Specific Heat Capacity & Calorimetry

Unit: Heat & Thermodynamics

NGSS Standards: HS-PS2-6, HS-PS3-1

MA Curriculum Frameworks (2006): 3.4

AP Physics 2 Learning Objectives: N/A

Knowledge/Understanding:

- specific heat capacity
- calorimetry

Skills:

- solve calorimetry (specific heat) problems

Language Objectives:

- Understand and correctly use the terms "specific heat capacity" and "calorimetry."
- Accurately describe and apply the concepts described in this section, using appropriate academic language.
- Set up and solve word problems relating to specific heat capacity and calorimetry.

Notes:

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

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

<u>specific heat capacity</u> (C): a measure of the amount of heat required per gram of a substance to produce a specific temperature change in the substance.

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.

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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 a constant known as "the gas constant."

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 or kJ)

m = mass (g or kg)

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

ΔT = temperature change (K or °C)

Because problems involving heat often involve large amounts of energy, specific heat capacity is often given in kilojoules per kilogram per degree Celsius.

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 $1\frac{\text{cal}}{\text{g}\cdot{}^\circ\text{C}} \equiv 1\frac{\text{kcal}}{\text{kg}\cdot{}^\circ\text{C}} = 4.18\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$.

You need to be careful with the units. If the mass is given in kilograms (kg), your specific heat capacity will have units of $\frac{\text{kJ}}{\text{kg}\cdot{}^\circ\text{C}}$ and the heat energy will come out in kilojoules (kJ). If mass is given in grams, you will use units of $\frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}$ and the heat energy will come out in joules (J).

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Specific Heat Capacities of Some Substances

Substance	Specific Heat Capacity ($\frac{kJ}{kg \cdot K}$)
water at 20°C	4.18
ethylene glycol (anti-freeze)	2.46
ice at −10°C	2.08
steam at 100°C	2.11
steam at 130°C	1.99
vegetable oil	2.00
air	1.012
aluminum	0.897
glass	0.84
iron	0.450
copper	0.385
brass	0.380
silver	0.233
lead	0.160
gold	0.129

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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.

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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 (Q_h) equals the heat gained by the cold object (Q_c). (However, remember that Q_h will be negative because the hot object is losing heat.)

$$Q_c = m_c C_c \Delta T_c$$
$$Q_h = m_h C_h \Delta T_h$$
$$Q_c = -Q_h$$
$$m_c C_c \Delta T_c = -m_h C_h \Delta T_h$$

Notice that there are six quantities that you need: the two masses (m_h and m_c), the two specific heat capacities (C_h and C_c), and the two temperature changes (ΔT_h and ΔT_c). (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 all but one of these and you will need to find the missing one.

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

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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 the two masses, the two specific heat capacities, and the two 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.

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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:

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

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

$$Q = -mC\Delta T$$
$$4.18\,\text{kJ} = -(0.050\,\text{kg})(0.897\,\tfrac{\text{kJ}}{\text{kg}\cdot\text{K}})\,\Delta T$$
$$4.18 = -(0.0449)(\Delta T)$$
$$\Delta T = \frac{4.18}{-0.0449} = -93.2^\circ\text{C}$$

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

$$\Delta T = T_f - T_i$$
$$-93.2 = 30 - T_i$$
$$T_i = 123.2^\circ\text{C}$$

This means the initial temperature must have been 123.2°C.

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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.

$$-Q_c = Q_w$$

$$-m_c C_c \,\Delta T_c = m_w C_w \,\Delta T_w$$

$$-(0.025)(0.385)(T_f - 95) = (0.075)(4.18)(T_f - 25)$$

$$-(0.009625)(T_f - 95) = (0.3138)(T_f - 25)$$

$$-(0.009625\,T_f - 0.9144) = 0.3138\,T_f - 7.845$$

$$-0.009625\,T_{fl} + 0.9144 = 0.3138\,T_f - 7.845$$

$$+0.009625\,T_f \qquad = +0.009625\,T_f$$

$$0.9144 = 0.3234\,T_f - 7.845$$

$$+7.845 = \qquad +7.845$$

$$8.759 = 0.3234\,T_f$$

$$\frac{8.759}{0.3234} = 27°\text{C} = T_f$$

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.

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Homework Problems

You will need to look up specific heat capacities in Table H of your reference tables on page 583.

1. 375 kJ of heat is added to a 25.0 kg granite rock. How much does the temperature increase?

   Answer: 19.0°C

2. A 0.040 kg block of copper at 95°C is placed in 0.105 kg of water at an unknown temperature. After equilibrium is reached, the the final temperature is 24°C. What was the initial temperature of the water?

   Answer: 21.5°C

3. A sample of metal with a specific heat capacity of $0.50\,\frac{\text{kJ}}{\text{kg}\cdot{}^\circ\text{C}}$ is heated to 98°C and then placed in an 0.055 kg sample of water at 22°C. When equilibrium is reached, the final temperature is 35°C. What was the mass of the metal?

   Answer: 0.0948 kg

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4. A 0.280 kg sample of a metal with a specific heat capacity of $0.43\,\frac{\text{kJ}}{\text{kg}\cdot{}^\circ\text{C}}$ is heated to 97.5°C then placed in an 0.0452 kg sample of water at 31.2°C. What is the final temperature of the metal and the water?

   Answer: 57°C

5. A sample of metal with mass m is heated to a temperature of T_m and placed into a mass of water M with temperature T_w. Once the system reaches equilibrium, the temperature of the water is T_f. Derive an expression for the specific heat capacity of the metal, C_m.

   Answer: $C_m = \dfrac{MC_w(T_f - T_w)}{m(T_m - T_f)}$

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6. You want to do an experiment to measure the conversion of gravitational potential energy to kinetic energy to heat by dropping 2.0 kg of copper off the roof of LEHS, a height of 14 m. How much will the temperature of the copper increase?
   (*Hint: Remember that potential energy is measured in* J *but specific heat capacity problems usually use* kJ.)

   Answer: 0.356°C

7. Based on your answer to question #5 above, you decide to modify your experiment by dropping the 2.0 kg bag of copper from a height of 2.0 m to the floor multiple times. How many times would you need to drop the copper bag to get a temperature increase of 2°C?
   (*Hint: Remember that potential energy is measured in J but specific heat capacity problems usually use kJ.*)

   Answer: 39 times

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