 1.54 MJ of heat in a room that contains 72.6 kg of air. Calculate the rise in air temperature in the room.

$$\Delta T = \frac{Q}{mc} = \frac{1.548 \times 10^6 \text{ J}}{72.6 \text{ kg} \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}} = 21.2\ ^\circ\text{C}$$

Q6

An engineer is doing an energy audit on a kitchen. She needs to work out how much electrical energy a 0.355 kg stainless steel electric kettle needs to heat 0.850 L of water from 15.0 °C to its boiling point. Calculate the energy needed, assuming that the kettle converts all the electrical energy to thermal energy and that it loses no heat to its surroundings.

electrical energy supplied = heat gained by kettle + heat gained by water

1 L of water has a mass of 1 kg

$Q = m_{kettle} \times C_{kettle} \times \Delta T_{kettle} + m_{water} \times C_{water} \times \Delta T_{water}$

$Q = (0.355\ \text{kg})(445\ \text{J kg}^{-1}\ \text{K}^{-1})(100\ ^{\circ}\text{C} - 15\ ^{\circ}\text{C}) + (0.850\ \text{kg})(4180\ \text{J kg}^{-1}\ \text{K}^{-1})(100\ ^{\circ}\text{C} - 15\ ^{\circ}\text{C})$
$= 315\ \text{kJ}$

Q7

A foundry operator finds that it takes 55.3 MJ of heat to heat a 286 kg mass of steel from 22.0 °C to 452 °C. Calculate the specific heat capacity of that steel.

$$c = \frac{Q}{m\Delta T} = \frac{255.3 \times 10^{6}\ \text{J}}{286\ \text{kg} \times (452\ °\text{C} - 22\ °\text{C})} = 450\ \text{J kg K}^{-1}$$

Q8

A gas burner supplies 2.84×10^5 J of heat to 2.75 kg of soup. The specific heat capacity of the soup is 4.13×10^3 J kg^{-1} K^{-1}. Determine the final temperature of the soup.

$$\Delta T = \frac{Q}{mc} = \frac{2.84 \times 10^5 \text{ J}}{2.75 \text{ kg} \times 4130 \text{ J kg}^{-1} \text{ K}^{-1}} = 25.0\,^\circ\text{C}$$

Q9

Refrigerators remove heat energy from objects you put in them. How much heat energy must a refrigerator remove from an empty aluminium pot of mass 865 g to cool it from a temperature of 120.0 °C to 55.0 °C?

$$\Delta T = \frac{Q}{mc} = \frac{1.548 \times 10^6 \text{ J}}{72.6 \text{ kg} \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}} = 21.2 \text{ °C}$$

Q10

You want to cook a potato in a microwave oven. If you put a 385 g potato in an oven at 18.0 °C, the potato absorbs 118 kJ of microwave energy and converts it to thermal energy. The final temperature of this potato is 98.6 °C. Calculate the potato's average specific heat capacity.

$$c_{av} = \frac{Q}{m\Delta T} = \frac{118 \times 10^3 \text{ J}}{0.385 \text{ kg} \times (98.6\,°\text{C} - 18\,°\text{C})} = 3800 \text{ J kg K}^{-1}$$

Q11

Explain why the filling in a meat pie can burn your mouth while the crust will not, even though they are both at the same temperature.

The crust has a lower heat capacity than the filling and hence has less heat energy to transfer to your mouth and therefore has less energy to raise the temperature of your mouth and burn you. A minor effect is that the liquid filling may be a better conductor of heat to your mouth.

Q12

Describe how you could measure the specific heat capacity of a new alloy.

Heat a measured mass, M of the alloy to a known temperature, T and put into a well insulated and measured mass, m of water at known temperature, t. The measured final temperature, T_f of the mixture can be related to the specific heat capacity of the alloy:

Heat lost by alloy + heat gained by water = 0

$M\, c_{alloy}\, (T_f - T) + m\, c_{water}\, (T_f - t) = 0$

hence c_{alloy} can be calculated.

Q13

Motorists may use ethylene glycol instead of water in their cars' cooling systems.
[a] Compare the time it takes for the coolant to reach 100 ºC in two identical cars, each producing the same amount of heat. One car has ethylene glycol in its radiator, while the other car has a water filled radiator.
[b] Which is the more efficient coolant? Explain why you make this choice.
[c] Explain how manufacturers could improve the cooling system of the car with the less efficient coolant without changing the type of coolant they use.

Q13 continued

(a)	Time to heat is inversely proportional to specific heat capacity. Ethylene glycol has a lower specific heat capacity than water and will reach 100 °C faster by a factor of: $\frac{c_{water}}{c_{glycol}} = \frac{4180\,J\,kg^{-1}\,K^{-1}}{2400\,J\,kg^{-1}\,K^{-1}} = 1.74$ So, it takes 1.74 times longer to heat the water.
(b)	Water has a significantly higher specific heat capacity than ethylene glycol. Other factors, such as boiling point and corrosive effects, are also important. In terms of its ability to absorb heat energy without a large rise in temperature water is more efficient. However, even under pressure water will boil at about 120 °C. If the designer wants to run an engine at higher temperature (which is potentially more efficient) then a higher boiling point liquid is needed. Ethylene glycol boils at 198 °C and also is less corrosive to the metal parts than water. Often a mixture of the two is used.
(c)	If a bigger mass of coolant was used, or if it were pumped through the system more rapidly, cooling could be improved.

Q14

You need to design a system of solar collectors that will collect and store thermal energy during the day and will deliver it as heat at night. Specify the essential properties of the thermal energy storage medium.

The storage system must be fully enclosed and very well lagged to prevent heat escaping through its walls, its upper and lower surfaces. It should have a low coefficient of expansion so there is very little increase in size and less chance of fracturing. It should have a high melting point. Its inner walls should be silvery or shiny to prevent heat escaping by radiation.

Q15

A camper wants to use water to remove 2.93 MJ of heat from an overheated metal barbecue plate. The water they want to use has a temperature of 20.0 °C. What is the smallest mass of water the camper can use without the water boiling?

$$m = \frac{Q}{c\Delta T} = \frac{2.93 \times 10^6 \text{ J}}{4180 \text{ J kg K}^{-1} \times (100\,°\text{C} - 20\,°\text{C})} = 8.76 \text{ kg}$$ (or just a little more than this in order to **prevent** the coolant water from boiling).

Q16

Ahmed is a heating consultant. One of his clients has a boiler that is 62% efficient and uses heating oil that releases 4.15×10^7 J kg^{-1} of heat energy when it burns in air. What mass of heating oil does the boiler need to heat 245 kg of water from 12.0 °C to 68.0 °C?

Energy required by water, $Q = m\,c\,\Delta T = 245\text{ kg} \times 4180\text{ J kg}^{-1}\text{ K}^{-1} \times (68\,°\text{C} - 12\,°\text{C})$
$= 57.35$ MJ

At 62% efficiency, the oil would therefore have to supply $\dfrac{57.35 \times 10^6\text{ J}}{0.62} = 92.5\text{ MJ}$

So mass of oil required, $m = \dfrac{Q}{Q_{\text{per kg}}} = \dfrac{92.5 \times 10^6\text{ J}}{4.15 \times 10^7\text{ J kg}^{-1}} = 2.23\text{ kg}$

Q17

On a cold winter night, why is it poor economy to allow the bathtub to drain immediately after you take a hot bath?

The longer the water remains in the bath tub, the more heat it will transfer to the colder air in the room as it attempts to reach the same ambient temperature and achieve thermal equilibrium. So it would effectively warm up the room.

Q18

Land and sea breezes result from the differential heating and cooling of land and water. Explain why water and land heat and cool at a different rate.

Water has a much higher specific heat capacity than land. Hence the same heat input from the sun will raise the temperature of the land by much more than that for an equivalent amount of water.

Q19

You want to heat a glass mug of water at 18.5 °C to 98.5 °C in a microwave oven. The mass of the glass is 215 g and it contains 145 g of water. How much microwave energy would the glass and water need to absorb? Assume the water converts all the microwave energy to thermal energy.

microwave energy supplied = heat gained by glass + heat gained by water,

$Q = (m_{glass}\, c_{glass}\, \Delta T_{glass}) + (m_{water}\, c_{water}\, \Delta T_{water})$

$Q = (0.215\ kg)(670\ J\ kg^{-1}\ K^{-1})(98.5\ ^{o}C - 18.5\ ^{o}C) + (0.145\ kg)(4180\ J\ kg^{-1}\ K^{-1})(98.5\ ^{o}C - 18.5\ ^{o}C) = 60\ kJ$

Q20

A cook pours 800 g of soup at 98.0 °C into a 100 g bowl of specific heat capacity 320 J kg^{-1} K^{-1}. The soup raises the temperature of the bowl from 10.0 °C to 97.0 °C. What is the specific heat capacity of the soup?

final temperature of soup, T_f = final temperature of the bowl = 97 °C

Heat lost by soup + heat gained by bowl = 0

$m_{soup}\, c_{soup}\, (T_f - T)_{soup} + m_{bowl}\, c_{bowl}\, (T_f - t)_{bowl} = 0$

$(0.800\ \text{kg})(c_{soup})(97\ °\text{C} - 98\ °\text{C}) + (0.100\ \text{kg})(320\ \text{J kg}^{-1}\ \text{K}^{-1})(97\ °\text{C} - 10\ °\text{C}) = 0$

$c_{soup} = 3480\ \text{J kg}^{-1}\ \text{K}^{-1}$

Q21

The host at a party gives you a 185 g cup of tea in a foam plastic cup. The tea is very hot at 85.5 ºC. You decide to cool the tea by adding 35.0 g of water at 18.0 ºC. Calculate the resulting temperature of your drink. Assume the tea has the same specific heat capacity as water, and that no heat is lost to the cup or the surroundings.

Heat lost by tea + heat gained by water = 0

$m_{tea}\, c_{tea}\, (T_f - T)_{tea} + m_{water}\, c_{water}\, (T_f - t)_{water} = 0$

$(0.185\text{ kg})(4180\text{ J kg}^{-1}\text{ K}^{-1})(T_f - 85.5\text{ °C}) + (0.035\text{ kg})(4180\text{ J kg}^{-1}\text{ K}^{-1})(T_f - 18\text{ °C}) = 0$

gives $T_f = 74.8$ °C

Q22

An engineer is designing a pumping system for a large aquarium. Water passes through a pump at the rate of 1.30 kL min^{-1}. The pump transfers energy to the water passing through at a rate of 10.0 kJ s^{-1}. 65.0% of the pump's energy becomes kinetic energy of the water; the rest of the energy becomes thermal energy in the water. Calculate the increase in the water's temperature over one hour if all the thermal energy remains in the water.

1 L water has mass 1 kg

Each hour, mass of water flowing, m = 1300 kg min^{-1} x 60 min h^{-1} = 78 000 kg h^{-1}

Each hour, energy transferred to water by the pump = 10 000 J s^{-1} x 3600 s h^{-1} = 3.6 x 10^7 J h^{-1}

35% of this energy is transferred as heat, Q = 0.35 x 3.6 x 10^7 J h^{-1} = 1.26 x 10^7 J h^{-1}

So, during the hour,

$$\Delta T = \frac{Q}{mc} = \frac{1.26 \times 10^7 \text{ J h}^{-1}}{78\,000 \text{ kg h}^{-1} \times 4180 \text{ J kg}^{-1} \text{ K}^{-1}} = 0.039\text{ °C}$$

Q23

A stainless steel kettle of mass 5.25 kg contains 1.55 kg of water. If the kettle converts 65.0% of the supplied electrical energy to thermal energy in the water and itself, calculate the total amount of electrical energy needed to raise the temperature of the kettle and water from 12.0 °C to 96.0 °C.

$$\text{electrical energy input} = \frac{\text{heat gained by kettle} + \text{heat gained by water}}{0.65} \text{ since it is 65\% efficient}$$

$$Q = \frac{(m_{kettle}\, c_{kettle}\, \Delta T_{kettle}) + (m_{water}\, c_{water}\, \Delta T_{water})}{0.65}$$

$$Q = \frac{(5.25\ \text{kg})(445\ \text{J kg}^{-1}\ \text{K}^{-1})(96\ ^\circ\text{C} - 12\ ^\circ\text{C}) + (1.55\ \text{kg})(4180\ \text{J kg}^{-1}\ \text{K}^{-1})(96\ ^\circ\text{C} - 12\ ^\circ\text{C})}{0.65}$$

$= 1.14 \times 10^6$ J (or 1.14 MJ)

Q24

You want to raise the temperature of a bath containing 40.0 kg of cold water at a temperature of 16.5 ºC to 45.0 ºC. What mass of hot water at a temperature of 75.3 ºC must you add to the cold water if the bath and its surroundings absorb 15.0% of the heat lost from the hot water as it cools to its final temperature?

85 % of the heat lost by hot water + heat gained by cold water = 0 (since bath & surroundings absorb 15%)

$0.85\ (m_{hot})(c_{hot})(T_f - T)_{tea} + m_{cold}\ c_{cold}\ (T_f - t)_{cold} = 0$

$(0.85)(m_{hot})(4180\ J\ kg^{-1}\ K^{-1})(75.3\ ^\circ C - 45\ ^\circ C) + (40\ kg)(4180\ J\ kg^{-1}\ K^{-1})(45\ ^\circ C - 16.5\ ^\circ C) = 0$

gives $m_{hot} = 44.3$ kg

Q25

A mechanic adds 655 g of ethylene glycol antifreeze at 22.0 ºC to your car's radiator. The radiator already contains 6.75 L of water at 92.0 ºC. If the 4.50 kg radiator is made of copper, calculate the final temperature of the mixture.

heat gained by glycol + (heat lost by radiator + heat lost by water) = 0

$(m_{glycol})(c_{glycol})(\Delta T_{glycol}) + (m_{radiator})(c_{radiator})(\Delta T_{radiator}) + (m_{water})(c_{water})(\Delta T_{water}) = 0$

$(0.655\ kg)(2400\ J\ kg^{-1}\ K^{-1})(T_f - 22^{\circ}C) + (4.5\ kg)(390\ J\ kg^{-1}\ K^{-1})(T_f - 92\ ^{\circ}C) + (6.75\ kg)(4180\ J\ kg^{-1}\ K^{-1})(T_f - 92\ ^{\circ}C) = 0$

gives $T_f = 88.5\ ^{\circ}C$