Lecture 34

• Heat
  ➢ Heat transfer
    ➢ Conduction
    ➢ Convection
    ➢ Radiation

http://www.physics.wayne.edu/~apetrov/PHY2130/
Lightning Review

Last lecture:

1. Thermal physics
   ✓ Heat. Specific heat and heat capacity of ideal gas.
   ✓ Latent heat and phase transitions

Review Problem: A 75 g cube of ice at -10.0 °C is placed in 0.500 kg of water at 50.0 °C in an insulating container so that no heat is lost to the environment. What will be the final temperature of this system?
Recall: Latent Heat

- During a phase change, the amount of heat is given as

\[ Q = m \cdot L \]

- \( L \) is the *latent heat* of the substance. Latent heat is the amount of heat per unit mass required to change the phase of a substance. The energy is used to form/break chemical bonds.
  - Latent means hidden or concealed
- Choose a positive sign if you are adding energy to the system and a negative sign if energy is being removed from the system
- *Latent heat of fusion* (\( L_f \)) is used for melting or freezing
- *Latent heat of vaporization* (\( L_v \)) is used for boiling or condensing
Example: A 75 g cube of ice at -10.0 °C is placed in 0.500 kg of water at 50.0 °C in an insulating container so that no heat is lost to the environment. What will be the final temperature of this system?

To find the final temperature of the system, note that no heat is lost to the environment; the heat lost by the water is gained by the ice.

\[ 0 = Q_{\text{ice}} + Q_{\text{w}} \]

\[ 0 = m_{\text{ice}} c_{\text{ice}} \Delta T + m_{\text{ice}} L_f + m_{\text{ice}} c_w (T_f - T_{\text{ice},i}) + m_w c_w (T_f - T_{\text{w},i}) \]

\[ 0 = m_{\text{ice}} c_{\text{ice}} \Delta T + m_{\text{ice}} L_f + (m_{\text{ice}} + m_w) c_w T_f - m_w c_w T_i \]

\[ 0 = 27 \text{ kJ} + (m_{\text{ice}} + m_w) c_w T_f - 105 \text{ kJ} \]

\[ T_f = 32.4 \, ^\circ \text{C} \]
Example: Compute the heat of fusion of a substance from these data: 31.15 kJ will change 0.500 kg of the solid at 21 °C to liquid at 327 °C, the melting point. The specific heat of the solid is 0.129 kJ/kg K.

Use conservation of energy: all energy went to heat up and melt the substance:

\[
Q = mc\Delta T + mL_f
\]

\[
L_f = \frac{Q - mc\Delta T}{m}
\]

\[
= \frac{31.15kJ - 0.500kg \cdot 0.129kJ/kgK \cdot (306K)}{0.500kg} = 22.8 \text{ kJ/kg}
\]
Phase Diagram

Phase diagram is a type of chart used to show conditions at which thermodynamically distinct phases can occur at equilibrium.

On a phase diagram, the **triple point** is the set of P and T where all three phases can coexist in equilibrium.

**Sublimation** is the process by which a solid transitions into a gas (and gas → solid).
The **critical point** marks the end of the vapor pressure curve. A path around this point (i.e. the path does not cross the curve) does not result in a phase transition. Past the critical point it is not possible to distinguish between the liquid and gas phases.
Methods of Heat Transfer

• Need to know the rate at which energy is transferred
• Need to know the mechanisms responsible for the transfer

• Methods include
  • Conduction
  • Convection
  • Radiation
1. Conduction

- The transfer can be viewed on an atomic scale
  - It is an exchange of energy between microscopic particles by collisions
  - Less energetic particles gain energy during collisions with more energetic particles
- Rate of conduction depends upon the characteristics of the substance
Conduction example

• The molecules vibrate about their equilibrium positions
• Particles near the flame vibrate with larger amplitudes
• These collide with adjacent molecules and transfer some energy
• Eventually, the energy travels entirely through the rod

Conduction can occur only if there is a difference in temperature between two parts of the conducting medium.
Conduction

- The slab allows energy to transfer from the region of higher temperature to the region of lower temperature.

\[ P = \frac{Q}{t} = kA \frac{T_h - T_c}{\Delta x} \]

Heat flow \hspace{1cm} \text{Thermal conductivity}
Conduction

- A is the cross-sectional area
- $\Delta x$ is the thickness of the slab or the length of a rod
- P is in Watts when Q is in Joules and t is in seconds

- k is the **thermal conductivity** of the material
  - Good conductors have high k values and good insulators have low k values
Home Insulation

Also

\[ \Delta T = P \frac{d}{\kappa A} = PR \]

where R is the **thermal resistance**.

This is convenient when heat is conducted through multiple layers because

\[ \Delta T_{\text{total}} = P \sum_{i=1}^{n} R_i. \]
Example: A metal rod with a diameter of 2.30 cm and a length of 1.10 m has one end immersed in ice at 0 °C and the other end in boiling water at 100 °C. If the ice melts at a rate of 1.32 grams every 175 s, what is the thermal conductivity of the metal? Assume no heat loss to the surrounding air.

Heat is conducted to the ice at a rate of

\[ P = \frac{Q_c}{\Delta t} = \kappa A \frac{\Delta T}{d}. \]

The heat conducted to the ice in a time period \( \Delta t \) is

\[ Q_c = \kappa A \frac{\Delta T}{d} \Delta t. \]

The heat needed to melt a given mass of ice is

\[ Q = m_{\text{ice}} L_f. \]

Since all the heat conducted by the rod is absorbed by the ice,

\[ \kappa A \frac{\Delta T}{d} \Delta t = m_{\text{ice}} L_f \]

\[ \kappa = \frac{m_{\text{ice}} L_f}{A \frac{\Delta T}{d} \Delta t} = \frac{(0.00132 \text{ kg})(1.10 \text{ m})(333.7 \times 10^3 \text{ J/kg})}{\pi (1.15 \times 10^{-2} \text{ m})^2 (100 \text{ K})(175 \text{ s})} \]

\[ = 66.6 \text{ W/m K}. \]
Example: For a temperature difference of 20 °C, one slab of material conducts 10.0 W/m²; another of the same shape conducts 20.0 W/m². What is the rate of heat flow per m² of surface when the slabs are placed side by side with a total temperature difference of 20 °C?

For each slab, the thermal resistance per square meter is

\[ R_1 = \frac{\Delta T}{P_1 / A} = \frac{20.0 \text{ K}}{10.0 \text{ W/m}^2} = 2.00 \text{ K/W/m}^2 \]

\[ R_2 = \frac{\Delta T}{P_2 / A} = \frac{20.0 \text{ K}}{20.0 \text{ W/m}^2} = 1.00 \text{ K/W/m}^2. \]

When the materials are placed in series, the rate of heat flow is

\[ P = \frac{\Delta T}{\sum_{i=1}^{2} R_i} = \frac{\Delta T}{R_1 + R_2} = 6.67 \text{ W/m}^2. \]
2. Convection

- Energy transferred by the movement of a substance

- When the movement results from differences in density, it is called *natural conduction*
- When the movement is forced by a fan or a pump, it is called *forced convection*

The rate of energy transport by convection is \[ P = hA\Delta T \]

where \( h \) is the coefficient of convection, \( A \) is a surface area, and \( \Delta T \) is the temperature difference between the surface and convecting fluid.
Convection example

• Air directly above the flame is warmed and expands
• The density of the air decreases, and it rises
• The mass of air warms the hand as it moves by
• Applications:
  • Radiators
  • Cooling automobile engines
3. Radiation

- Radiation does not require physical contact
- All objects radiate energy continuously in the form of electromagnetic waves due to thermal vibrations of the molecules

- All bodies emit electromagnetic (EM) radiation. The perfect absorber and emitter of EM radiation is called a blackbody.

- Rate of radiation is given by Stefan’s Law

\[ P = \sigma A T^4 \]

where \( A \) is the surface area of the emitting body, \( T \) is its temperature, and \( \sigma = 5.670 \times 10^{-8} \text{ W/m}^2\text{ K}^4 \) is the Stefan-Boltzmann constant.
Radiation example

- The electromagnetic waves carry the energy from the fire to the hands
- No physical contact is necessary
Radiation equation

Since an ideal blackbody does not exist, Stefan’s law is written as

\[ P = \sigma A e T^4 \]

- P is the rate of energy transfer, in Watts
- \( \sigma = 5.6696 \times 10^{-8} \text{ W/m}^2 \text{ K}^4 \)
- A is the surface area of the object
- e is a constant called the *emissivity*
  - e varies from 0 to 1 (0 is for a perfect reflector and 1 is for blackbody)
- T is the temperature in Kelvins
A spectrum shows the amount of radiation emitted at a particular wavelength. For a blackbody, the peak of the spectrum is determined only by its temperature.

Wien’s law \[ \lambda_{\text{max}} T = 2.898 \times 10^{-3} \text{ m K} \]
Energy Absorption and Emission by Radiation

• With its surroundings, the rate at which the object at temperature T with surroundings at $T_o$ radiates is

$$P_{\text{net}} = \sigma A e (T^4 - T_o^4)$$

• When an object is in equilibrium with its surroundings, it radiates and absorbs at the same rate
  • Its temperature will not change
Example: Determine solar energy over the area of 1 m\(^2\). Temperature of Sun’s surface is 6000 K and temperature of surroundings is 300 K.

Given:

Area: \(A = 1 \text{ m}^2\)
Temperatures:
\(T_1 = 6000 \text{ K}\)
\(T_2 = 300 \text{ K}\)

Find:

Power = ?

Use Stefan’s law:

\[ \text{Power} = \alpha A \varepsilon \left( T_1^4 - T_2^4 \right) \]

Temperature of Sun’s surface \hspace{1cm} \text{Temperature on the Earth}

\[
\text{Power} = \alpha A \varepsilon \left( 6000K^4 - 300K^4 \right) \\
= \left( 5.67 \times 10^{-8} \right) \left( 1 \text{m}^2 \right) \left( 1 \right) \left( 1.3 \times 10^{15} K^4 \right) \\
= 7.3 \times 10^7 \text{ J/s}
\]
Ideal Absorbers and Reflectors

- An *ideal absorber* is defined as an object that absorbs all of the energy incident on it
  - \( e = 1 \)
- This type of object is called a *black body*
  - An ideal absorber is also an ideal radiator of energy
- An *ideal reflector* absorbs none of the energy incident on it
  - \( e = 0 \)
Applications of Radiation

- **Clothing**
  - Black fabric acts as a good absorber
  - White fabric is a better reflector

- **Thermography**
  - The amount of energy radiated by an object can be measured with a thermograph

- **Body temperature**
  - Radiation thermometer measures the intensity of the infrared radiation from the eardrum
The use of fiberglass insulation in the outer walls of a building is intended to minimize heat transfer through what process?

- a. conduction
- b. radiation
- c. convection
- d. vaporization
Resisting Energy Transfer

- Dewar flask/thermos bottle
- Designed to minimize energy transfer to surroundings
- Space between walls is evacuated to minimize conduction and convection
- Silvered surface minimizes radiation
- Neck size is reduced
Atmosphere Warming

• Greenhouse example
  • Visible light is absorbed and re-emitted as infrared radiation
  • Convection currents are inhibited by the glass

• Earth’s atmosphere is also a good transmitter of visible light and a good absorber of infrared radiation