# Thermodynamics

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# Chapter Two

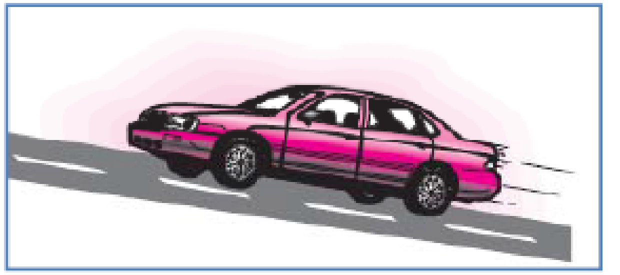
# ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS

## 2.1 INTRODUCTION

- We are told repeatedly that energy cannot be created or destroyed during a process; it can only change from one form to another.

## 2.2 FORMS OF ENERGY

- **Energy** can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the total energy **E** of a system.
- **Macroscopic** the energy are those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies
- **Microscopic** the energy are those related to the molecular structure of a system and the degree of the molecular activity, and they are independent of outside reference frames. The sum of all the microscopic forms of energy is called the **internal energy** of a system and is denoted by **U**.



The macroscopic energy of an object changes with velocity and elevation.

- **Kinetic energy (KE).** The energy that a system possesses as a result of its motion relative to some reference frame. When all parts of a system move with the same velocity, the kinetic energy is expressed as

$$KE = m\frac{V^2}{2} \quad \text{(kJ)}$$

$$ke = \frac{V^2}{2} \quad \text{(kJ/kg)}$$

Where **V** denotes the velocity of the system

- **Potential energy (PE)** The energy that a system possesses as a result of its elevation in a gravitational field and is expressed as

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

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

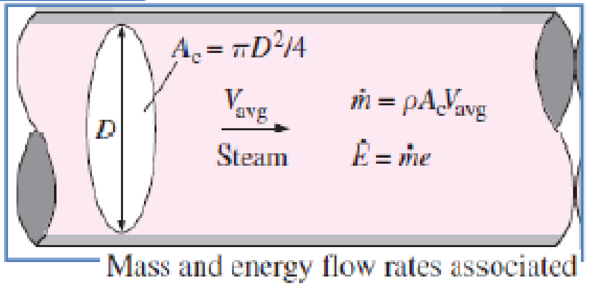
Where: - **g** is the gravitational acceleration and
**z** is the elevation of the center of gravity

- **Total energy** of a system consists of the kinetic, potential, and internal energies and is expressed as

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

- **Mass flow rate m** which is the amount of mass flowing through a cross section per unit time.
- **Volume flow rate V** which is the volume of a fluid flowing through a cross section per unit time.

$$\textit{Mass flow rate:} \qquad \dot{m} = \rho\dot{V} = \rho A_c V_{\mathrm{avg}} \qquad (\mathrm{kg/s})$$




Mass and energy flow rates associated with the flow of steam in a pipe of inner diameter $D$ with an average velocity of $V_{avg}$.

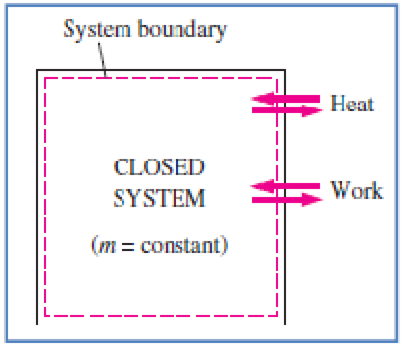
$m = \rho V$.

Where $\rho$ is the fluid density,
$Ac$ is the cross sectional area of flow, and
$V_{avg}$ is the average flow velocity normal to $Ac$.

$$\textit{Energy flow rate:} \qquad \dot{E} = \dot{m}e \qquad (\mathrm{kJ/s\ or\ kW})$$

## Mechanical Energy

- **Mechanical energy** can be defined as 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** are the familiar forms of mechanical energy. Thermal energy is not mechanical energy, however, since it cannot be converted to work directly and completely.
- A **pump** transfer's mechanical energy to a fluid by raising its pressure, and a **turbine** extracts mechanical energy from a fluid by dropping its pressure.



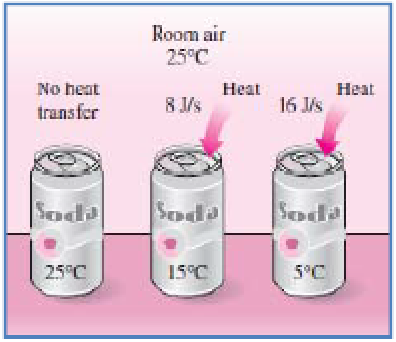

## 2.3 ENERGY TRANSFER BY HEAT

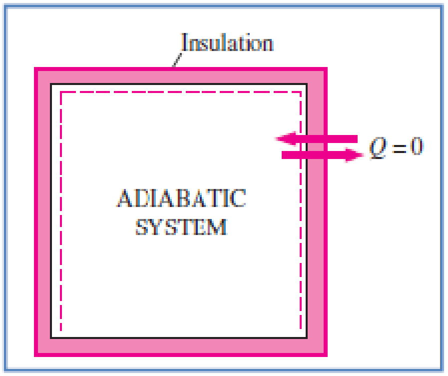
- Energy can cross the boundary of a closed system in two distinct forms: heat and work

$$Q_{net} = \sum Q_{in} - \sum Q_{out}$$

$$q = \frac{Q}{m}$$

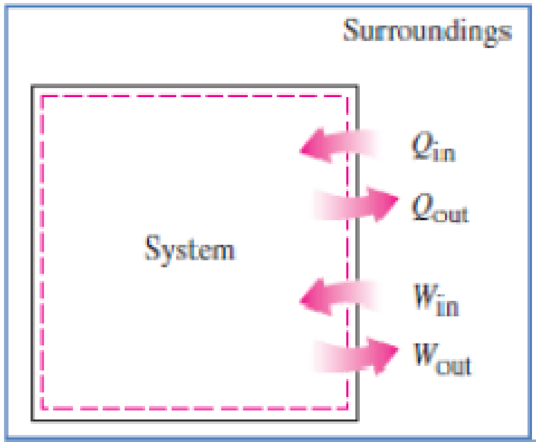
- **Heat** is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference
- **Temperature difference** is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.
- **Adiabatic process** A process during which there is no heat transfer.



## 2.4 ENERGY TRANSFER BY WORK

- Work, like heat, is an energy interaction between a system and its surroundings. As mentioned earlier, energy can cross the boundary of a closed system in the form of heat or work. Therefore, *if the energy crossing the boundary of a closed system is not heat, it must be work*. Heat is easy to recognize: Its driving force is a temperature difference between the system and its surroundings.
- **Work** is 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.
- **Sign convention** for heat and work interactions is as follows: *heat transfer to a system and work done by a system are positive;*

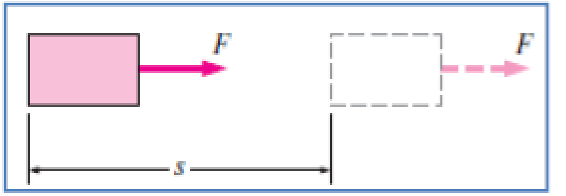



Specifying the directions of heat and work.

## 2.5 MECHANICAL FORMS OF WORK

- The work done by a constant force *F* on a body displaced a distance *s* in the direction of the force is given by

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




- The work done is proportional to the force applied (F) and the distance traveled (s).
- If the force F is not constant, the work done is obtained by adding (i.e., integrating) the differential amounts of work,

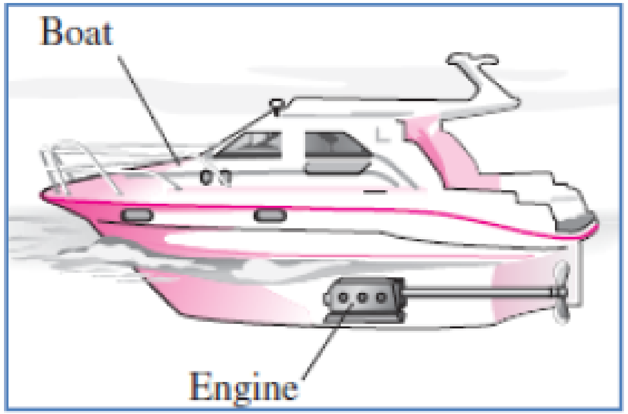
$$W = \int_1^2 F\, ds \qquad \text{(kJ)}$$

- There are two requirements for a work interaction between a system and its surroundings to exist: (1) There must be a force acting on the boundary, and (2) the boundary must move.

## Shaft Work

- Energy transmission with a rotating shaft is very common in engineering practice. Often the torque T applied to the shaft is constant, which means that the force *F* applied is also constant.

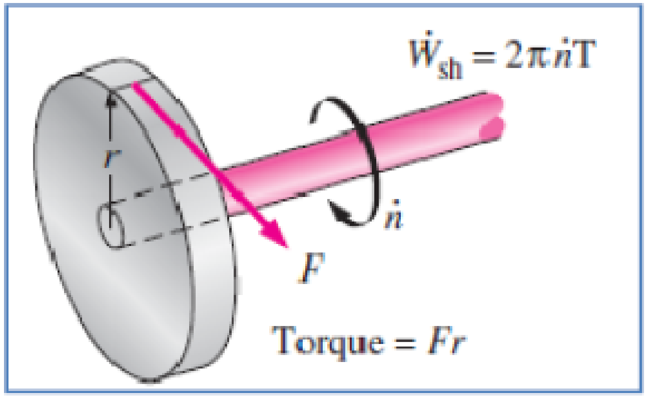
$$\mathrm{T} = Fr \quad \rightarrow \quad F = \frac{\mathrm{T}}{r}$$




- For a specified constant torque, the work done during n revolutions is determined as follows: A force F acting through a moment arm r generates a torque T of

Then the shaft work is determined from

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



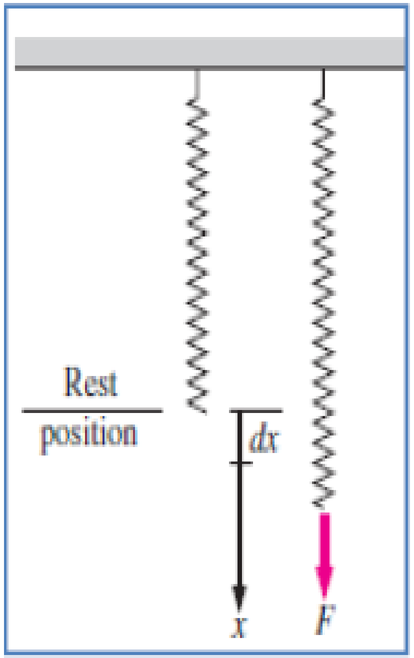

- The power transmitted through the shaft is the shaft work done per unit time, which can be expressed as

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

## Spring Work

- It is common knowledge that when a force is applied on a spring, the length of the spring changes When the length of the spring changes by a differential amount *dx* under the influence of a force *F*, the work done is

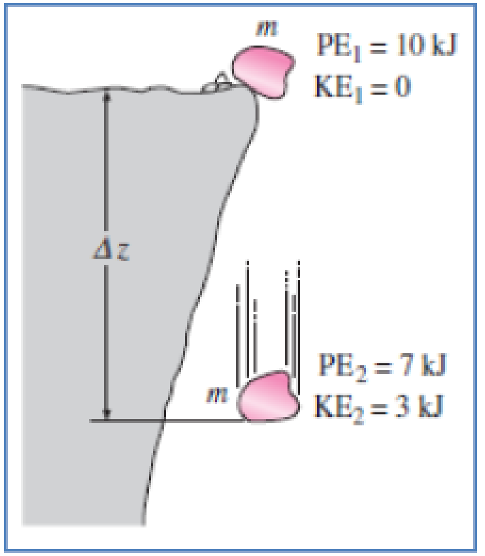
$$W_{spring} = \frac{1}{2}k(x_2^2 - x_1^2) \qquad \text{(kJ)}$$




**Where** $k$ is the spring constant and has the unit kN/m.
$x_1$ and $x_2$ are the initial and the final displacements of the spring, respectively,

## 2.6 THE FIRST LAW OF THERMODYNAMICS

- We have considered various forms of energy such as heat *Q*, work *W*, and total energy *E* individually, and no attempt is made to relate them to each other during a process. The **first law of thermodynamics**, also known as the **conservation of energy** principle,




## 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. That is,

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

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

## Energy Change of a System, $E_{system}$

- The determination of the energy change of a system during a process involves the evaluation of the energy of the system at the beginning and at the end of the process,

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

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

- The change in the total energy of a system during a process is the sum of the changes in its internal, kinetic, and potential energies and can be expressed as

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

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

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

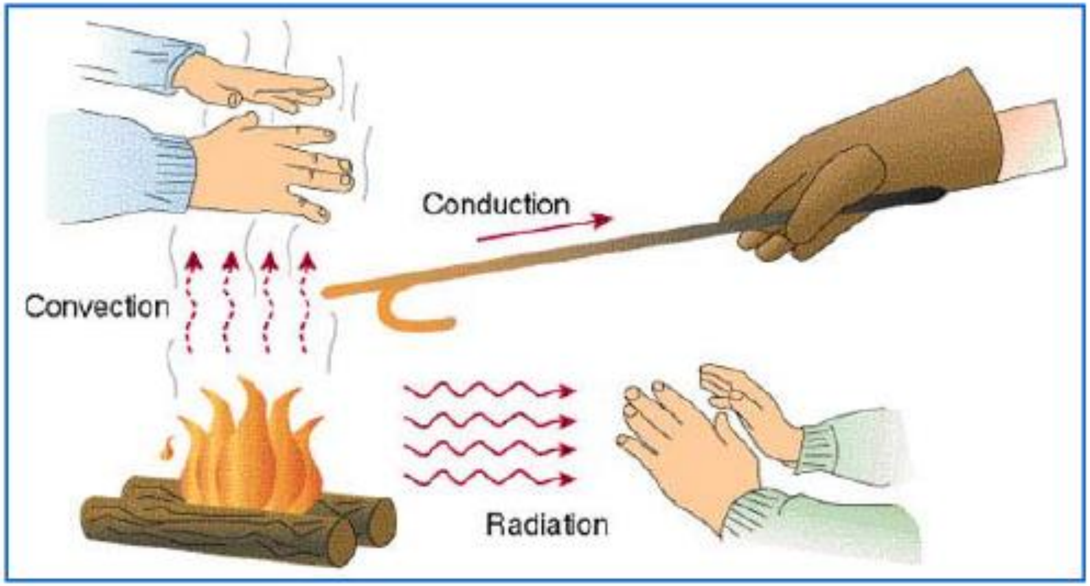
$$\Delta PE = mg(z_2 - z_1)$$

## Mechanisms of Heat Transfer

Heat can be transferred in three different ways: ***conduction, convection,*** and ***radiation.***

### Conduction

$$\dot{Q}_{cond} = k_t A \frac{\Delta T}{\Delta x} \qquad (W)$$




### Convection

$$\dot{Q}_{conv} = hA(T_s - T_f) \qquad (W)$$

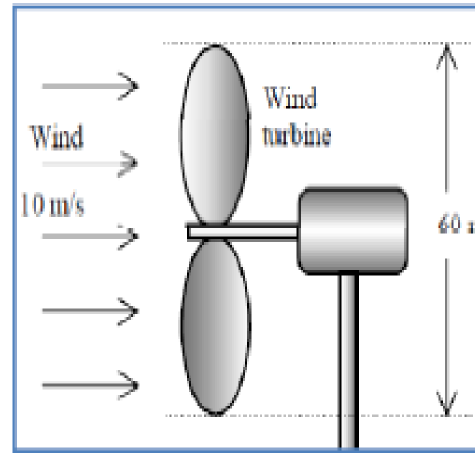
### Radiation

$$\dot{Q}_{rad} = \varepsilon\sigma A(T_s^4 - T_{surr}^4) \qquad (W)$$

## Solved Problem

**Problem 2.1:-** At a certain location, wind is blowing steadily at 10 m/s. Determine the mechanical energy of air per unit mass and the power generation potential of a wind turbine with 60-m-diameter blades at that location. Take the air density to be 1.25 kg/m$^3$.

**Solution: -**




$$e_{mech} = ke = \frac{V^2}{2} = \frac{(10\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 0.050\ \text{kJ/kg}$$

$$\dot{m} = \rho V A = \rho V \frac{\pi D^2}{4} = (1.25\ \text{kg/m}^3)(10\ \text{m/s})\frac{\pi(60\ \text{m})^2}{4} = 35{,}340\ \text{kg/s}$$

$$\dot{W}_{max} = \dot{E}_{mech} = \dot{m}e_{mech} = (35{,}340\ \text{kg/s})(0.050\ \text{kJ/kg}) = \mathbf{1770\ kW}$$

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**Problem 2.2:-** Determine the work required to deflect a linear spring with a spring constant of 70 kN/m by 20 cm from its rest position.

**Solution:**

$$W_{spring} = \frac{1}{2}k(x_2^2 - x_1^2) = \frac{1}{2}(70\ \text{kN/m})(0.2^2 - 0)\ \text{m}^2 = 1.4\ \text{kN}\cdot\text{m} = \mathbf{1.4\ kJ}$$

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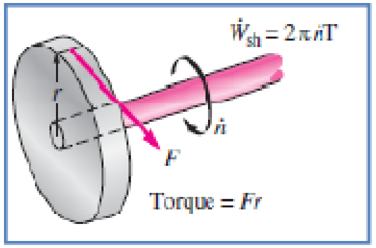
**Problem 2.3:-** Determine the power transmitted through the shaft of a car when the torque applied is 200 N · m and the shaft rotates at a rate of 4000 revolutions per minute (rpm)




**Solution:-**

$$\dot{W}_{sh} = 2\pi\dot{n}T = (2\pi)\left(4000\,\frac{1}{\text{min}}\right)(200\ \text{N}\cdot\text{m})\left(\frac{1\ \text{min}}{60\ \text{s}}\right)\left(\frac{1\ \text{kJ}}{1000\ \text{N}\cdot\text{m}}\right)$$

$$= 83.8\ \text{kW} \qquad (\text{or } 112\ \text{hp})$$

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**Problem 2.4:-** A rigid tank contains a hot fluid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel.

**Solution:-**

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

$$W_{sh,in} - Q_{out} = \Delta U = U_2 - U_1$$

$$100\ \text{kJ} - 500\ \text{kJ} = U_2 - 800\ \text{kJ}$$

$$U_2 = 400\ \text{kJ}$$

Therefore, the final internal energy of the system is 400 kJ.

## Home works

**Problem 2.1:-** Determine the energy required to accelerate an 800- kg car from rest to 100 km/h on a level road. ***Ans.: 309 kJ***

**Problem 2.2:-**

Water is being heated in a closed pan on top of arange while being stirred by a paddle wheel. During the process, 30 kJ of heat is transferred to the water, and 5 kJ of heat is lost to the surrounding air. The paddle-wheel work amounts to 500 N · m. Determine the final energy of the system if its initial energy is 10 kJ. **Ans.: 35.5 kJ**