Objectives

- Introduce the concept of energy forms.
- Discuss the nature of internal energy.
- Define the concept of heat and three mechanisms of heat transfer: conduction, convection, and radiation.
- Define the concept of work, including electrical work and several forms of mechanical work.
- Introduce the first law of thermodynamics, energy balances, and mechanisms of energy transfer to or from a system.
- Define energy conversion efficiencies.
- Implications of energy conversion on the environment.

Introduction

The first law of thermodynamics: energy can be neither created nor destroyed during a process; it can only change forms.

Energy can transfer between a system and surroundings.

Forms of Energy

- Energy can exist in numerous forms: internal energy, U, (thermal energy, chemical and nuclear energy).

Physical Insight to Internal Energy

Thermal energy = Sensible + Latent energy

Sensible energy: The portion of the internal energy of a system associated with the kinetic energies of the molecules.

Latent energy: The internal energy associated with the phase of a system.

Nuclear energy: The tremendous amount of energy associated with the strong bonds within the nucleus of the atom itself.

- Nuclear energy by fusion is released when two small nuclei combine into a larger one.
- The best known fusion reaction involves the split of the uranium atom (the U-235 isotope) into other elements and is commonly used to generate electricity in nuclear power plants (440 of them in 2004, generating 363,000 MW worldwide).
**Physical Insight to Internal Energy**

**Chemical energy:** The internal energy associated with the atomic bonds in a molecule.

**Thermal = Sensible + Latent**

**Internal energy = Sensible + Latent + Chemical + Nuclear**

The internal energy of a system is the sum of all forms of the microscopic energies.

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**Total Energy of Stationary Systems**

- **Internal energy (U):** The sum of all the microscopic forms of energy.
- **Kinetic energy (KE):** The energy that a system possesses as a result of its motion relative to some reference frame.
- **Potential energy (PE):** The energy that a system possesses as a result of its elevation in a gravitational field.

Total energy of a stationary system

\[ E = U + KE + PE = U + m \frac{v^2}{2} + mgz \quad (J) \]

Total energy per unit mass

\[ e = \frac{E}{m} \quad (J/kg) \]

Total energy per unit mass

\[ e = u + ke + pe = u + \frac{v^2}{2} + gz \quad (J/kg) \]

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**Energy of Flowing Fluid**

**Flow energy (or flow work):** The energy required to push the mass into or out of the control volume. This work is necessary for maintaining a continuous flow through a control volume.

\[ F = PA \]

\[ W_{flow} = FL = PAL = PV \quad (J) \]

The flow energy per unit mass:

\[ W_{flow} = PV \quad (J/kg) \]

Since \( v = \frac{1}{\rho} \)

Hence \( W_{flow} = \frac{P}{\rho} \quad (J/kg) \)

\[ e = \frac{P}{\rho} \quad (J/kg) \]

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**Mechanical Energy**

**Mechanical energy:** The form of energy that can be converted to mechanical work completely and directly by a mechanical device such as an ideal turbine.

**Kinetic and potential energies:** Two forms of mechanical energy.

- **Kinetic energy per unit mass:** \( KE = \frac{m v^2}{2} \) (J) or use unit (kJ)
- **Potential energy per unit mass:** \( PE = mgz \) (J) or (kJ)

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**Mass of a Fluid**

**Mass:** \( m = \rho V \)

\[ \frac{m}{t} = \rho \frac{V}{t} \]

**Mass flow rate:** the amount of mass flowing through a cross section per unit time

Volume flow rate:

\[ \dot{V} = \frac{V}{t} \quad (m^3/s) \]

**Mass flow rate:** \( \dot{m} = \rho \dot{V} = \rho A V_{avg} \quad (kg/s). \)

Where \( V_{avg} \) is the average velocity

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**Mechanical Energy of a Fluid**

**Mechanical energy of a flowing fluid per unit mass:** \( \epsilon_{mech} = \frac{P}{\rho} + \frac{v^2}{2} + gz \)

\[ \rho \frac{P}{kg/m^3} \]

\[ \frac{N/m^2}{kg/m^3} \]

\[ \frac{N/m^2 m}{kg/m^3 kg/m} \]

\[ \frac{N/m^2}{kg/kg} \]

**Rate of mechanical energy of a flowing fluid**

\[ \dot{\epsilon}_{mech} = \dot{m} \epsilon_{mech} = \dot{m} \left( \frac{P}{\rho} + \frac{v^2}{2} + gz \right) \quad (W) \]

**Mechanical energy change of a fluid during incompressible flow per unit mass**

\[ \Delta \epsilon_{mech} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \quad (J/kg) \]

**Rate of mechanical energy change of a fluid during incompressible flow**

\[ \dot{\Delta \epsilon}_{mech} = \dot{m} \Delta \epsilon_{mech} = \dot{m} \left( \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right) \quad (W) \]
Total Energy of Systems

Total energy per unit mass of a stationary system:

\[ e = u + ke + pe = u + \frac{1}{2} \rho v^2 + gz \]  

(J/kg)

Mechanical energy per unit mass

Total energy per unit mass of a fluid system:

\[ e = u + \frac{P}{\rho} + \frac{1}{2} \rho v^2 + gz \]  

(J/kg)

Mechanical energy per unit mass

Energy Transfer

- The total energy of a system, can be contained or stored in a system, and thus can be viewed as the static forms of energy.
- The forms of energy not stored in a system can be viewed as the dynamic forms of energy or as energy interactions.
- The only two forms of energy interactions associated with a closed system are heat transfer and work.
- The difference between heat transfer and work: An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise it is work.

Energy Transfer by Heat

\[ q = \frac{Q}{m} \]  

(1/kg)

Heat transfer per unit mass

\[ Q = \dot{Q} \Delta t \]  

(kJ)

Amount of heat transfer when heat transfer rate is constant

\[ Q = \int_{t_i}^{t_f} \dot{Q} dt \]  

(kJ)

Amount of heat transfer when heat transfer rate changes with time

Energy is recognized as heat transfer only as it crosses the system boundary.

Heat Transfer Mechanism:

- **Conduction:** The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interaction between particles.

\[ \text{Conduction} \]

- **Convection:** The transfer of energy between a solid surface and the adjacent fluid that is in motion, and it involves the combined effects of conduction and fluid motion.

\[ \text{Convection} \]

- **Radiation:** The transfer of energy due to the emission of electromagnetic waves (or photons).

\[ \text{Radiation} \]
Energy Transfer by Work

• **Work**: The energy transfer associated with a force acting through a distance.
  - A rising piston, a rotating shaft, and an electric wire crossing the system boundaries are all associated with work interactions

• **Formal sign convention**: Heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative.
  - Alternative to sign convention is to use the subscripts in and out to indicate direction. This is the primary approach in this text.

Power is the work done per unit time:

\[ w = \frac{W}{\Delta t} \text{ (W) or (kW)} \]

Heat versus Work

• Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are boundary phenomena.

• Systems possess energy, but not heat or work.
  - Both are associated with a process, not a state.
  - Unlike properties, heat or work has no meaning at a state.

• Both are **path functions** (i.e., their magnitudes depend on the path followed during a process as well as the end states).

Electrical Work

Electrical work

\[ W_e = V I \text{ (J)} \]

Electrical power

\[ W_e = \frac{V I}{\Delta t} \text{ (W) or (J/s)} \]

When potential difference and current change with time

\[ W_e = \int V I \, dt \text{ (J)} \]

When potential difference and current remain constant

\[ W_e = V I \Delta t \text{ (J)} \]

Mechanical Work

• There are two requirements for a work interaction between a system and its surroundings to exist:
  - there must be a **force** acting on the boundary.
  - the boundary must **move**.

Shaft Work

A force \( F \) acting through a moment arm \( r \) generates a torque \( T \)

\[ T = Fr \rightarrow F = \frac{T}{r} \]

This force acts through a distance \( s \)

Shaft work

\[ W_s = Fs = \left( \frac{T}{r} \right) \cdot 2\pi n = \frac{2\pi n T}{r} \text{ (J)} \]

The power transmitted through the shaft is the shaft work done per unit time

\[ W_s = \frac{2\pi n T}{\Delta t} \text{ (W)} \]

Spring Work

When the length of the spring changes by a differential amount \( dx \) under the influence of a force \( F \), the work done is

\[ \delta W_{spring} = F \, dx \]

For linear elastic springs, the displacement \( x \) is proportional to the force applied

\[ F = kx \text{ (N)} \]

\[ W_{spring} = \int kx \, dx \]

\[ W_{spring} = \frac{1}{2}k(x_2^2 - x_1^2) \text{ (J)} \]

\( x_1 \) and \( x_2 \): the initial and the final displacements

Properties are point functions (have exact differentials (\( d \))). Path functions have inexact differentials (\( \delta \)).

Specifying the directions of heat and work.
Work Done on Elastic Solid Bars

\[ W_{\text{elastic}} = \int_1^2 F \, dx = \int_1^2 \sigma \, A \, dx \] (J)

Work Associated with the Stretching of a Liquid Film

\[ W_{\text{surface}} = \int \sigma \, dA \] (J)

The First Law of Thermodynamics

- The first law of thermodynamics (the conservation of energy principle) provides a sound basis for studying the relationships among the various forms of energy and energy interactions.
- The first law states that energy can be neither created nor destroyed during a process; it can only change forms.
- The First Law: For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.

Energy Change of a System, \( \Delta E_{\text{system}} \)

Energy change = Energy at final state - Energy at initial state

\[ \Delta E_{\text{system}} = E_{\text{final}} - E_{\text{initial}} = E_2 - E_1 \]

Internal, kinetic, and potential energy changes

\[ \Delta U = m(u_2 - u_1) \]

\[ \Delta KE = \frac{1}{2} m(V_2^2 - V_1^2) \]

\[ \Delta PE = mg(z_2 - z_1) \]

Mechanical Energy and Work

**EXAMPLE 2-9  Power Needs of a Car to Accelerate**

Determine the power required to accelerate a 900-kg car shown in Fig. 2-36 from rest to a velocity of 60 km/h in 20 s on a level road.

Analysis: The work needed to accelerate a body is simply the change in the kinetic energy of the body.

\[ W_a = \frac{1}{2} m(V_f^2 - V_i^2) = \frac{1}{2} (900 \, \text{kg})(80,000 \, \text{m}^2/3600 \, \text{J}) = 222,000 \, \text{J} = 222 \, \text{kJ} \]

The average power is determined from

\[ W = \frac{W_a}{\Delta t} = \frac{222 \, \text{kJ}}{20 \, \text{s}} = 11.1 \, \text{kW} \]

**FIGURE 2-36**

Energy Balance

The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.

**Mechanisms of Energy Transfer**

The energy content of a control volume can be changed by mass flow as well as heat and work interactions.
## Mechanisms of Energy Transfer

A closed mass involves only heat transfer and work. The net energy transfer by heat, work, and mass is given by:

\[ E_{in} - E_{out} = \Delta E_{system} \quad (J) \]

Where \( E_{in} \) and \( E_{out} \) are the net energy transfer by heat, work, and mass, and \( \Delta E_{system} \) is the change in internal, kinetic, potential, etc., energies. The rate of net energy transfer by heat, work, and mass is:

\[ \frac{dE}{dt} = \frac{dE_{system}}{dt} \quad (\text{W}) \]

where \( \frac{dE}{dt} \) is the rate of change in internal, kinetic, potential, etc., energies.

\[ \Delta E = (dE/dt) \Delta t \]

\[ e_{in} - e_{out} = \Delta E_{system} \quad (J/kg) \]

\[ W_{net} = \dot{Q}_{net} \quad (\text{W}) \quad \text{(for a cycle)} \]

\[ Q = \dot{Q} \Delta t \quad (J) \]

\[ W = \dot{W} \Delta t \quad (J) \]

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## Adiabatic System

For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process. The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.

In the absence of any work interactions, the energy change of a system is equal to the net heat transfer. The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

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## Work Done to Raise or to Accelerate a Body

An elevator car with a mass of 2204.7 lbm is initially stopped at a position of 5 ft high. A motor is needed to drive the elevator within 2 s to a position of 11.562 ft with a velocity of 2 m/s. How much power is needed for the motor?

- **Mass**: 2204.7 lbm = 1000 kg
- **Initial Position**: 5 ft = 1.524 m
- **Final Position**: 11.562 ft = 3.524 m
- **Velocity**: 2 m/s
- **Time**: 2 s

The energy change due to raising the elevator can be calculated as:

\[ \Delta E = m g (Z_2 - Z_1) + \frac{1}{2} m v_f^2 \]

\[ = 1000 \times 9.8 \times (3.524 - 1.524) + \frac{1}{2} \times 1000 \times (2)^2 \]

\[ = 12000 \text{ J} \]

The power required can be calculated as:

\[ P = \frac{\Delta E}{t} \]

\[ = \frac{12000}{2} = 6000 \text{ W} \]

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## The First Law of Thermodynamics

The air contained in a room loses heat to the surroundings at a rate of 50 kJ/min while work is supplied to the room by a furnace that draws a current of 10 A at 120 V. What is the net amount of energy change of the air in the room during a 30-min period?

\[ \Delta E = W_{in} - Q_{out} = (W_{in} - Q_{out}) \Delta t = (VI - Q_{out}) \Delta t \]

\[ \Delta E = (120 \times 10) - (50 \times 1000) \times (30 \times 60) \]

\[ = 660000 \text{ J} \]

\[ = 660 \text{ kJ} \]

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## Energy Conversion Efficiencies

**Efficiency** is a frequently used term in thermodynamics, and it indicates how well an energy conversion or transfer process is accomplished. Efficiency is calculated as:

\[ \text{Efficiency} = \frac{\text{Desired output}}{\text{Required input}} \]

**Performance** is desired output over required input:

\[ \text{Performance} = \frac{\text{Desired output}}{\text{Required input}} \]

**Efficiency of a water heater**: The ratio of the energy delivered to the house by hot water to the energy supplied to the water heater.
The efficiency of a cooking appliance represents the fraction of the energy supplied to the appliance that is transferred to the food.

### Energy Conversion Efficiencies

**Mechanical efficiency:**

\[
\eta_{\text{mech}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{1}{1 - \text{Combustion efficiency}}
\]

**Lower heating value (LHV):** When the water leaves as a vapor.

**Higher heating value (HHV):** When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.

### Efficiencies of Mechanical and Electrical Devices

**Turbine:** A device that converts the energy of a working fluid to mechanical energy.

**Pump:** A device that supplies mechanical energy to a fluid.

**Generator:** A device that converts mechanical energy to electrical energy.

**Generator efficiency:**

\[
\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{W_{\text{electric}}}{W_{\text{thermal}}}
\]

The overall efficiency of a turbine-generator is the product of the efficiency of the turbine and the efficiency of the generator, and represents the fraction of the mechanical energy of the fluid converted to electrical energy.

\[
\eta_{\text{overall}} = \eta_{\text{turbine}} \times \eta_{\text{generator}} = \frac{W_{\text{net,electric}}}{HHV \times m_{\text{net}}}
\]

Currently, the overall efficiency is about 60% for large-scale power plants.
Efficiencies of Mechanical and Electrical Devices

The water in a large lake is to be used to generate electricity by the installation of a hydraulic turbine-generator at a location where the depth of the water is 50 m (Fig. 2-60). Water is to be supplied at a rate of 5000 kg/s. If the electric power generated is measured to be 1862 kW and the generator efficiency is 95 percent, determine (a) the overall efficiency of the turbine-generator, (b) the mechanical efficiency of the turbine, and (c) the shaft power supplied by the turbine to the generator.

The mechanical energy of water at the exit is negligible, $\Delta E_{\text{mech, in}} = 0$

For the fluid passing the turbine:

$\Delta E_{\text{mech, fluid}} = m gh$

The overall efficiency of the turbine-generator system:

$\eta_{\text{overall}} = \frac{W_{\text{shaft, out}}}{\Delta E_{\text{mech, fluid}}} = \frac{1862\,000}{2455\,000} = 0.76$

The mechanical efficiency of the turbine can be derived from:

$\eta_{\text{mech}} = \eta_{\text{overall}} \eta_{\text{generator}} \Rightarrow \eta_{\text{mech}} = \frac{0.76}{0.95} = 0.80$

The shaft power output of the turbine:

$W_{\text{shaft, out}} = \Delta E_{\text{mech, fluid}} \times \eta_{\text{mech}} = 2455\,000 \times 0.8 = 196400\, W$

Energy and Environment

Energy conversion processes are often accompanied by environmental pollution.

- Pollutants emitted during the combustion of fossil fuels are responsible for smog, acid rain, and global warming.
- The environmental pollution has reached such high levels that it became a serious threat to vegetation, wildlife, and human health.

Motor vehicles are the largest source of air pollution. Each liter of gas by a car produces about 2.5kg CO₂. Annual: 12,000 miles (600 gallons gas) for each car – produce 12,000 lbm CO₂ per year.

Summary

- Forms of energy
  - Macroscopic = kinetic + potential
  - Microscopic = Internal energy (sensible + latent + chemical + nuclear)
- Energy transfer by heat
- Energy transfer by work
- Mechanical work (shaft work, spring work)
- The first law of thermodynamics
  - Energy balance
  - Energy change in a system
  - Mechanisms of energy transfer (heat, work, mass flow)
- Energy conversion efficiencies
  - Efficiencies of mechanical and electrical devices (turbines, pumps)

A 1995 report: The earth has already warmed about 0.5°C during the last century, and they estimate that the earth’s temperature will rise another 2°C by the year 2100.

- A rise of this magnitude can cause severe changes in weather patterns with storms and heavy rains and flooding at some parts and drought in others, major floods due to the melting of ice at the poles, loss of wetlands and coastal areas due to rising sea levels, and other negative results.
- Improved energy efficiency, energy conservation, and using renewable energy sources help minimize global warming.