Chapter 12

Principles of Thermodynamics

- Energy is conserved
- **FIRST LAW OF THERMODYNAMICS**
  - Examples: Engines (Internal $\rightarrow$ Mechanical)
    - Friction (Mechanical $\rightarrow$ Internal)
- All processes must increase entropy
- **SECOND LAW OF THERMODYNAMICS**
- Entropy is measure of disorder
- Engines can not be 100% efficient

Example 12.1
A cylinder of radius 5 cm is kept at pressure with a piston of mass 75 kg.

a) What is the pressure inside the cylinder? 1.950x10^5 Pa
b) If the gas expands such that the cylinder rises 12.0 cm, what work was done by the gas? 183.8 J
c) What amount of the work went into changing the gravitational PE of the piston? 88.3 J
d) Where did the rest of the work go? Compressing the outside air

Example 12.2a
A massive copper piston traps an ideal gas as shown to the right. The piston is allowed to freely slide up and down and equilibrate with the outside air.

The pressure inside the cylinder is _________ the pressure outside.
  
  a) Greater than
  b) Less than
  c) Equal to

Example 12.2b
A massive copper piston traps an ideal gas as shown to the right. The piston is allowed to freely slide up and down and equilibrate with the outside air.

The temperature inside the cylinder is _________ the temperature outside.
  
  a) Greater than
  b) Less than
  c) Equal to
Example 12.2c
A massive copper piston traps an ideal gas as shown to the right. The piston is allowed to freely slide up and down and equilibrate with the outside air.

If the gas is heated by a steady flame, and the piston rises to a new equilibrium position, the new pressure will be _________ than the previous pressure.

a) Greater than
b) Less than
c) Equal to

Example 12.3a
Outside Air: Room T, Atm. P
A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (a) Weight is slowly added to the piston, isothermally compressing the gas to half its original volume (b)

P_b is _________ P_a

a) Greater than
b) Less than
c) Equal to

ΔU = Q - PΔV
W = PΔV

Example 12.3b
Outside Air: Room T, Atm. P
A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (a) Weight is slowly added to the piston, isothermally compressing the gas to half its original volume (b)

T_b is _________ T_a

a) Greater than
b) Less than
c) Equal to

ΔU = Q - PΔV
W = PΔV

Example 12.3c
Outside Air: Room T, Atm. P
A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (a) Weight is slowly added to the piston, isothermally compressing the gas to half its original volume (b)

W_ab is _________ 0

a) Greater than
b) Less than
c) Equal to

Vocabulary: W_ab is work done by gas between a and b

ΔU = Q - PΔV
W = PΔV

Example 12.3d
Outside Air: Room T, Atm. P
A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (a) Weight is slowly added to the piston, isothermally compressing the gas to half its original volume (b)

U_b is _________ U_a

a) Greater than
b) Less than
c) Equal to

ΔU = Q - PΔV
W = PΔV

Some Vocabulary
- Isobaric • P = constant
- Isovolumetric • V = constant
- Isothermal • T = constant
- Adiabatic • Q = 0
A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down.
The system initially equilibrates at room temperature (a)
Weight is slowly added to the piston, isothermally compressing the gas to half its original volume (b)

Example 12.3e

\[ Q_{ab} \text{ is } \begin{cases} & a) \text{ Greater than} \\ & b) \text{ Less than} \\ & c) \text{ Equal to} \end{cases} \]

\[ \Delta U = Q - P \Delta V \]
\[ W = P \Delta V \]

Vocabulary: \( Q_{ab} \) is heat added to gas between a and b

Example 12.4a

\[ P_b \text{ is } \begin{cases} & a) \text{ Greater than} \\ & b) \text{ Less than} \\ & c) \text{ Equal to} \end{cases} \]

\[ \Delta U = Q - P \Delta V \]
\[ W = P \Delta V \]

Example 12.4b

\[ W_{ab} \text{ is } \begin{cases} & a) \text{ Greater than} \\ & b) \text{ Less than} \\ & c) \text{ Equal to} \end{cases} \]

\[ \Delta U = Q - P \Delta V \]
\[ W = P \Delta V \]

Example 12.4c

\[ Q_{ab} \text{ is } \begin{cases} & a) \text{ Greater than} \\ & b) \text{ Less than} \\ & c) \text{ Equal to} \end{cases} \]

\[ \Delta U = Q - P \Delta V \]
\[ W = P \Delta V \]

Example 12.4d

\[ U_b \text{ is } \begin{cases} & a) \text{ Greater than} \\ & b) \text{ Less than} \\ & c) \text{ Equal to} \end{cases} \]

\[ \Delta U = Q - P \Delta V \]
\[ W = P \Delta V \]

Example 12.4e

\[ T_b \text{ is } \begin{cases} & a) \text{ Greater than} \\ & b) \text{ Less than} \\ & c) \text{ Equal to} \end{cases} \]

\[ \Delta U = Q - P \Delta V \]
\[ W = P \Delta V \]
Example 12.5a
A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (a) The gas is cooled, isobarically compressing the gas to half its original volume (b) $P_b$ is _______ $P_a$

\[ \Delta U = Q - P \Delta V \]

\[ W = P \Delta V \]

- a) Greater than
- b) Less than
- c) Equal to

Example 12.5b
A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (a) The gas is cooled, isobarically compressing the gas to half its original volume (b) $W_{ab}$ is _______ 0

\[ \Delta U = Q - P \Delta V \]

\[ W = P \Delta V \]

- a) Greater than
- b) Less than
- c) Equal to

Example 12.5c
A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (a) The gas is cooled, isobarically compressing the gas to half its original volume (b) $T_b$ is _______ $T_a$

\[ \Delta U = Q - P \Delta V \]

\[ W = P \Delta V \]

- a) Greater than
- b) Less than
- c) Equal to

Example 12.5d
A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (a) The gas is cooled, isobarically compressing the gas to half its original volume (b) $U_b$ is _______ $U_a$

\[ \Delta U = Q - P \Delta V \]

\[ W = P \Delta V \]

- a) Greater than
- b) Less than
- c) Equal to

Example 12.5e
A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (a) The gas is cooled, isobarically compressing the gas to half its original volume (b) $Q_{ab}$ is _______ 0

\[ \Delta U = Q - P \Delta V \]

\[ W = P \Delta V \]

- a) Greater than
- b) Less than
- c) Equal to

Work from closed cycles
Consider cycle $A \rightarrow B \rightarrow A$

\[ W_{A \rightarrow B} \]

\[ -W_{B \rightarrow A} \]
Work from closed cycles

Consider cycle $A \rightarrow B \rightarrow A$

$$W_{A \rightarrow B \rightarrow A} = \text{Area}$$

Reverse the cycle, make it counter clockwise

$$-W_{B \rightarrow A} = W_{A \rightarrow B}$$

Example 12.6

a) What amount of work is performed by the gas in the cycle IAFI?

$$W = 3.04 \times 10^5 \text{ J}$$

b) How much heat was inserted into the gas in the cycle IAFI?

$$Q = 3.04 \times 10^5 \text{ J}$$

c) What amount of work is performed by the gas in the cycle IBFI?

$$W = -3.04 \times 10^5 \text{ J}$$

Example 12.7

Consider a monotonic ideal gas.

a) What work was done by the gas from A to B?

$$20,000 \text{ J}$$

b) What heat was added to the gas between A and B?

$$20,000 \text{ J}$$

c) What work was done by the gas from B to C?

$$-10,000 \text{ J}$$

d) What heat was added to the gas between B and C?

$$-25,000 \text{ J}$$

e) What work was done by the gas from C to A?

$$0 \text{ J}$$

f) What heat was added to the gas from C to A?

$$15,000 \text{ J}$$

Example Continued

Take solutions from last problem and find:

a) Net work done by gas in the cycle

$$W_{AB} + W_{BC} + W_{CA} = 10,000 \text{ J}$$

b) Amount of heat added to gas

$$Q_{AB} + Q_{BC} + Q_{CA} = 10,000 \text{ J}$$

This does NOT mean that the engine is 100% efficient!
Example 12.8b

In going from A to B to C, the change of the internal energy of the gas is _______ 0.

a) >
b) <
c) =

Example 12.8c

In going from A to B to C, the amount of heat added to the gas is _______ 0.

a) >
b) <
c) =

Example 12.8d

In going from A to B to C to D to A, the work done BY the gas is _______ 0.

a) >
b) <
c) =

Example 12.8e

In going from A to B to C to D to A, the change of the internal energy of the gas is _______ 0.

a) >
b) <
c) =

Example 12.8f

In going from A to B to C to D to A, the heat added to the gas is _______ 0.

a) >
b) <
c) =

Entropy

- Measure of Disorder of the system (randomness, ignorance)
- \( S = k_B \log(N) \)
- \( N = \# \) of possible arrangements for fixed \( E \) and \( Q \)
Entropy

• Total Entropy always rises (2nd Law of Thermodynamics)
• Adding heat raises entropy

$$\Delta S = Q/T$$

Defines temperature in Kelvin!

Why does Q flow from hot to cold?

• Consider two systems, one with $T_A$ and one with $T_B$
• Allow $Q > 0$ to flow from $T_A$ to $T_B$
• Entropy changed by:

$$\Delta S = Q/T_B - Q/T_A$$

• If $T_A > T_B$, then $\Delta S > 0$
• System will achieve more randomness by exchanging heat until $T_B = T_A$

Efficiencies of Engines

• Consider a cycle described by:
  - $W =$ work done by engine
  - $Q_{\text{hot}} =$ heat that flows into engine from source at $T_{\text{hot}}$
  - $Q_{\text{cold}} =$ heat exhausted from engine at lower temperature, $T_{\text{cold}}$
• Efficiency is defined:

$$e = \frac{W}{Q_{\text{hot}}} = \frac{Q_{\text{hot}} - Q_{\text{cold}}}{Q_{\text{hot}}} = 1 - \frac{Q_{\text{cold}}}{Q_{\text{hot}}}$$

Since $\Delta S = Q/T > 0$

$$\frac{Q_{\text{cold}}}{T_{\text{cold}}} > \frac{Q_{\text{hot}}}{T_{\text{hot}}} \Rightarrow \frac{Q_{\text{cold}}}{T_{\text{hot}}} > \frac{T_{\text{cold}}}{T_{\text{hot}}} \Rightarrow e < 1 - \frac{T_{\text{cold}}}{T_{\text{hot}}}$$

Carnot Engines

• Idealized engine
• Most efficient possible

$$e = \frac{W}{Q_{\text{hot}}} = 1 - \frac{T_{\text{cold}}}{T_{\text{hot}}}$$

Example 12.9

An ideal engine (Carnot) is rated at 50% efficiency when it is able to exhaust heat at a temperature of 20 ºC. If the exhaust temperature is lowered to -30 ºC, what is the new efficiency.

$$e = 0.585$$
Refrigerators

Given: Refrigerated region is at \( T_{\text{cold}} \)
Heat exhausted to region with \( T_{\text{hot}} \)

Find: Efficiency

\[
e = \frac{Q_{\text{cold}}}{W} = \frac{Q_{\text{hot}} - Q_{\text{cold}}}{Q_{\text{hot}} / Q_{\text{cold}} - 1}
\]

Since \( \Delta S = Q / T > 0 \)

\[
\frac{Q_{\text{hot}}}{T_{\text{hot}}} > \frac{Q_{\text{cold}}}{T_{\text{cold}}} \Rightarrow \frac{Q_{\text{hot}}}{T_{\text{cold}}} > \frac{Q_{\text{hot}}}{T_{\text{hot}}} \Rightarrow \frac{e}{1 - Q_{\text{cold}} / Q_{\text{hot}}} < \frac{1}{T_{\text{hot}} / T_{\text{cold}} - 1}
\]

Note: Highest efficiency for small \( T \) differences

Heat Pumps

Given: Inside is at \( T_{\text{hot}} \)
Outside is at \( T_{\text{cold}} \)

Find: Efficiency

\[
e = \frac{Q_{\text{hot}}}{W} = \frac{1 - Q_{\text{cold}} / Q_{\text{hot}}}{1 - Q_{\text{hot}} / Q_{\text{cold}}}
\]

Since \( \Delta S = Q / T > 0 \),

\[
\Delta S = Q / T > 0,
\]

Like Refrigerator: Highest efficiency for small \( \Delta T \)

Example 12.10

A modern gas furnace can work at practically 100% efficiency, i.e., 100% of the heat from burning the gas is converted into heat for the home. Assume that a heat pump works at 50% of the efficiency of an ideal heat pump.

If electricity costs 3 times as much per kw-hr as gas, for what range of outside temperatures is it advantageous to use a heat pump?

Assume \( T_{\text{inside}} = 295 \) °K.

\[
T = 295 \cdot 5 \div 6 = 245.8 \text{ K} = -27 \text{ °C}
\]

Example 12.11a

An engine does an amount of work \( W \), and exhausts heat at a temperature of 50 degrees C. The chemical energy contained in the fuel must be greater than, and not equal to, \( W \).

a) True
b) False

Example 12.11b

A locomotive is powered by a large engine that exhausts heat into a large heat exchanger that stays close to the temperature of the atmosphere. The engine should be more efficient on a very cold day than on a warm day.

a) True
b) False

Example 12.11c

An air conditioner uses an amount of electrical energy \( U \) to cool a home. The amount of heat removed from the home must be less than or equal to \( U \).

a) True
b) False
Example 12.11d

A heat pump uses an amount of electrical energy $U$ to heat a home. The amount of heat added to a home must be less than or equal to $U$.

a) True
b) False