Thermodynamics: An Engineering Approach, 6th Edition
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Chapter 2
ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS

SUMMARY

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FORMS OF ENERGY

- **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.

Kinetic energy

$$\mathrm{KE} = m\frac{V^2}{2} \qquad (\mathrm{kJ})$$

Kinetic energy per unit mass

$$\mathrm{ke} = \frac{V^2}{2} \qquad (\mathrm{kJ/kg})$$

Potential energy

$$\mathrm{PE} = mgz \qquad (\mathrm{kJ})$$

Potential energy per unit mass

$$\mathrm{pe} = gz \qquad (\mathrm{kJ/kg})$$

Total energy of a system

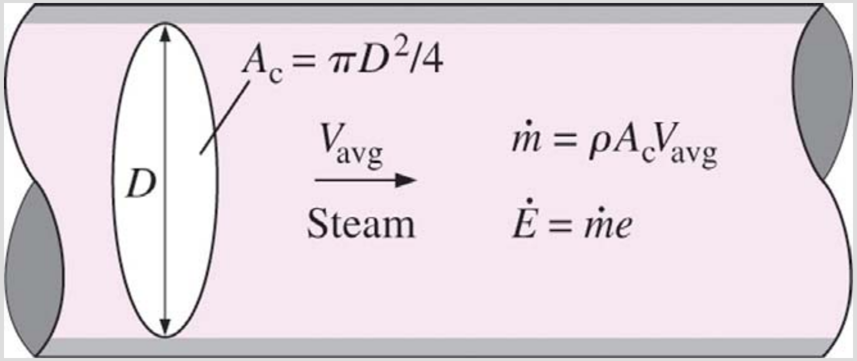
$$E = U + \mathrm{KE} + \mathrm{PE} = U + m\frac{V^2}{2} + mgz \qquad (\mathrm{kJ})$$

Energy of a system per unit mass

$$e = u + \mathrm{ke} + \mathrm{pe} = u + \frac{V^2}{2} + gz \qquad (\mathrm{kJ/kg})$$

Mass flow rate

$$\dot{m} = \rho \dot{V} = \rho A_c V_{avg} \qquad \text{(kg/s)}$$



Energy flow rate

$$\dot{E} = \dot{m}e \qquad \text{(kJ/s or kW)}$$

Total energy per unit mass

$$e = \frac{E}{m} \qquad \text{(kJ/kg)}$$

Mechanical Energy

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

Kinetic and potential energies: The familiar forms of mechanical energy.

Mechanical energy of a flowing fluid per unit mass

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

Rate of mechanical energy of a flowing fluid

$$\dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

Mechanical Energy

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

$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \qquad (\text{kJ/kg})$$

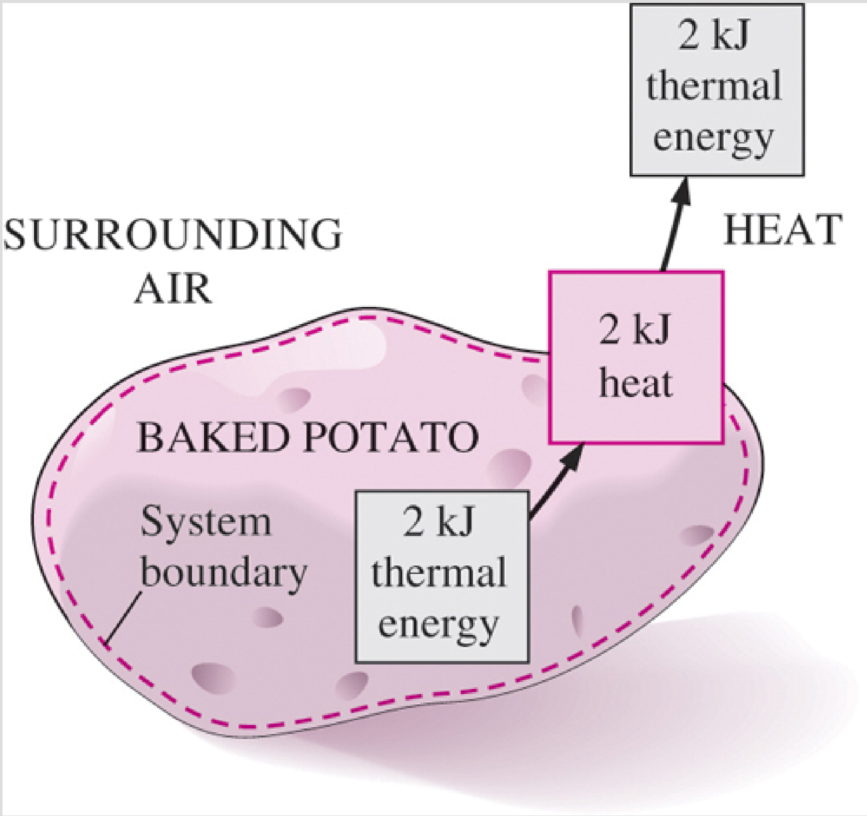
Rate of mechanical energy change of a fluid during incompressible flow

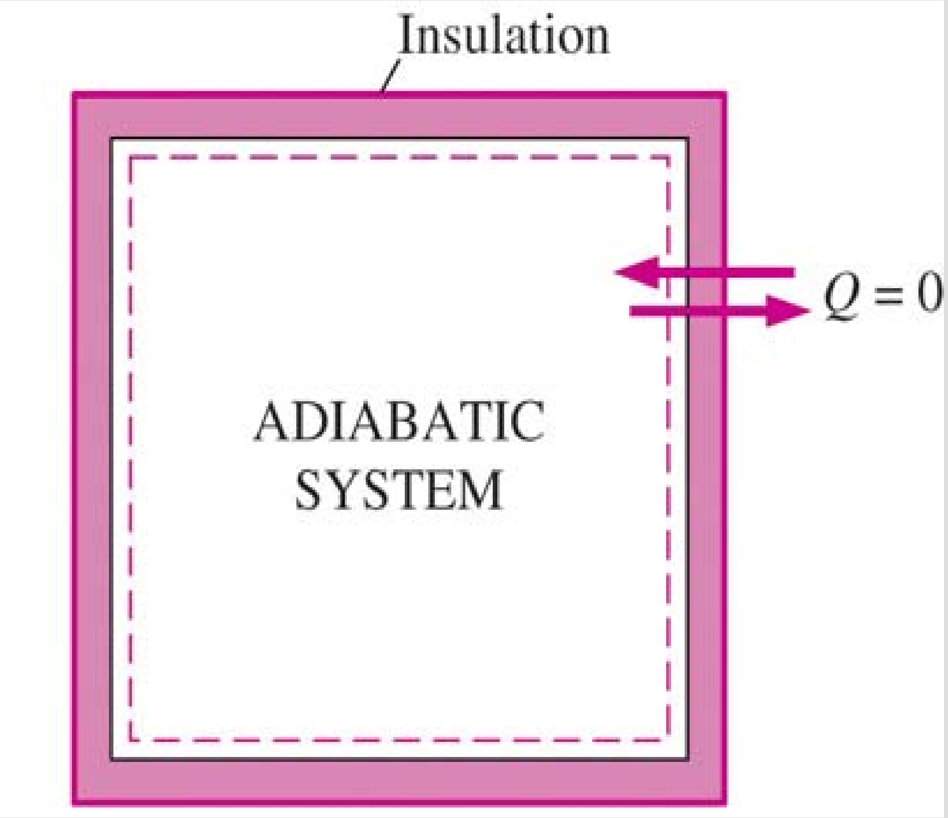
$$\Delta \dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \qquad (\text{kW})$$

Example: (Wind Energy)

Wind energy Power = $\dot{E} = \dot{m}\left(\frac{V^2}{2}\right)$

Wind energy per unit mass = $e = \left(\frac{V^2}{2}\right)$





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

During an adiabatic process, a system exchanges no heat with its surroundings.

Historical Background on Heat (Cont'd)

Heat transfer mechanisms:

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

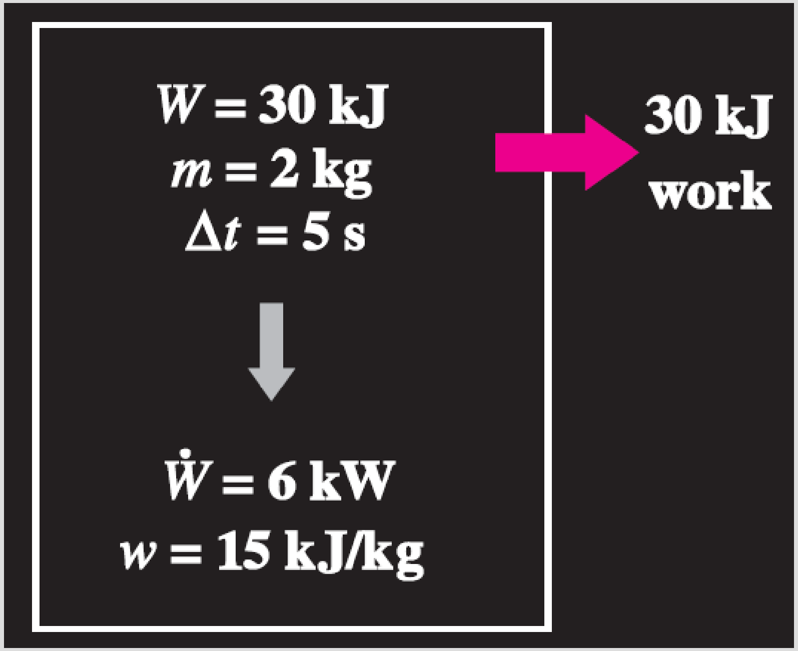
ENERGY TRANSFER BY WORK

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

Work done per unit mass

$$w = \frac{W}{m} \qquad (\text{kJ/kg})$$



Power is the work done per unit time (kW)

Heat vs. 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).

$$\int_1^2 \delta W = W_{12} \qquad (not\ \Delta W)$$

Path functions have inexact differentials (δ)

Electrical Work

Electrical work

$$W_e = \mathbf{V}N$$

Electrical power

$$\dot{W}_e = \mathbf{V}I \qquad (\text{W})$$

When potential difference and current change with time

$$W_e = \int_1^2 \mathbf{V}I\,dt \qquad (\text{kJ})$$

When potential difference and current remain constant

$$W_e = \mathbf{V}I\,\Delta t \qquad (\text{kJ})$$

Work = Force × Distance

$$W = Fs \qquad (\text{kJ})$$

When force is not constant

$$W = \int_1^2 F\,ds \qquad (\text{kJ})$$

MECHANICAL FORMS OF WORK

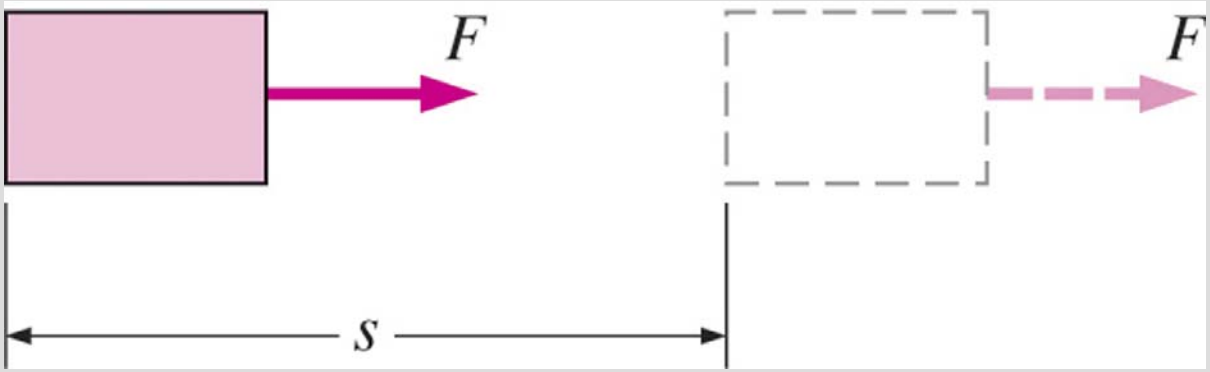
- There are two requirements for a work interaction between a system and its surroundings to exist:
  - ✓ there must be a ***force*** acting on the boundary.
  - ✓ the boundary must ***move***.

Work = Force × Distance

$$W = Fs \qquad (\mathrm{kJ})$$

When force is not constant

$$W = \int_1^2 F\, ds \qquad (\mathrm{kJ})$$



The work done is proportional to the force applied (*F*) and the distance traveled (*s*).

Shaft Work

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

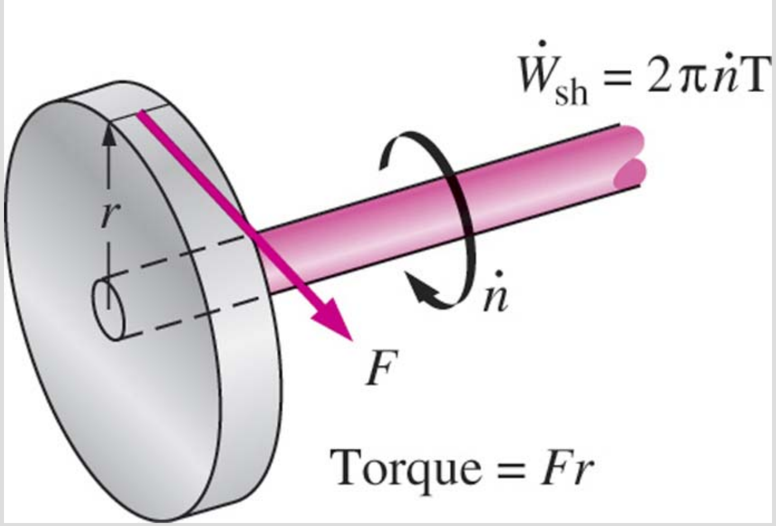
$$\mathrm{T} = Fr \quad \rightarrow \quad F = \frac{\mathrm{T}}{r}$$

This force acts through a distance (s)

$$s = (2\pi r)n$$

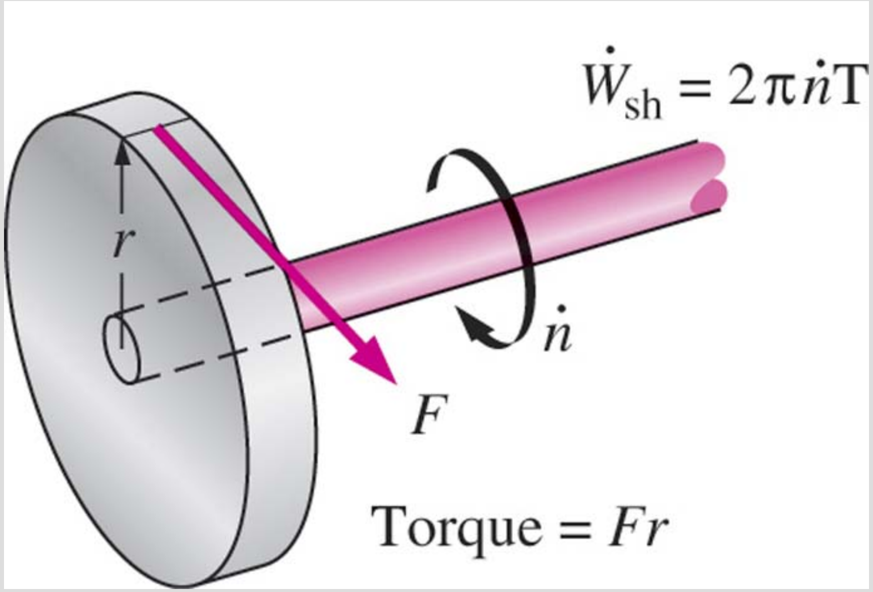
Shaft work

$$W_{sh} = Fs = \left(\frac{\mathrm{T}}{r}\right)(2\pi rn) = 2\pi n\mathrm{T} \qquad (\mathrm{kJ})$$

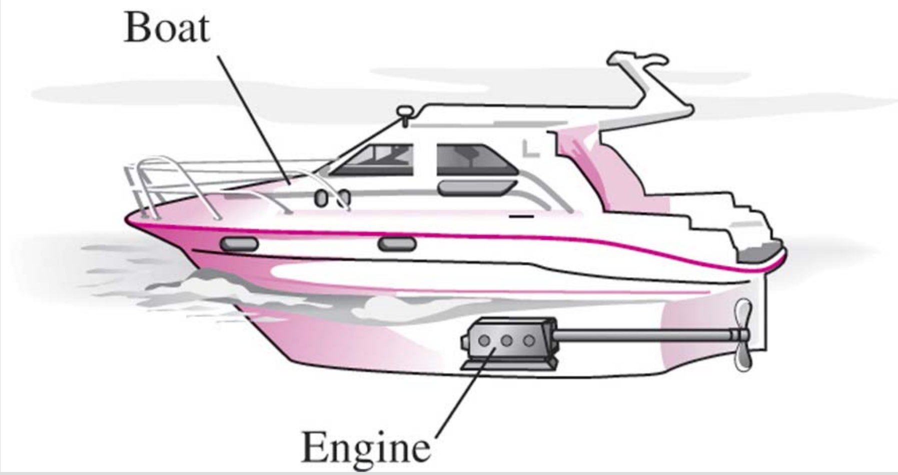


The power transmitted through the shaft is the shaft work done per unit time

$$\dot{W}_{sh} = 2\pi\dot{n}\mathrm{T} \qquad (\mathrm{kW})$$



Shaft work is proportional to the torque applied and the number of revolutions of the shaft.



Energy transmission through rotating shafts is commonly encountered in practice.

Spring Work

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

$$F = kx \qquad (\text{kN})$$

k: **spring constant (kN/m)**

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

$$\delta W_{\text{spring}} = F\,dx$$

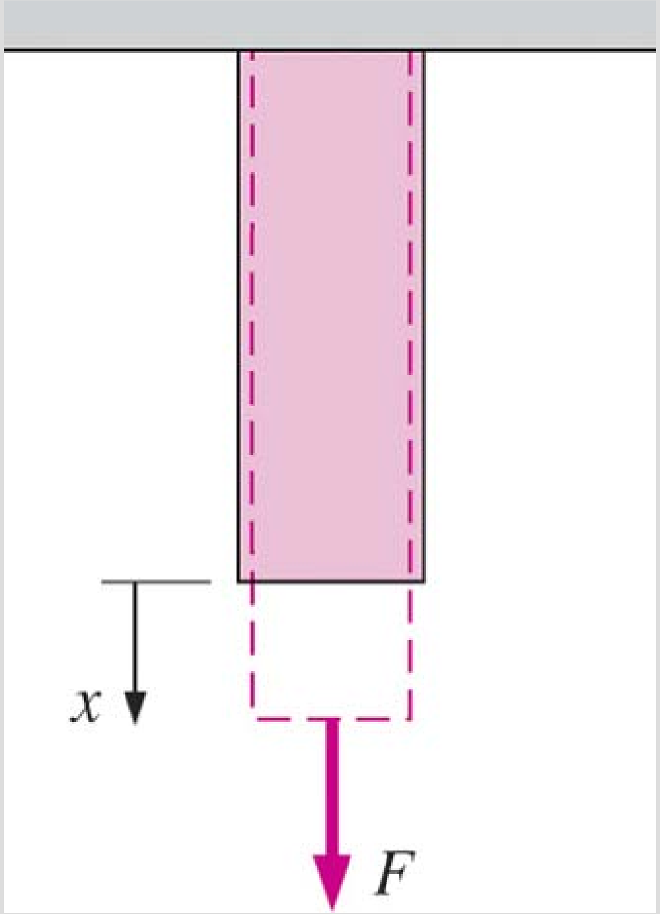
Substituting and integrating yield

$$W_{\text{spring}} = \tfrac{1}{2}k\left(x_2^2 - x_1^2\right) \qquad (\text{kJ})$$

x_1 and x_2: the initial and the final displacements

Work Done on Elastic Solid Bars

$$W_{\text{elastic}} = \int_1^2 F\,dx = \int_1^2 \sigma_n A\,dx \qquad \text{(kJ)}$$

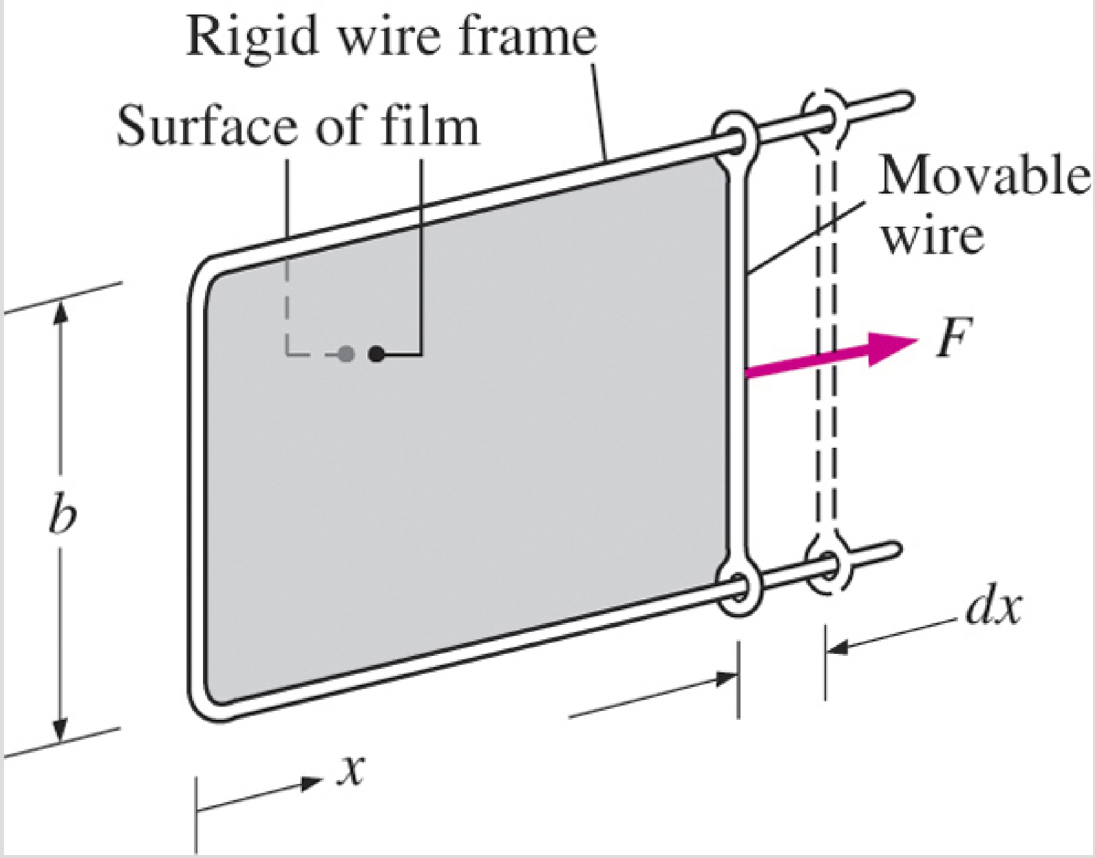


Solid bars behave as springs under the influence of a force.

Work Associated with the Stretching of a Liquid Film

$$W_{surface} = \int_1^2 \sigma_s \, dA \qquad \text{(kJ)}$$

where $dA = 2b\,dx$ is the change in the surface area of the film.



Stretching a liquid film with a movable wire.

Work done to raise or to Accelarate a Body

Examples:

1. **Power needs of a car to climb a hill at constant velocity**

$$P.E = \dot{W}_g = mg\,\Delta Z/\Delta t = mgV_{vertical} = mg(V\sin\alpha)$$

2. **Work needs of a car to accelerate**

$$K.E = W_a = \frac{1}{2}m\left(V_2^2 - V_1^2\right)$$

3. **Power needs of a car to accelerate**

$$K.E = \dot{W}_a = \frac{1}{2}m\left(V_2^2 - V_1^2\right)/\Delta t$$

Non-mechanical Forms of Work

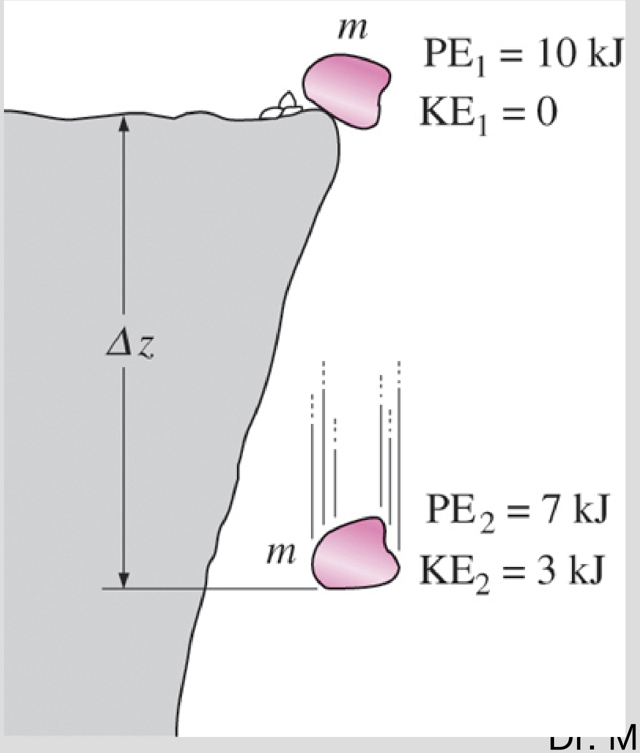
Electrical work: The generalized force is the ***voltage*** (the electrical potential) and the generalized displacement is the *electrical charge.*

Magnetic work: The generalized force is the ***magnetic field strength*** and the generalized displacement is the total ***magnetic dipole moment.***

Electrical polarization work: The generalized force is the ***electric field strength*** and the generalized displacement is the ***polarization of the medium****.*

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***.



Energy cannot be created or destroyed; it can only change forms.

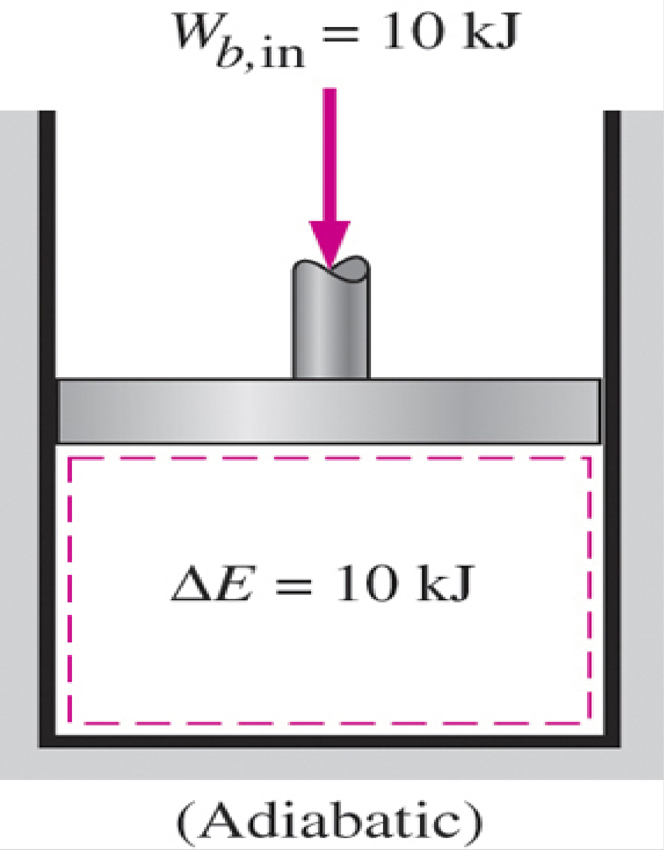
Energy Balance

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.

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

$$E_{in} - E_{out} = \Delta E_{system}$$

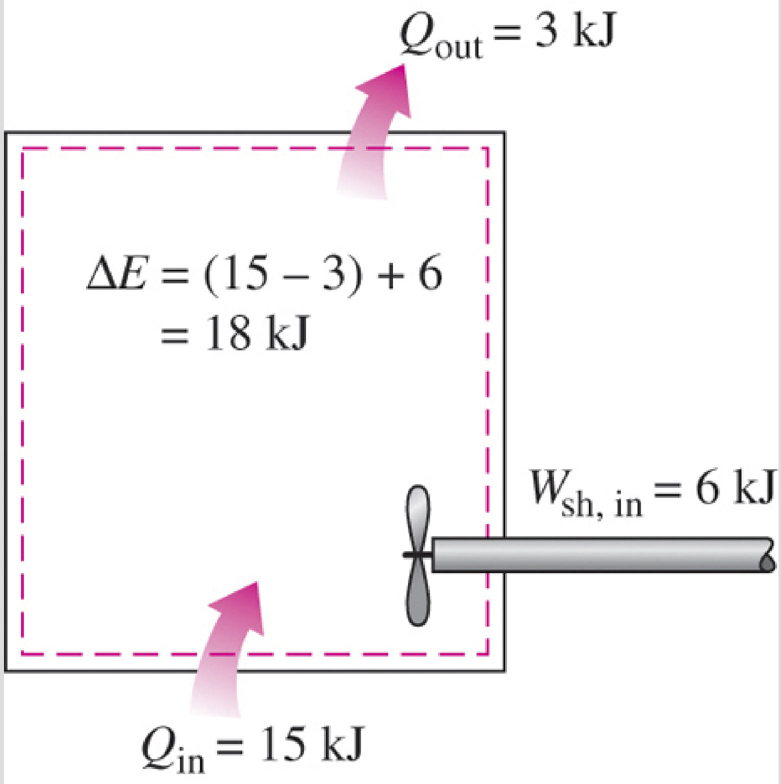
The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.



Energy Balance

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

$$E_{in} - E_{out} = \Delta E_{system}$$



The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

Energy Change of a System, ΔE_{system}

Energy change = Energy at final state − Energy at initial state

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

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

$$\Delta PE = mg(z_2 - z_1)$$

Stationary Systems

$$z_1 = z_2 \rightarrow \Delta PE = 0$$

$$V_1 = V_2 \rightarrow \Delta KE = 0$$

$$\Delta E = \Delta U$$

Mechanisms of Energy Transfer, E_{in} and E_{out}

- Heat transfer
- Work transfer
- Mass flow

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{system}$$

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}} \quad \text{(kJ)}$$

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad \text{(kW)}$$

Constant Rate

$$Q = \dot{Q}\,\Delta t \quad \text{(kJ)}$$

$$W = \dot{W}\,\Delta t$$

$$\Delta E = (dE/dt)\,\Delta t$$

Mechanisms of Energy Transfer, E_{in} and E_{out}

Examples:

1. Accelerate of Air by a Fan

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE}{dt} = 0$$

$$\dot{W}_{elec,in} = \dot{m}_{air}(ke_{out}) = \dot{m}_{air}\frac{V_{out}^2}{2}$$

2. Heating Effect of a Fan

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE}{dt} = 0$$

$$\dot{W}_{elec,in} = \dot{Q}_{out})$$

3. Annual Lighting Cost of a Class Room

Lighting Power = Power consumed per Lamp X No. Of Lamps

Lighting Energy = Lighting Power X Operating Hours

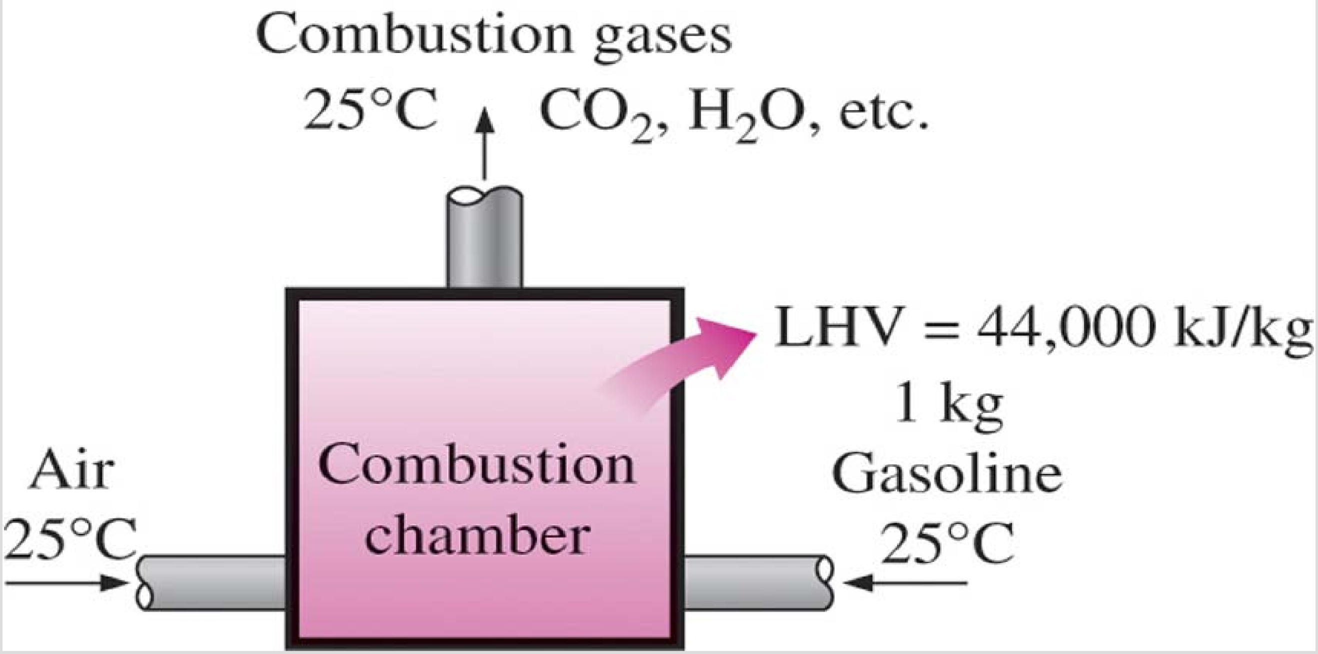
Lighting Cost = Lighting Energy X Unit cost

$$\eta_{\text{combustion}} = \frac{Q}{\text{HV}} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

Heating value of the fuel: The amount of heat released when a unit amount of fuel at room temperature is completely burned and the combustion products are cooled to the room temperature.

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.



The definition of the heating value of gasoline.

The efficiency of space heating systems of residential and commercial buildings is usually expressed in terms of the **annual fuel utilization efficiency (AFUE)**, which accounts for the combustion efficiency as well as other losses such as heat losses to unheated areas and start-up and cool down losses.

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

- **Generator efficiency:** The ratio of the electrical power output to the mechanical power input.

- **Thermal efficiency of a power plant:** The ratio of the net electrical power output to the rate of fuel energy input.

Overall efficiency of a power plant

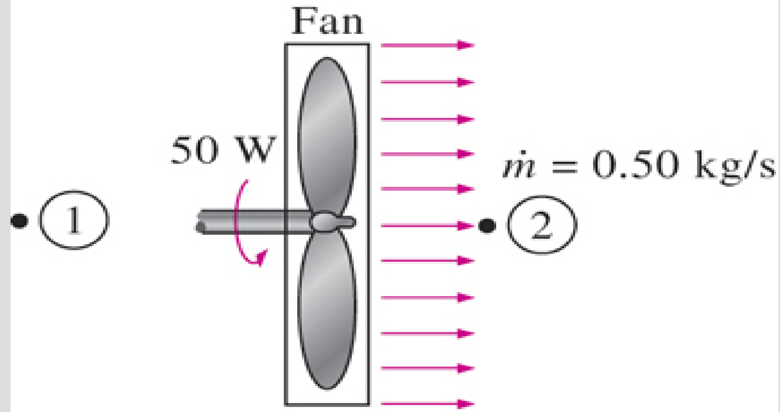
$$\eta_{\text{overall}} = \eta_{\text{combustion}}\,\eta_{\text{thermal}}\,\eta_{\text{generator}} = \frac{\dot{W}_{\text{net,electric}}}{\text{HHV} \times \dot{m}_{\text{net}}}$$

Efficiencies of Mechanical and Electrical Devices

Mechanical efficiency

$$\eta_{mech} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{mech,out}}{E_{mech,in}} = 1 - \frac{E_{mech,loss}}{E_{mech,in}}$$

The mechanical efficiency of a fan is the ratio of the kinetic energy of air at the fan exit to the mechanical power input.



$V_1 = 0,\ V_2 = 12$ m/s
$z_1 = z_2$
$P_1 = P_2$

$$\eta_{mech,\ fan} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{m}V_2^2/2}{\dot{W}_{shaft,in}}$$

$$= \frac{(0.50\text{ kg/s})(12\text{ m/s})^2/2}{50\text{ W}}$$

$$= 0.72$$

Efficiencies of Mechanical and Electrical Devices

The effectiveness of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by the **pump efficiency** and **turbine efficiency**,

$$\eta_{\text{pump}} = \frac{\text{Mechanical energy increase of the fluid}}{\text{Mechanical energy input}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{pump}}}$$

$$\Delta \dot{E}_{\text{mech,fluid}} = \dot{E}_{\text{mech,out}} - \dot{E}_{\text{mech,in}}$$

$$\eta_{\text{turbine}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decrease of the fluid}} = \frac{\dot{W}_{\text{shaft,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|} = \frac{\dot{W}_{\text{turbine}}}{\dot{W}_{\text{turbine},e}}$$

$$|\Delta \dot{E}_{\text{mech,fluid}}| = \dot{E}_{\text{mech,in}} - \dot{E}_{\text{mech,out}}$$

Pump efficiency

$$\eta_{motor} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{shaft,out}}{\dot{W}_{elect,in}}$$

Generator efficiency

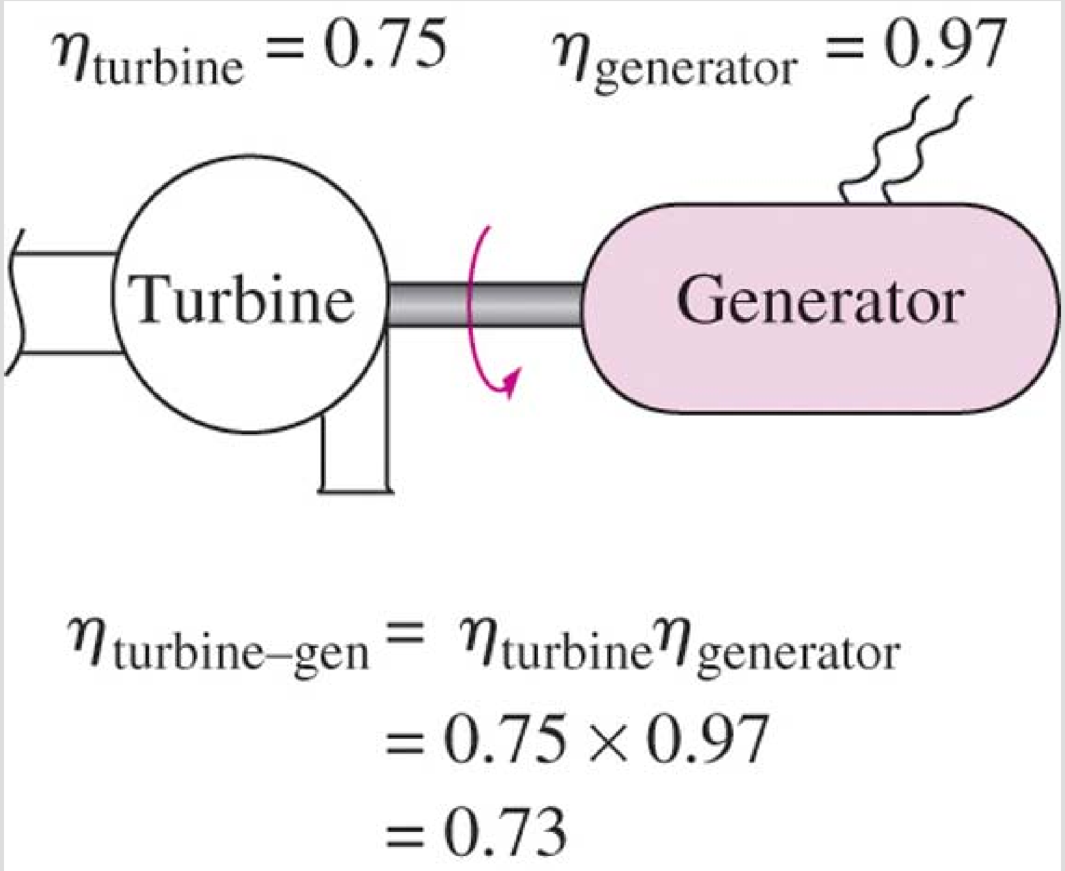
$$\eta_{generator} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{elect,out}}{\dot{W}_{shaft,in}}$$

Pump-Motor overall efficiency

$$\eta_{pump-motor} = \eta_{pump}\eta_{motor} = \frac{\dot{W}_{pump,u}}{\dot{W}_{elect,in}} = \frac{\Delta\dot{E}_{mech,fluid}}{\dot{W}_{elect,in}}$$

Turbine-Generator overall efficiency

$$\eta_{turbine-gen} = \eta_{turbine}\eta_{generator} = \frac{\dot{W}_{elect,out}}{\dot{W}_{turbine,e}} = \frac{\dot{W}_{elect,out}}{|\Delta\dot{E}_{mech,fluid}|}$$

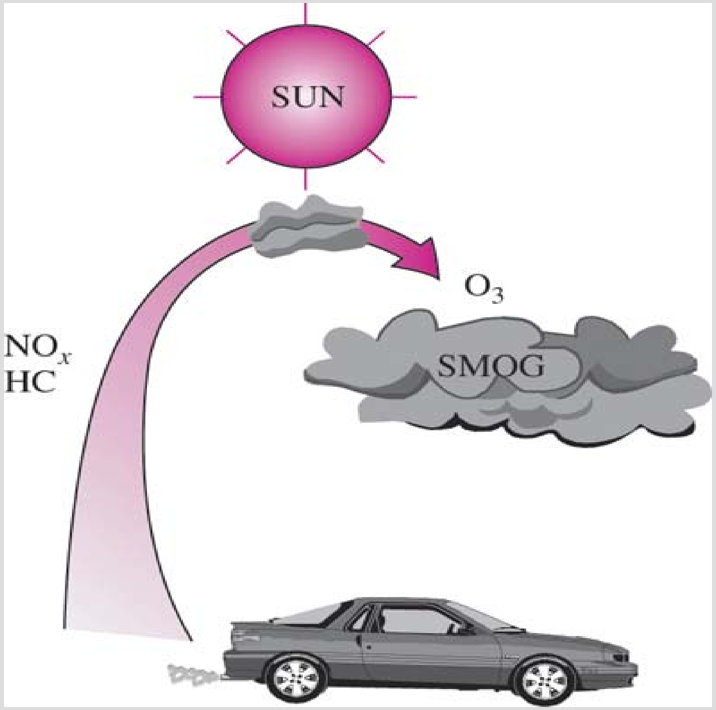


The overall efficiency of a turbine–generator is the product of the efficiency of the turbine and the efficiency of the generator, and represents the fraction of the mechanical energy of the fluid converted to electric energy.

Ozone and Smog

- **Smog:** Made up mostly of ground-level ozone (O_3), but it also contains numerous other chemicals, including carbon monoxide (CO), particulate matter such as soot and dust, volatile organic compounds (VOCs) such as benzene, butane, and other hydrocarbons.

- **Hydrocarbons** and **nitrogen oxides** react in the presence of sunlight on hot calm days to form ground-level ozone.



Ozone and Smog

Ozone irritates eyes and damages the air sacs in the lungs where oxygen and carbon dioxide are exchanged, causing eventual hardening of this soft and spongy tissue.
It also causes shortness of breath, wheezing, fatigue, headaches, and nausea, and aggravates respiratory problems such as asthma

- The other serious pollutant in smog is **carbon monoxide**, which is a colorless, odorless, poisonous gas.
- It is mostly emitted by motor vehicles.
- It deprives the body's organs from getting enough oxygen by binding with the red blood cells that would otherwise carry oxygen. It is fatal at high levels.
- Suspended particulate matter such as dust and soot are emitted by vehicles and industrial facilities. Such particles irritate the eyes and the lungs.

Acid Rain

- The sulfur in the fuel reacts with oxygen to form sulfur dioxide (SO_2), which is an air pollutant.
- The main source of SO_2 is the electric power plants that burn high-sulfur coal.
- Motor vehicles also contribute to SO_2 emissions since gasoline and diesel fuel also contain small amounts of sulfur.
- The sulfur oxides and nitric oxides react with water vapor and other chemicals high in the atmosphere in the presence of sunlight to form sulfuric and nitric acids .
- The acids formed usually dissolve in the suspended water droplets in clouds or fog.
- These acid-laden droplets, which can be as acidic as lemon juice, are washed from the air on to the soil by rain or snow. This is known as **Acid Rain**.

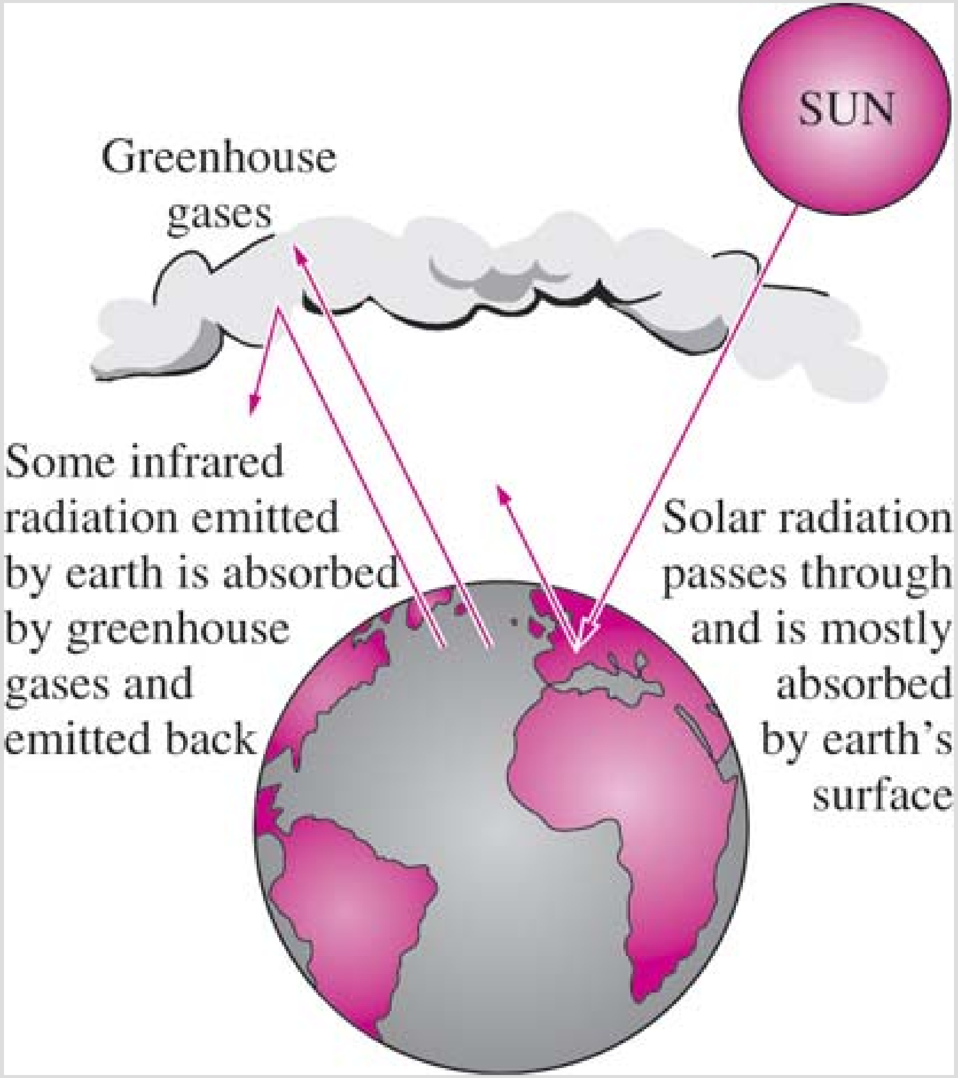
The Greenhouse Effect: Global Warming

- **Greenhouse effect**: Glass allows the solar radiation to enter freely but blocks the infrared radiation emitted by the interior surfaces. This causes a rise in the interior temperature as a result of the thermal energy buildup in a space (i.e., car).
- The surface of the earth, which warms up during the day as a result of the absorption of solar energy, cools down at night by radiating part of its energy into deep space as infrared radiation.
- **Carbon dioxide (CO_2),** water vapor, and trace amounts of some other gases such as methane and nitrogen oxides act like a blanket and keep the earth warm at night by blocking the heat radiated from the earth. The result is **global warming**.
- These gases are called "**Greenhouse Gases**," with CO_2 being the primary component.
- **CO_2** is produced by the burning of fossil fuels such as **coal, oil, and natural gas**.

The Greenhouse Effect: Global Warming

Gases causes the green House Effect are

1. Carbon dioxide (CO_2)
2. water vapor
3. Methane
4. nitrogen oxides



The greenhouse effect on earth.

THE END