

Heat Transfer

Thermal energy

Thermal energy is the total kinetic energy of the molecules of a substance. It is the energy needed to raise the temperature of a substance to its actual temperature from absolute zero, which is -273 degrees Celsius or 0 kelvin. It is measured in joules, kilojoules, or other units of energy.

Heat (Q) is the thermal energy that can be transferred between two systems by virtue of a temperature difference. It is much smaller than the total thermal energy because normal temperature differences are small. For example, when a hot drink cools down, it loses thermal energy or heat to the surroundings due to a difference in temperature. When the liquid reaches room temperature it still has lots of thermal energy, but no more heat is transferred because there is no temperature difference.

Temperature measures the average kinetic energy of the molecules of a substance. Kinetic energy includes all of their motion: vibration, translation, and rotation. Molecules are always moving except at absolute zero, which is defined as the temperature at which all motion stops.

Learning goals

Heat is transferred from higher temperature to lower temperature regions until equilibrium is reached.

Students can explain heat capacity and give everyday examples.

Note: This is one section of the “Science of Heat Transfer” chapter of the Engineering Energy Efficiency Project. See: <http://concord.org/engineering>

Heat storage

The heat stored in a material, called its heat capacity or thermal mass, is

$$Q = c_p m \Delta T$$

Q = heat (kJ)

c_p = specific heat (kJ/kg K)

m = mass (kg)

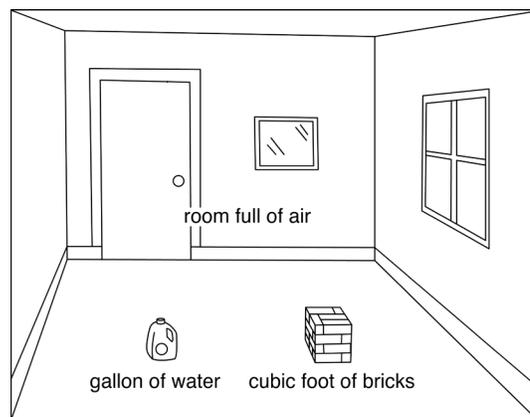
ΔT = change in temperature of the material (degrees Kelvin (K), or degrees Celsius (°C))

Expressed in words, this equation says that the heat stored in a material depends on its heat capacity per unit mass (different for different materials), its mass (how much of it there is), and the change in temperature of the object. The symbol (ΔT) means “change in temperature.” It could also be written as ($T_2 - T_1$).

Note the units for c_p (kJ/kg K). It is the amount of energy that it takes to raise one kilogram of a material one degree Kelvin (which is the same as one degree Celsius).

Note that heat capacity ($c_p m$) is the total heat per degree of temperature change stored in an object. “Heat capacity” is the total heat; “specific heat” is the heat per unit mass. Heat capacity is sometimes called “thermal mass.”

Different materials can store different amounts of heat because they have different specific heats. For example, for a given change in temperature, the same amount of heat is stored in a roomful of air, a cubic foot of bricks, or a gallon of water.



Ask students: What is an example of heat storage? What affects how much can be stored?

Air doesn't hold much heat, and most heat storage in buildings is in the solid materials – plaster walls, concrete floors, etc. Very little of it is in the air, which is quick to heat up, and quick to cool down.

Water has a very high heat capacity, that is, it takes a lot of energy to change the temperature of water a small amount, compared to many other materials. This is very significant in both natural and man-made systems. For example, much more heat is stored in the world's oceans than in its atmosphere, which is important when thinking about climate change. As another example, a much smaller volume of water is needed than air to transport heat from one place to another – say from the furnace to the rooms of a house.

Heat flows from a hotter to a colder body until the two are in thermal equilibrium at the same temperature. The total amount of heat remains the same, unless heat is lost from the system or gained from the outside. This is the principle of Conservation of Energy.

This principle can be used to measure the amount of heat stored in a material. If heat is allowed to flow between two objects at different temperatures, the heat gained by one object (A) is equal to the heat lost by the other one (B).

$$(c_p m \Delta T)_A + (c_p m \Delta T)_B = 0$$
$$(c_p m \Delta T)_A = -(c_p m \Delta T)_B$$

Use this principle to explore the factors that affect heat storage.

Two blocks of aluminum, one at 80° C and the other at 20° C, are placed in contact and surrounded by very good insulation. The warmer block is twice as large as the other. What will be the final temperature of each block? Explain how you figured it out.

The heat lost by one block must equal the heat gained by the other, so the smaller block's temperature must change twice as much as the larger block's temperature. This will be true if the smaller block changes by 40 °C and the larger block changes by 20 °C. The resulting temperature (60 °C) is the weighted average.

Experiment

HEAT CAPACITY

Tools & materials

- Temperature sensor
- Computer
- 200g or greater scale
- Hot tap water
- Cold tap water
- Water at room temperature (left overnight)
- Small paper or thin plastic or Styrofoam sample cups (not glass or ceramic)

One or more of the following test materials:

- Vegetable oil at room temperature
- Detergent to cut the oil
- Small nails at room temperature
- Pebbles at room temperature
- Sand at room temperature

Approximate heat capacities (J/g°C): vegetable oil: 1.7; olive oil 2.0; iron (nails): .45; sand: .84

In this experiment you will compare the specific heat capacity of various materials with a quick and simple test. If two equal masses of water at different temperatures are mixed together, the final temperature of the mixture is halfway between the two starting temperatures. If equal masses of water and some other material are mixed in the same way, the final temperature may not be at the halfway mark. That is the test you will use to compare the heat capacity of other materials to the heat capacity of water.

Procedure & data collection - Part I

1. Test water against water to practice your technique. Weigh out equal masses of water at different temperatures into two small sample cups. Be sure to tare the scale, that is, subtract the mass of the cup from the measurement. Pick an amount that will fill the mixing cup about three-quarters full when the two are combined.

Note: the greater the difference in temperature of the two samples, the more accurate the result will be.

2. Attach the temperature sensor to the computer.
3. Measure the temperature of each sample.
4. Quickly combine the two samples into a mixing cup, mix them, and measure their resulting temperature. If you are quick about it, the temperature will not drop.
5. Record your results in the table below.

Table 1: Heat capacity

	Water A	Water B	Combination
Mass			
Temperature			
Halfway point $(TempA + TempB) / 2 =$ _____			
Measured combination temperature = _____			
Difference = _____			

Analysis

Since Water A and Water B had the same mass and specific heat capacity, the combination should be at the average temperature of the two. How close were you?

What could account for the difference?

Procedure & data collection - Part II

1. Test water against oil. Weigh out equal masses of water and oil at different temperatures. Pick the same amount as before.
2. Attach the temperature sensor to the computer.
3. Add a few drops of detergent to the water, so that the oil and water will mix.
4. Measure the temperature of each sample.
5. Quickly combine the two samples, mix them, and measure their resulting temperature.
6. Record your results in the table below.

Table 2: Heat capacity

	Water	Oil	Combination
Mass			
Temperature	$T_w =$	$T_o =$	$T_f =$

Analysis

Using the equation introduced earlier and doing some algebra (see page 3), the specific heat of oil compared to water is

$$C_{\text{oil}}/C_{\text{water}} = (T_{\text{water}} - T_{\text{final}})/(T_{\text{final}} - T_{\text{oil}})$$

= (change in water temperature) / (change in oil temperature)

Your finding: $C_{\text{oil}} / C_{\text{water}} =$ _____

Is the specific heat capacity of oil greater or less than that of water?

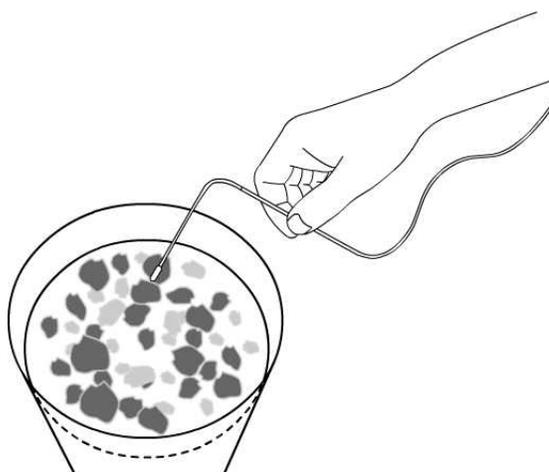
Since C_{water} is 4.18 J/g°C, what is C_{oil} ? _____

Procedure & data collection - Part III

1. Test water against another material – iron (nails) or rock (pebbles or sand). These have been chosen because they are granular and will quickly reach an equilibrium temperature with water even if they don't mix by dissolving.
2. Attach the temperature sensor to the computer.
3. Make sure the test material has been allowed to come to room temperature by sitting around for an hour or two.
4. Weigh out equal masses of water and test material. Pick the same masses as before.
5. Measure the temperature of each sample. Use room temperature for the test material.
6. Quickly pour the water onto the test material and stir the mixture. Measure their resulting temperature.
7. Record your results in the table below.

Table 3: Heat capacity

	Water	Test material	Combination
Mass			
Temperature	$T_w =$	$T_t =$	$T_f =$



Analysis

A previously noted,

$$C_{\text{test}}/C_{\text{water}} = (T_{\text{water}} - T_{\text{final}})/(T_{\text{final}} - T_{\text{test}})$$

= (change in water temperature) / (change in test material temperature)

Your finding: $C_{\text{test}} / C_{\text{water}} =$ _____

Is the specific heat capacity of the test material greater or less than that of water?

Since C_{water} is 4.18 J/g°C, what is C_{test} ? _____

Use these as discussion questions. As an extension, present this challenge: "If sunshine is used to heat a house, it is very intense for a few hours and then goes away all night. How does one maintain a constant temperature in the house in that situation, neither too hot during the day or too cold at night?"

Answer: thermal storage capacity will diminish both overheating and cooling off. But it must be thermally connected to the sunlight (light-absorbing surfaces) and the air to be useful.

Connection to buildings: Heat storage capacity

Application

How would a building with a high heat capacity (masonry) behave differently from a building with a low heat capacity (wood frame)?

- It would take longer to heat up, if they were both cold to start with.
- The temperature would be steadier.

When and where is it useful to store heat? Think about different contexts, such as houses, food, cooking, or water and give at least three examples.

As a general answer, whenever the heat source is intermittent and a constant temperature is desired.

- In a passive solar house, heat gained during the day should be stored in the walls and floor.
- A crock pot is heavy ceramic, partly to even out the temperature since heat is added in short bursts.
- The ocean stores an enormous amount of heat, which evens out the annual temperature changes in coastal regions.
- A thermos keeps hot drinks hot and cold drinks cold.
- A hot water bottle stores heat in water and releases it slowly to your body.
- A hot water tank typically has enough water for several showers, because the water doesn't heat up again as fast as the shower uses it up.

Rank these materials for their ability to store heat, from most to least: masonry, air, water, wood.

water, masonry, wood, air