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 to its actual temperature. 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 asubstance. 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.

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

To download Energy2D software, go to http://energy.concord.org/energy2d/

To run the models in this chapter, go to http://energy.concord.org/htb

Note the video tutorial.

Heat storage

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

$$Q = c_p m \Delta T$$

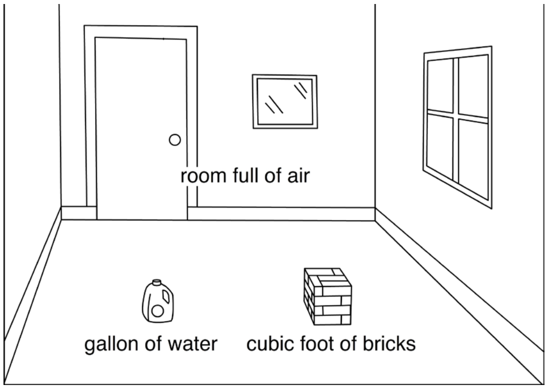
Q = heat (kJ)
c_p = specific heat (kJ/kg K)
m = mass (kg)
ΔT = change in temperature of the material (degrees Kelvin - K, or degrees Celsius - °C)

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.



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).

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

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

The following set of models allows you to use this principle to explore the factors that affect heat storage.

Energy2D

1A: Measuring heat storage

The first model you can try has two identical rectangular objects that are in contact. They have different initial temperatures that can be adjusted. Open Model 1A and follow the instructions, then answer the following questions.

When you run the model, what happens?

Why do the two thermometers reach the same temperature?

Record the results of at least three different setups of initial temperature differences.

Results from Model 1A		
Initial temperature of left object	Initial temperature of right object	Final temperature

In Model 1A, what rule can be used to determine the final temperature of the two objects if the objects are identical?

Why does a warm object feel warm when you touch it?

Energy2D

1B: Heat storage depends on specific heat

Substances vary greatly in their ability to store thermal energy. The specific heat is a property of a substance that tells how much the temperature goes up when a given amount of energy is added. A large specific heat means you have to put a lot of energy into it each each degree increase in temperature.

In this model the specific heat c_p of each object is different, as shown by the labels in the boxes. Note that the mass of the two objects in the model is the same. The temperature difference is fixed. But the specific heats can be adjusted. Open Model 1B and follow the instructions, then answer the following questions.

Predict the final temperature under each circumstance using the equation:

$$(c_p m\Delta T)_{\text{left}} = -(c_p m\Delta T)_{\text{right}}$$

Write your predicted results and the measured results of your three experiments below.

Results from Model 1B

Left-hand c_p	Left-hand initial temperature	Right-hand c_p	Right-hand initial temperature	Final temperature
1000	40	2000	10	

Make a general claim. For two materials with different heat capacities, how will the equilibrium temperature be affected?

1C: Heat storage depends on size

Energy2D

In this model the specific heat of each rectangular object is different, as shown in the label below them. The size of an object is a stand-in for mass in the equation, that is, how much material there is. According to the rule of conservation of energy, the amount of heat flowing in or out from the left rectangle must be equal to the amount of heat flowing out or in from the right rectangle.

$$(c_p A \Delta T)_{\text{left}} = -(c_p A \Delta T)_{\text{right}}$$

where A_{left} is the size (area) of the left object and A_{right} is the size (area) of the right object

Open Model 1C and follow the instructions, then answer the following questions.

Record the results of your experiments below. Note that these should all be results where the final temperature is close to 25 °C (within 1 °C).

Results from Model 1C

Left-hand c_p	Left-hand area	Right-hand c_p	Right-hand area
1000		2000	
1000		500	

Use the following equation to explain your results.

$$(c_p A \Delta T)_{\text{left}} = -(c_p A \Delta T)_{\text{right}}$$

Why does it take longer to heat up a bigger house?

Energy2D

2A: Regulating temperature

This model compares the rate of temperature rise when the heat capacities of the boxes are different but the power inputs are the same. This is an exaggerated version of a masonry house (large heat capacity) compared to a wood-frame house (small heat capacity). Open Model 2A and follow the instructions, then answer the following questions.

Which box heated up more quickly? Why?

After you turn the heater on and off, describe the graphs. Which curve was steadier and which was more variable? What was the range of temperature variation in each?

In the model, the power input is the same for both boxes. Why does the temperature change more for one than the other?

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)?

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.