PHYS11 CH:12.1-12.4

Laws of Thermodynamics and Applications

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March, 2025

Overview

Learning Objectives

By the end of this lesson, you will be able to:

- Explain the concept of thermal equilibrium and the zeroth law
- Apply the first law of thermodynamics to calculate energy, work, and heat
- Understand entropy and the second law of thermodynamics
- Describe the working principles of heat engines, heat pumps, and refrigerators
- Calculate thermal efficiency of heat engines
- Relate thermodynamic principles to real-world applications

- **Thermal Equilibrium:** Two systems have the same temperature
- **Thermal Contact:** Heat can transfer between objects
- Two objects in thermal contact will eventually reach thermal equilibrium
- At equilibrium, there is no net heat transfer

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Important Point

Thermal equilibrium occurs when two bodies are in contact with each other and can freely exchange energy.

The Zeroth Law of Thermodynamics

Zeroth Law Statement

If two systems, A and B, are in thermal equilibrium with each other, and B is in thermal equilibrium with a third system, C, then A is also in thermal equilibrium with C.

phys11-thermo-zeroth-law.jpg

Pressure and Thermal Expansion

Pressure:

- Force per unit area

$$P = \frac{F}{A}$$

- SI unit: Pascal (Pa) = N/m^2

Thermal Expansion:

- Change in size due to temperature change
- Results from increased molecular motion
- Important in engineering and everyday applications (bridges, thermostats, etc.)

Why does thermal expansion occur?

An increase in temperature causes intermolecular distances to increase as particles gain kinetic energy.

Ideal Gas Law

Ideal Gas Law

$$PV = NkT$$

where:

- P = pressure (Pa)
- V = volume (m^3)
- N = number of particles
- k = Boltzmann constant (1.38×10^{-23} J/K)
- T = absolute temperature (K)

Real vs. Ideal Gases

A real gas behaves most like an ideal gas at:

- High temperatures
- Low pressures

Under these conditions, particle interactions become negligible.

Energy Transfer: Heat and Work

Two Methods of Energy Transfer

- **Heat (Q):** Energy transferred solely due to a temperature difference
- **Work (W):** Energy transfer that doesn't rely on temperature difference

Pressure-Volume Work

$$W = P\Delta V$$

- Work is done *by* a system when it *expands* ($\Delta V > 0$)
- Work is done *on* a system when it is *compressed* ($\Delta V < 0$)

[Diagram showing work done by/on a gas in a piston] phys11-thermo-work-done-by-gas-piston.png

First Law of Thermodynamics

First Law Statement

The change in internal energy of a system equals the net heat transferred into the system minus the net work done by the system.

$$\Delta U = Q - W$$

where:

- ΔU = change in internal energy
- Q = net heat transferred into the system
- W = net work done by the system

Key Insights

- The first law is an application of the conservation of energy
- Internal energy (U) depends only on the state of the system
- Q and W represent energy in transit; only ΔU represents stored energy

Entropy

What is Entropy?

- A measure of a system's disorder
- The reduced availability of energy to do work
- SI unit: joules per kelvin (J/K)

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Change in Entropy

$$\Delta S = \frac{Q}{T}$$

where:

- ΔS = change in entropy
- Q = heat transferred

Second Law of Thermodynamics

Second Law Statement

For any spontaneous process, the total entropy of a system either increases or remains constant; it never decreases.

Implications of the Second Law

- Heat flows spontaneously from higher to lower temperature, never the reverse
- Energy tends to disperse from concentrated to dispersed states
- Perfect heat engines (100% efficiency) are impossible
- All natural processes are irreversible

Everyday Examples

- Air freshener molecules dispersing in a room
- Ice melting in water
- Spreading of salt in water

Heat Engines

- **Heat Engine:** Device that converts thermal energy to mechanical work
- Uses temperature difference between hot and cold reservoirs
- Works through a cyclic process
- Examples: steam engines, internal combustion engines, gas turbines

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Cyclic Process

A process that returns to its original state at the end of every cycle, so that the change in internal energy is zero ($\Delta U = 0$).

Thermal Efficiency

Thermal Efficiency Formula

$$\text{eff} = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h}$$

where:

- eff = thermal efficiency
- W = work output
- Q_h = heat input from hot reservoir
- Q_c = heat output to cold reservoir

Important Points

- Efficiency is always less than 100%
- Some heat is always lost to the environment
- Efficiency would be 100% only if $Q_c = 0$ (impossible due to the second law)
- For a cyclical process, work output $W = Q_h - Q_c$

Heat Pumps and Refrigerators

Heat Pump:

- Transfers heat from cold to hot environment
- Requires work input
- Used for heating buildings
- Energy efficient compared to direct heating

Refrigerator:

- A type of heat pump
- Removes heat from inside to outside
- Components: compressor, condenser, expansion valve, evaporator

Advantage of Heat Pumps

A heat pump supplies energy by heat from the cold, outside air and also from the energy generated by the work done.

[Diagram showing heat pump/refrigerator cycle] phys11-thermo-heat-pump-refrigerator-cycle.png

"I do" Example

Problem

Some amount of energy is transferred by heat into a system. The net work done by the system is 50 J, while the increase in its internal energy is 30 J. What is the amount of net heat?

Solution

1. Use the first law of thermodynamics: $\Delta U = Q - W$
2. Given information:
   - $\Delta U = 30$ J (increase in internal energy)
   - $W = 50$ J (net work done by the system)
3. Rearrange the equation to solve for Q:

$$\begin{aligned} Q &= \Delta U + W \\ &= 30 \text{ J} + 50 \text{ J} \\ &= 80 \text{ J} \end{aligned}$$

4. Therefore, the amount of net heat transferred to the system is 80 J.

"We do" Example

Problem

Assume 310 J of heat enter a system, after which the system does 120 J of work. What is the change in its internal energy? Would this amount change if the energy transferred by heat were added after the work was done instead of before?

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Solution Steps

1. Apply the first law of thermodynamics: $\Delta U = Q - W$
2. Given information:
   - $Q = 310$ J (heat entering the system)
   - $W = 120$ J (work done by the system)
3. Calculate the change in internal energy:

$$\begin{aligned} \Delta U &= Q - W \\ &= 310 \text{ J} - 120 \text{ J} \\ &= 190 \text{ J} \end{aligned}$$

"You do" Example

Problem

A coal power station functions at 40.0 percent efficiency. What is the amount of work it does if it takes in 4.00×10 J by heat?

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Hints

- Use the thermal efficiency formula: $\text{eff} = \frac{W}{Q_h}$
- Efficiency is given as a percentage (40.0%)
- Heat input (Q_h) is 4.00×10 J

Take some time to work this out. Then we'll discuss the solution.

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Answer

The work done by the power station is 1.60×10 J.

Key Equations

First Law of Thermodynamics:

$$\Delta U = Q - W$$
$$PV = NkT$$
$$P = \frac{F}{A}$$
$$W = P\Delta V$$

Second Law and Applications:

$$\Delta S = \frac{Q}{T}$$
$$\text{eff} = \frac{W}{Q_h}$$
$$W = Q_h - Q_c$$

Laws of Thermodynamics Summary

Zeroth Law

If two systems are each in thermal equilibrium with a third system, they are in thermal equilibrium with each other.

First Law

Energy can be transferred and transformed, but it cannot be created or destroyed.

$\Delta U = Q - W$

Second Law

For any spontaneous process, the total entropy of a system either increases or remains constant; it never decreases.

Practical Applications

Heat engines, power plants, refrigerators, heat pumps, and many industrial processes rely on thermodynamic principles.

Thank You!

Questions?

Remember to review the key laws and concepts for the upcoming quiz!