Heat Transfer

Unit: Heat & Thermodynamics

NGSS Standards: HS-PS2-6, HS-PS3-2

MA Curriculum Frameworks (2006): 3.1

AP Physics 2 Learning Objectives: 1.E.3.1, 5.B.6.1

Knowledge/Understanding:

- heat transfer via conduction, radiation & convection

Skills:

- calculate heat transfer using Fourier's Law of Heat Conduction

Language Objectives:

- Understand and correctly use the terms "conduction," "convection," "radiation," "conductor," and "insulator."
- Accurately describe and apply the concepts described in this section using appropriate academic language.
- Set up and solve word problems relating to Fourier's Law of Heat Conduction.

Labs, Activities & Demonstrations:

- radiometer & heat lamp
- heat metal in contact with block of wood
- ladder of matches

Notes:

Heat transfer is the flow of heat energy from one object to another. Heat transfer usually occurs through three distinct mechanisms: conduction, radiation, and convection.

conduction: transfer of heat through collisions of particles by objects that are *in direct contact* with each other. Conduction occurs when there is a net transfer of momentum from the molecules of an object with a higher temperature transfer to the molecules of an object with a lower temperature.

Use this space for summary and/or additional notes:

thermal conductivity (*k*): a measure of the amount of heat that a given length of a substance can conduct in a specific amount of time. Thermal conductivity is measured in units of $\frac{J}{m \cdot s \cdot {}^\circ C}$ or $\frac{W}{m \cdot {}^\circ C}$.

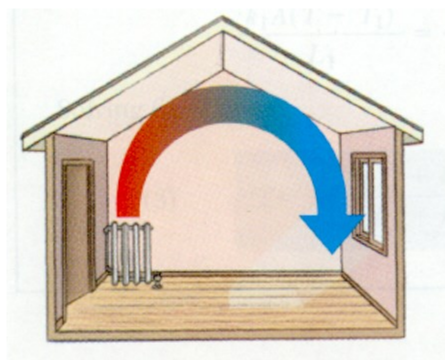
conductor: an object that allows heat to pass through itself easily; an object with high thermal conductivity.

insulator: an object that does not allow heat to pass through itself easily; a poor conductor of heat; an object with low thermal conductivity.

radiation: transfer of heat ***through space*** via electromagnetic waves (light, microwaves, *etc.*)

convection: transfer of heat ***by motion of particles*** that have a higher temperature exchanging places with particles that have a lower temperature. Convection usually occurs when air moves around a room.

Natural convection occurs when particles move because of differences in density. In a heated room, because cool air is more dense than warm air, the force of gravity is stronger on the cool air, and it is pulled harder toward the ground than the warm air. The cool air displaces the warm air, pushing it upwards out of the way.



In a room with a radiator, the radiator heats the air, which causes it to expand and be displaced upward by the cool air nearby. When the (less dense) warm air reaches the ceiling, it spreads out, and it continues to cool as it spreads. When the air reaches the opposite wall, it is forced downward toward the floor, across the floor, and back to the radiator.

Forced convection can be achieved by moving heated or cooled air using a fan. Examples of this include ceiling fans and convection ovens. If your radiator does not warm your room enough in winter, you can use a fan to speed up the process of convection. Remember to point the fan upwards—the fan needs to increase the natural convection that is already present, not oppose it!

Use this space for summary and/or additional notes.

Calculating Heat Transfer by Conduction

Heat transfer by conduction can be calculated using Fourier's Law of Heat Conduction:

$$\frac{Q}{t} = -kA\frac{\Delta T}{L}$$

where:

- Q = heat transferred (J)
- t = time (s)
- k = coëfficient of thermal conductivity ($\frac{\text{W}}{\text{m}\cdot{}^\circ\text{C}}$)
- A = cross-sectional area (m^2)
- ΔT = temperature difference (K or °C)
- L = length (m)

The minus sign is because heat transfer is calculated assuming that the system is the heat source. (Heat is moving out of the system, so we use a negative number.)

For insulation (the kind you have in the walls and attic of your home), the effectiveness is measured by the "R value", where:

$$R_i = \frac{L}{k}$$

and therefore:

$$\frac{Q}{t} = -\frac{1}{R_i}A\,\Delta T$$

The industry uses this definition because most people think larger numbers are better. Therefore a larger "R value" means less heat is transferred (lost) through the insulation, which means the insulation is doing a better job of preventing the heat loss.

R-values are not covered on the AP exam, but it's useful to understand what they mean when you're insulating your house.

Use this space for summary and/or additional notes.

Sample Problems:

Q: A piece of brass is 5.0 mm (0.0050 m) thick and has a cross-sectional area of 0.010 m^2. If the temperature on one side of the metal is 65°C and the temperature on the other side is 25°C, how much heat will be conducted through the metal in 30. s? The coefficient of thermal conductivity for brass is $120 \frac{\text{W}}{\text{m}\cdot{}^\circ\text{C}}$.

A: $\frac{Q}{t} = -kA\frac{\Delta T}{L}$

$$\frac{Q}{30} = -(120)(0.010)\left(\frac{65-25}{0.0050}\right)$$

$$\frac{Q}{30} = -9600$$

$$Q = -288\,000\text{ J} = -288\text{ kJ}$$

(Note that because the quantities of heat that we usually measure are large, values are often given in kilojoules or megajoules instead of joules.)

Q: Suppose your house has 15 cm-thick insulation, with an R value of 16, the temperature inside your house is 21°C and the temperature outside is 0.0°C. How much heat is lost through one square meter of insulation over an 8-hour (28 800 s) period?

A: An R value of 16 means $\frac{L}{k} = 16$, which means $\frac{k}{L} = \frac{1}{16}$.

$$\frac{Q}{t} = -kA\frac{\Delta T}{L} = -\frac{k}{L}A\Delta T$$

$$\frac{Q}{28800} = -\frac{1}{16}(1)(21)$$

$$\frac{Q}{28800} = -1.3125$$

$$Q = -37800\text{ J} = -37.8\text{ kJ}$$

Use this space for summary and/or additional notes.

Homework Problems

You will need to look up coefficients of thermal conductivity in Table H of your reference tables on page 583.

1. The surface of a hot plate is made of 12.0 mm (0.012 m) thick aluminum and has an area of 64 cm^2 (which equals 0.0064 m^2). If the heating coils maintain a temperature of 80.°C underneath the surface and the air temperature is 22°C, how much heat can be transferred through the plate in 60. s?

   Answer: −464 000 J or −464 kJ

2. A cast iron frying pan is 5.0 mm thick. If it contains boiling water (100°C), how much heat will be transferred into your hand if you place your hand against the bottom for two seconds?
   (Assume your hand has an area of 0.0040 m^2, and that body temperature is 37°C.)

   Answer: −8 064 J or −8.064 kJ

Use this space for summary and/or additional notes.

3. A plate of metal has thermal conductivity k and thickness L. One side has a temperature of T_h and the other side has a temperature of T_c, derive an expression for the cross-sectional area A that would be needed in order to transfer a certain amount of heat, Q, through the plate in time t.

   Answer: $A = \dfrac{QL}{kt\,(T_h - T_c)}$

4. Suppose the attic in your home is insulated with 27 cm of insulation with an R-value of 22, and the total surface area of the roof is 75 m^2. During a 24-hour period, the temperature outside is −5.0°C, and the temperature inside is 21°C. How much heat is lost through the roof during that 24-hour period? (Note: 24 h = 86 400 s.)

   Answer: −7 658 181 J or −7 658 kJ

Use this space for summary and/or additional notes.