Lecture 24

Goals:
• Chapters 17, thermodynamics

Assignment
• HW-10 due Tuesday, Nov 29
• Monday: Read Chapter 18
• Third test on Thursday, December 1

First Law of Thermodynamics

\[ \Delta U + \Delta K + \Delta E_{\text{thermal}} = \Delta E_{\text{system}} = W_{\text{external}} + Q \]

- For systems where there is no change in mechanical energy:

\[ \Delta E_{\text{thermal}} = W_{\text{external}} + Q \]

- 1 calorie = 4.186 Joules
- 1 food calorie = 1000 calories
Isothermal expansion (const T)

- Temperature does not change
  \[ \Delta E_{\text{thermal}} = 0 \]
- Work done on the gas is:
  \[ W < 0 \]

- From first law of thermodynamics we conclude:
  \[
  \Delta E_{\text{thermal}} = W + Q = 0 \\
  Q = -W
  \]

Work in a isothermal process

\[
W = - \int_{\text{initial}}^{\text{final}} P \, dV \\
W = - nRT \int_{V_i}^{V_f} \frac{1}{V} \, dV \\
W = - nRT \ln \left( \frac{V_f}{V_i} \right)
\]
**Isothermal compression**

- What is the change in thermal energy?
  
  \[
  A) \Delta E_{\text{thermal}} = 0 \\
  B) \Delta E_{\text{thermal}} < 0 \\
  C) \Delta E_{\text{thermal}} > 0
  \]

- What is the work done on the gas?
  
  \[
  A) W = 0 \\
  B) W < 0 \\
  B) W > 0
  \]

- What direction is the thermal energy flow?
  
  \[
  A) Q = 0 \\
  B) Q < 0 \\
  B) Q > 0
  \]

**Adiabatic processes**

- Processes where there is no thermal energy transfer to or from the system:
  
  \[
  Q = 0
  \]

- This does not mean that there is no change in temperature.

- For adiabatic processes:
  
  \[
  PV^{\gamma} = \text{constant}
  \]
Thermal Properties of Matter

Heat of Transformation

Latent heat of transformation $L$ is the energy required for 1 kg of substance to undergo a phase change. $(J / kg)$

\[ Q = \pm ML \]

Heat of vaporization for water is $L=2.3 \times 10^6$ J/kg.

\[ Q = +2.3 \times 10^6 \text{ J} \]

\[ Q = -2.3 \times 10^6 \text{ J} \]
Temperature change and specific heat

- Specific heat \( c \) of a substance is the energy required to raise the temperature of 1 kg by 1 K. (Units: J / K kg)

\[ Q = M c \Delta T \]

- Specific heat for water is \( c = 4190 \text{ J/K kg} \).

\[ Q = +4190 \text{ J} \]

\[ Q = -4190 \text{ J} \]

Exercise

- The specific heat \( (Q = M c \Delta T) \) of aluminum is about twice that of iron. Consider two blocks of equal mass, one made of aluminum and the other one made of iron, initially in thermal equilibrium.

- Heat is added to each block at the same constant rate until it reaches a temperature of 500 K. Which of the following statements is true?

(a) The iron takes less time than the aluminum to reach 500 K

(b) The aluminum takes less time than the iron to reach 500 K

(c) The two blocks take the same amount of time to reach 500 K
Specific heat for gases

For gases we typically use molar specific heat (Units: J / K mol )

\[ Q = n \ C \Delta T \]

For gases there is an additional complication. Since we can also change the temperature by doing work, the specific heat depends on the path.

\[ Q = n \ C_V \Delta T \] (temperature change at constant V)
\[ Q = n \ C_P \Delta T \] (temperature change at constant P)

Relationship between \( C_P \) and \( C_V \)

For path 1
\[ \Delta E_{\text{thermal}} = W + Q = nC_V \Delta T \]

For path 2
\[ \Delta E_{\text{thermal}} = W + Q = -P \Delta V + nC_P \Delta T \]
\[ = -nR \Delta T + nC_P \Delta T \]

Equating both paths we get

\[ C_P = C_V + R \]
Monoatomic vs diatomic gases

- Molar specific heats of all monatomic gases are around
  \[ C_V = 12.5 \text{ J/K mol} \]

- Molar specific heats of all diatomic gases are around
  \[ C_V = 20.8 \text{ J/K mol} \]

Energy transfer mechanisms

- Thermal conduction (or conduction)

- Convection

- Thermal Radiation
Thermal conduction

- Energy transferred by direct contact.

**Rate of energy transfer** \( (\text{J} / \text{s} \text{ or } \text{W}) \)

- Through a slab of area \( A \) and thickness \( \Delta x \), with opposite faces at different temperatures, \( T_c \) and \( T_h \)

\[
\frac{Q}{\Delta t} = k A \frac{(T_h - T_c)}{\Delta x}
\]

- \( k \): Thermal conductivity \((\text{J} / \text{s} \text{ m}^2 \text{°C})\)

Energy transfer mechanisms

- **Convection:**
  - Energy is transferred by flow of substance
  - Natural convection: from differences in density
  - Forced convection: from pump of fan

- **Radiation:**
  - Energy is transferred by photons
    - e.g.: infrared lamps
  - Stefan’s Law
    \[
    \mathcal{P} = \sigma A e T^4 \quad (\text{power radiated})
    \]
  - \( \sigma = 5.7 \times 10^{-8} \text{ W/m}^2 \text{ K}^4 \), \( T \) is in Kelvin, and \( A \) is the surface area
  - \( e \) is a constant called the emissivity
**Micro-macro connection: Atomic scale**

What is the typical size of an atom or a small molecule?

A) $10^{-6}$ m  
B) $10^{-10}$ m  
C) $10^{-15}$ m

$r \approx 1$ angstrom = $10^{-10}$ m

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**Percentage of molecules**

Nitrogen molecules near room temperature

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