Specific Heat Capacity & Calorimetry

Unit: Thermal Physics

Knowledge/Understanding:

- specific heat capacity
- calorimetry

Skills:

- solve calorimetry (specific heat) problems

Notes:

Different objects have different abilities to hold heat. For example, if you enjoy eggplant Parmesan, you may have noticed that the eggplant holds much more heat (and burns your mouth much more readily) than the cheese or the bread crumb coating.

The amount of heat that a given mass of a substance can hold is its specific heat capacity.

specific heat capacity: a measure of the amount of heat required per gram of a substance to produce a specific temperature change in the substance. (Note that specific heat capacity is usually given in kilojoules per kilogram per Kelvin (or degree Celsius). Be careful with this—in most other equations, energy is measured in joules.)

C_p: specific heat capacity, measured at constant pressure. For gases, this means the measurement was taken allowing the gas to expand as it was heated.

C_v: specific heat capacity, measured at constant volume. For gases, this means the measurement was made in a sealed container, allowing the pressure to rise as the gas was heated.

For solids and liquids, $C_p \approx C_v$ because the pressure and volume change very little as they are heated. For gases, $C_p > C_v$ (always). For ideal gases, $C_p - C_v = R$, where R is the gas constant. (We will see the gas constant again when we study fluid mechanics.)

When there is a choice, C_p is more commonly used than C_v because it is easier to measure. When dealing with solids and liquids, most physicists just use C for specific heat capacity and don't worry about the distinction.

Calculating Heat from a Temperature Change

The amount of heat gained or lost when an object changes temperature is given by the equation:

$$Q = mC\,\Delta T$$

where:

Q = heat (J)

m = mass (kg)

C = specific heat capacity ($\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$)

ΔT = temperature change (K or °C)

Again, remember that the traditional units for C are kJ rather than J.

You may sometimes see the units for C given in $\frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}$ or $\frac{\text{cal}}{\text{g}\cdot{}^\circ\text{C}}$.

Note that $1\,\frac{\text{kJ}}{\text{kg}\cdot\text{K}} \equiv 1\,\frac{\text{kJ}}{\text{kg}\cdot{}^\circ\text{C}} \equiv 1\,\frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}$ and $1\,\frac{\text{cal}}{\text{g}\cdot{}^\circ\text{C}} \equiv 1\,\frac{\text{kcal}}{\text{kg}\cdot{}^\circ\text{C}} = 4.184\,\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$.

Specific Heat Capacity & Calorimetry

Specific Heat Capacities of Some Substances

Substance	**Specific Heat Capacity** $\left(\frac{kJ}{kg \cdot K}\right)$
water at 20°C	4.181
ethylene glycol (anti-freeze)	2.460
ice at -10°C	2.080
steam at 100°C	2.11
steam at 130°C	1.99
vegetable oil	2.000
air	1.020
aluminum	0.900
glass	0.840
iron	0.444
copper	0.385
brass	0.380
silver	0.240
lead	0.160
gold	0.129

Calorimetry

calorimetry: the measurement of heat flow

In a calorimetry experiment, heat flow is calculated by measuring the mass and temperature change of an object and applying the specific heat capacity equation.

calorimeter: an insulated container for performing calorimetry experiments.

coffee cup calorimeter: a calorimeter that is only an insulated container—it does not include a thermal mass (such as a mass of water). It is usually made of styrofoam, and is often nothing more than a styrofoam coffee cup.

bomb calorimeter: a calorimeter for measuring the heat produced by a chemical reaction. A bomb calorimeter is a double-wall metal container with water between the layers of metal. The heat from the chemical reaction makes the temperature of the water increase. Because the mass and specific heat of the calorimeter (water and metal) are known, the heat produced by the reaction can be calculated from the increase in temperature of the water.

Solving Coffee Cup Calorimetry Problems

Most coffee cup calorimetry problems involve placing a hot object in contact with a colder one. Many of them involve placing a hot piece of metal into cold water.

To solve the problems, assume that both objects end up at the same temperature. The heat lost by the hot object equals the heat gained by the cold object. (However, remember that Q will be negative for the hot object because it is losing heat.)

$$Q_{cold} = m_{cold}C_{cold}\Delta T_{cold}$$
$$Q_{hot} = m_{hot}C_{hot}\Delta T_{hot}$$
$$Q_{cold} = -Q_{hot}$$
$$m_{cold}C_{cold}\Delta T_{cold} = -m_{hot}C_{hot}\Delta T_{hot}$$

Notice that there are six quantities that you need: the two masses, the two specific heat capacities (C), and the two temperature changes (ΔT). (You might be given initial and final temperatures for either or both, in which case you'll need to subtract.) The problem will give you five of the six, and you will need to find the missing one.

Don't fret about the negative sign. The value of ΔT will be negative for the hot object (because it is cooling off), and the two minus signs will cancel.

Steps for Solving Coffee Cup Calorimetry Problems

1. Identify the variables for both the hot and cold substance. This can be tricky because you have two different masses, two different specific heat capacities, and two different temperature changes. For each quantity, you have to identify both the variable and which substance it applies to.

2. Look up the specific heat capacities of the substances involved.

3. Plug each set of numbers into the equation $Q = mC\,\Delta T$. (*I.e.,* you'll have *two separate* $Q = mC\,\Delta T$ equations.)

    a. Remember that for the substance that is cooling off, heat is going out of the system, which means the equation will be $Q = -mC\,\Delta T$.

    b. Because ΔT will be negative for the substance that was cooling off, the two negative signs will cancel.

4. Use the fact that Q is the same for both equations to solve for the unknown quantity. This will involve doing one of the following:

    a. Calculate the value of Q from one equation and use it in the other equation.

    b. If you need to find the final temperature, set the two $mC\,\Delta T$ expressions (or $mC\,(T_f - T_i)$ expressions) equal to each other.

Sample Problems:

Q: An 0.050 kg block of aluminum is heated and placed in a calorimeter containing 0.100 kg of water at 20°C. If the final temperature of the water was 30°C, to what temperature was the aluminum heated?

A: The heat gained by the water equals the heat lost by the aluminum.

The heat gained by the water is:

$$\begin{aligned} Q &= mC\,\Delta T \\ Q &= (0.100\ \text{kg})(4.18\ \tfrac{\text{kJ}}{\text{kg}\cdot\text{K}})(+10^\circ C) \\ Q &= 4.18\ \text{kJ} \end{aligned}$$

The heat lost by the metal must therefore be 4.18 kJ.

$$\begin{aligned} Q &= -mC\,\Delta T \\ 4.18\ \text{kJ} &= -(0.050\ \text{kg})(0.900\ \tfrac{\text{kJ}}{\text{kg}\cdot\text{K}})\,\Delta T \\ 4.18 &= -(0.045)(\Delta T) \\ \frac{4.18}{-0.045} &= -92.9 = \Delta T = -93^\circ C \end{aligned}$$

The temperature of the aluminum was −93°C (*i.e.,* it went down by 93°C)

$$\begin{aligned} \Delta T &= T_f - T_i \\ -93 &= 30 - T_i \\ T_i &= 123^\circ C \end{aligned}$$

This means the initial temperature must have been 123°C.

Q: An 0.025 kg block of copper at 95°C is dropped into a calorimeter containing 0.075 kg of water at 25°C. What is the final temperature?

A: Once again, the heat lost by the copper equals the heat gained by the water.

$$\begin{aligned}
-Q_{\text{copper}} &= Q_{\text{water}} \\
-m_{\text{copper}}C_{\text{copper}}\,\Delta T_{\text{copper}} &= m_{\text{water}}C_{\text{water}}\,\Delta T_{\text{water}} \\
-(0.025\text{ kg})(0.385\,\tfrac{\text{kJ}}{\text{kg}\cdot\text{K}})(T_{final}-95^\circ C) &= (0.075\text{ kg})(4.18\,\tfrac{\text{kJ}}{\text{kg}\cdot\text{K}})(T_{final}-25^\circ C) \\
-(0.009625)(T_{final}-95) &= (0.3138)(T_{final}-25) \\
-(0.009625\,T_{final}-0.9144) &= 0.3138\,T_{final}-7.845 \\
-0.009625\,T_{final}+0.9144 &= \quad 0.3138\,T_{final}-7.845 \\
+0.009625\,T_{final} \qquad\qquad &= +0.009625\,T_{final} \\
0.9144 &= 0.3234\,T_{final}-7.845 \\
+7.845 &= \qquad\qquad\quad +7.845 \\
8.759 &= 0.3234\,T_{final} \\
\frac{8.759}{0.3234} &= 27^\circ C = T_{final}
\end{aligned}$$

Note that because the specific heat of the water is so much higher than that of copper, and because the mass of the water was larger than the mass of the copper, the final temperature ended up much closer to the initial water temperature.