Engineering Thermodynamics I

Lecture 3

First Law of Thermodynamics and Energy

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Lecture learning outcomes:

At the end of this lecture, you will be able to:

i. Understand the principle of energy conservation and express it using thermodynamic equations.

ii. Define internal energy, kinetic energy, and potential energy and understand their roles in a system's total energy.

iii. Explain the mechanisms of energy transfer such as heat, work, and mass flow

iv. Differentiate between conduction, convection, and radiation as heat transfer mechanisms.

v. Calculate and interpret boundary work for different processes

vi. Analyze closed systems with no mass transfer, applying the energy balance equation

Content

1. First Law of Thermodynamics
2. Energy of a System
3. Mechanisms of Energy Transfer
4. Energy Transfer by Heat and Work
5. Boundary Work
6. Some Typical Processes
7. The First Law for a Closed System

Summary

References

1. The First Law of Thermodynamics

- The **First Law of Thermodynamics is** the law that relates the various forms of energies for system of different types.
- It is simply the expression of the conservation of energy principle.
- It states that ***energy cannot be created or destroyed; it can only change forms or be transferred from one system to another [1]***.
- During an interaction between a system and its surroundings, the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings.
- First law of thermodynamics is based on experimental observations.
- It is a cornerstone in understanding energy systems.

1. The First Law of Thermodynamics **Cont…**

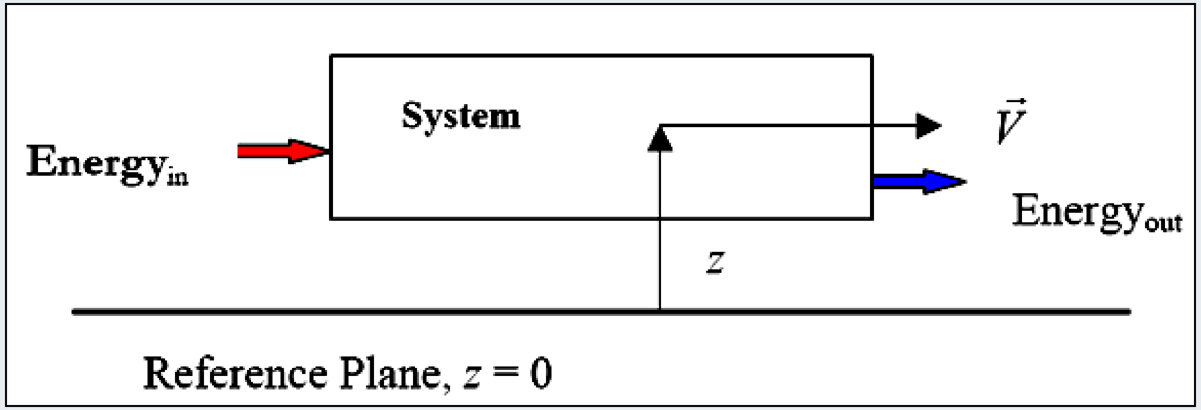


Figure 1: Energy of a system

url: https://slideplayer.com/slide/15788401/88/images/30/System+CM.+Energyin.+Energyout.+z.+Reference+Plane%2C+z+%3D+0..jpg

- The first law of thermodynamics is expressed as [2]

$$\begin{pmatrix} Total\ Energy \\ Entering\ the\ System \end{pmatrix} - \begin{pmatrix} Total\ Energy \\ Leaving\ the\ System \end{pmatrix} = \begin{pmatrix} The\ Change\ in\ Total \\ Energy\ of\ the\ System \end{pmatrix}$$

1. The First Law of Thermodynamics Cont…

- The total energy of the system, E_{system}, is given as

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

$$E_{system} = Internal\ Energy + Kinetic\ Energy + Potential\ Energy$$

$$E_{system} = U + KE + PE$$

$$E_{in} - E_{out} = \Delta U + \Delta KE + \Delta PE$$

2. Energy of a System

- Energy can be viewed as the ability to cause change.
- Energy can exist in numerous forms such as:
    - Thermal,
    - Kinetic,
    - Potential,
    - Mechanical,
    - Electric,
    - Magnetic,
    - Chemical, and
    - Nuclear
- Their sum constitutes the total energy E of a system.

2. Energy of a System

Cont…

- In thermodynamic analysis, energy can be grouped in to two forms:
  - Microscopic
  - Macroscopic
- **Microscopic forms of 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.

Example:- Latent energy

Chemical energy

Nuclear energy

2. Energy of a System

- **Macroscopic forms of energy** are those a system possesses as a whole with respect to some outside reference frame,

Example:- Kinetic Energy

Potential Energy

- The macroscopic energy of a system is related to motion and the influence of some external effects such as gravity, magnetism, electricity, and surface tension.

2. Energy of a System

Cont…

- When all parts of a system move with the same velocity, the kinetic energy (KE) is expressed as:

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

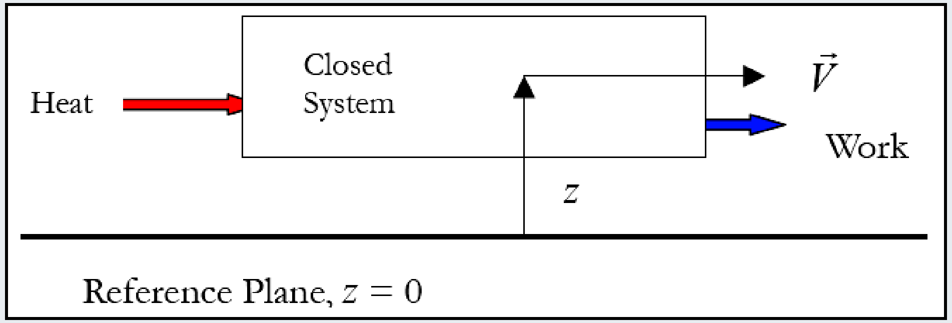


Figure 2: Energy balance for closed system
url: https://image.slideserve.com/1413503/slide3-l.jpg

Or on a unit mass basis,

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

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

$$PE = mgz \qquad\qquad pe = gz \quad (kJ/kg)$$

where : g - the gravitational acceleration and

z -the elevation of the centre of gravity of a system

2. Energy of a System

Cont…

- The magnetic, electric, and surface tension effects are significant in some specialized cases only and are usually ignored.

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

$$E = U + KE + PE$$

$$E = U + m\frac{V^2}{2} + mgz$$

on a unit mass basis,

$$e = u + ke + pe \qquad\qquad e = u + \frac{V^2}{2} + gz$$

2. Energy of a System

Cont…

Stationary System

- A stationary thermodynamic system refers to a system in which its properties, such as temperature, pressure, and internal energy, do not change with time.
- The change in the total energy E of a stationary system is identical to the change in its internal energy U.

$$E_{in} - E_{out} = \Delta U + \Delta KE + \Delta PE$$

$$\Delta E = \Delta U$$

3. Mechanisms of Energy Transfer

- **Heat Transfer (Q)**:
  - Heat transfer to a system - increases the internal energy of the system
  - Heat transfer from a system – decreases the internal energy of the system
- **Work Transfer (W)**:
  - Work done on a system - increases the energy of the system
  - Work done by the system - decreases the energy of the system
- **Mass Flow (m)**:
  - Mass enters a system - increases the energy of the system
  - Mass leaves the system - decreases the energy in the system

3. Mechanisms of Energy Transfer

- In thermodynamics, energy transfer for:

  Closed systems - Two primary mechanisms

  - **heat transfer** and
  - **work**

  Open Systems - Three primary mechanisms

  - **heat transfer**,
  - **work**, and
  - **mass transfer**

Energy transfer for Closed Systems

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

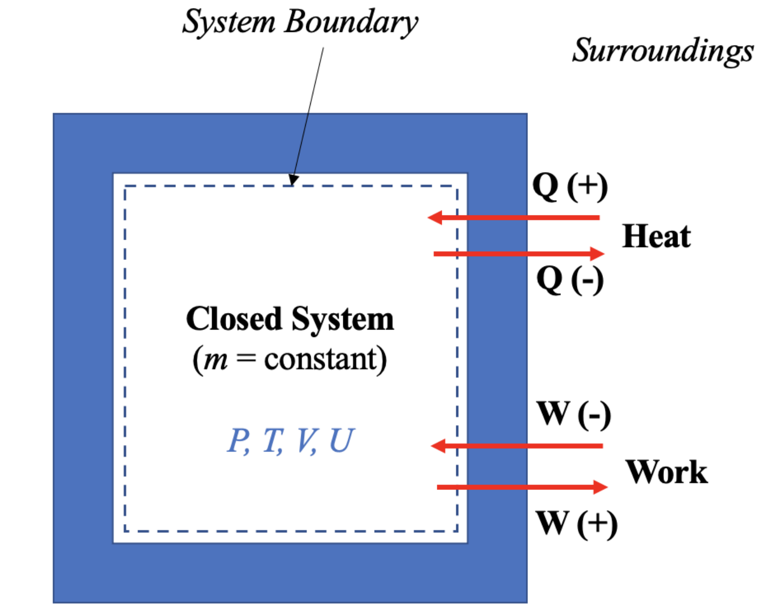
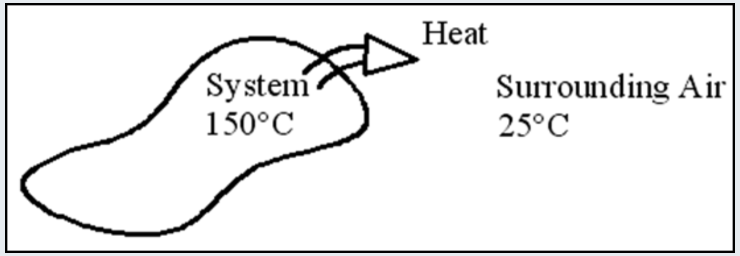


Figure 3: Energy transfer by heat and work
url: https://pressbooks.bccampus.ca/thermo1/wp-content/uploads/sites/499/2021/07/Heat-and-work-to-closed-systems.png

4. Energy Transfer by Heat and Work

i. Energy transport by heat

- **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 [2].
- This transfer occurs naturally and is governed by three main mechanisms: **conduction**, **convection**, and **radiation**.



4. Energy Transfer by Heat and Work

i. Energy transport by heat

- As a form of energy, heat has energy units, kJ
- The amount of heat transferred during the process between two states (states 1 and 2) is denoted by Q_{12}, or just Q
- Sometimes it is desirable to know the rate of heat transfer $\dot{Q}$ (the amount of heat transferred per unit time)
- Heat transfer **per unit mass** of a system is denoted by q and is determined from:

$$q = \frac{Q}{m} \quad (kJ/kg)$$

4. Energy Transfer by Heat and Work

Cont…

Heat Transfer Mechanisms:

1. **Heat transfer by Conduction:** it is the process of transferring thermal energy through a solid material or between objects in direct physical contact.

2. **Heat transfer by Convection:** Heat convection occurs in fluids (liquids or gases) and involves the movement of particles to transfer heat. It is the combined effects of conduction and fluid motion.

3. **Heat transfer by Radiation:** the transfer of energy due to the emission of electromagnetic waves (or photons).

4. Energy Transfer by Heat and Work

Cont…

- A process during which there is no heat transfer is called an **adiabatic process.**
- There are two ways a process can be adiabatic:
  - Well insulated
  - Both the system and the surroundings are at the same temperature

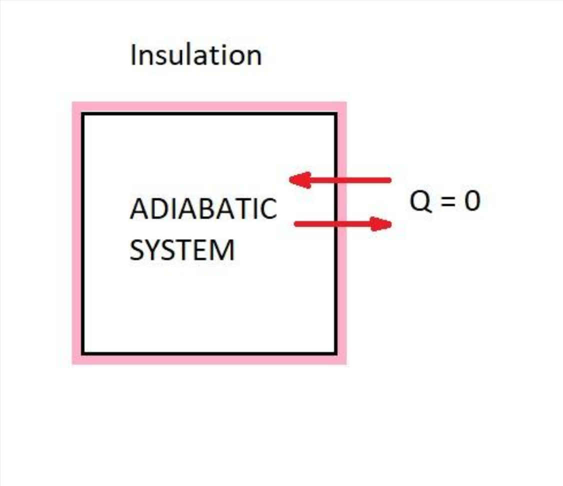


Figure 2: An adiabatic system

url: https://sbainvent.com/wp-content/uploads/2019/11/ADIABATIC-SYSTEM.jpg

4. Energy Transfer by Heat and Work

ii. Energy transport by Work

- If the energy crossing the boundary of a closed system is not heat, it must be work.
- An energy interaction that is not caused by a temperature difference between a system and its surroundings is work.
- It is the energy transfer associated with a force acting through a distance.

Example:- A rising piston,

A rotating shaft

4. Energy Transfer by Heat and Work

Cont…

ii. Energy transport by Work

- Work is also a form of energy transferred like heat and, therefore, has energy units kJ.
- The work done during a process between states 1 and 2 is denoted by W_{12}, or simply W.
- The work done **per unit time** is called **power** and is denoted by $\dot{W}$ .The unit of power is kJ/s, or kW.
- The work done **per unit mass** of a system is denoted by w and is expressed as

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

4. Energy Transfer by Heat and Work

Cont…

The similarities between Heat and Work

- Both are recognized at the boundaries of a system as they cross the boundaries.
- Both are associated with a process, not a state. Unlike thermodynamic properties, both heat and work has no meaning at a state.
- Both are path functions – their magnitude depends on the path followed during a process.

4. Energy Transfer by Heat and Work

Sign convention for energy transported by heat and work

- In thermodynamics, understanding how heat and work are quantified and their directions of flow is vital for energy systems.
- Since heat and work are **directional quantities**, the specification of both the **magnitude** and **direction is required for complete analysis.**
- The **sign convention** for heat and work interactions is as follows [3]:
  - heat transfer to a system: +ve
  - heat transfer from a system: -ve
  - work done by a system: +ve
  - work done on a system: -ve

4. Energy Transfer by Heat and Work

Sign convention for energy transported by heat, work and mass

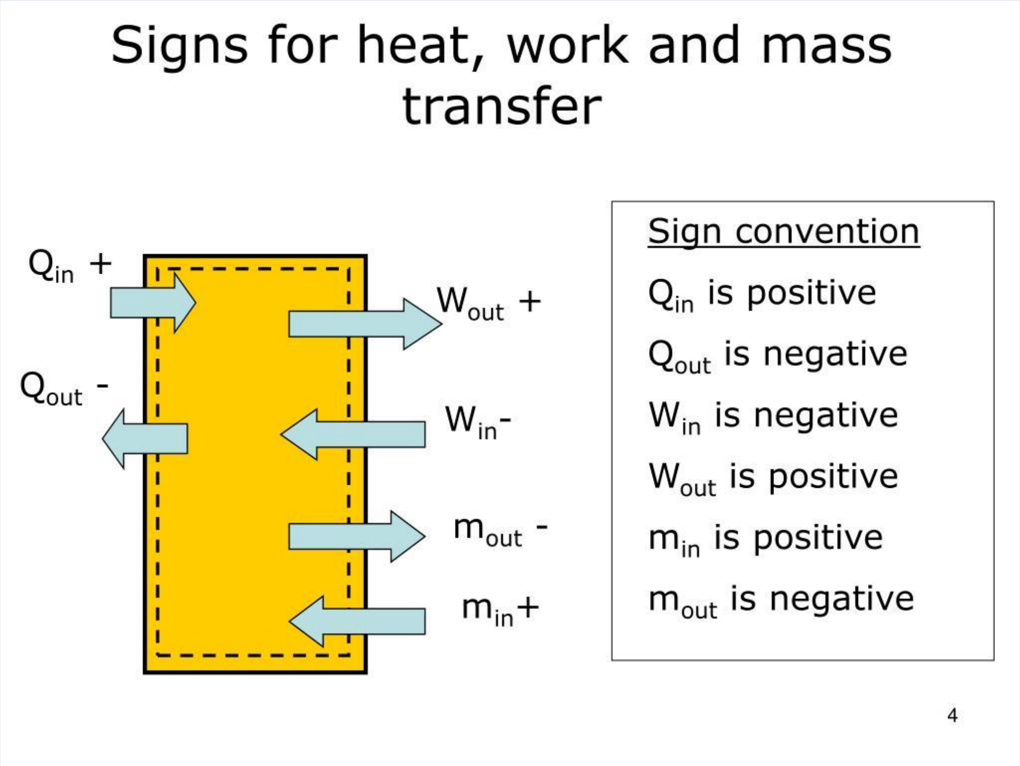


Figure 3: Sign convention for heat, work and mass transfer
url: https://image3.slideserve.com/6788916/slide4-l.jpg

5. Boundary Work

- Boundary work is the work done by a system as its boundary expands or contracts due to pressure. Or, The work associated with a moving boundary.
- It's most commonly associated with processes involving gases in a piston-cylinder assembly, where the system's volume changes.

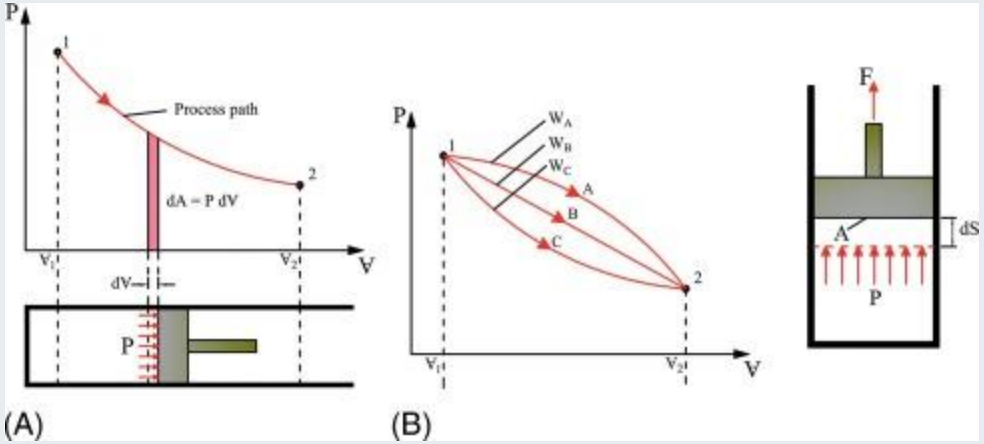


Figure 4: Boundary work [4]

Url:https://ars.els-cdn.com/content/image/3-s2.0-B9780323906265000197-f06-04-9780323906265.jpg

$$W_b = \int_1^2 \delta W_b$$

$$\delta W_b = Fds = \frac{F}{A} Ads = PdV$$

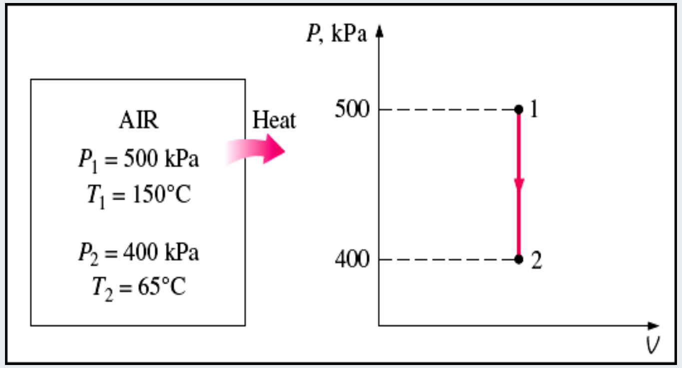
$$W_b = \int_1^2 PdV$$

$$Area = A = \int_1^2 dA = \int_1^2 PdV$$

6. Some Typical Processes

i. Boundary work at constant volume process

- In a constant volume process, the system's volume remains unchanged (ΔV=0).
- The formula for boundary work is: $W_b = \int_1^2 PdV$
- If the volume does not change, $dV = 0$, which means: $W_b = 0$



$$W_b = \int_1^2 PdV = 0$$

Figure 5: Boundary work at constant volume

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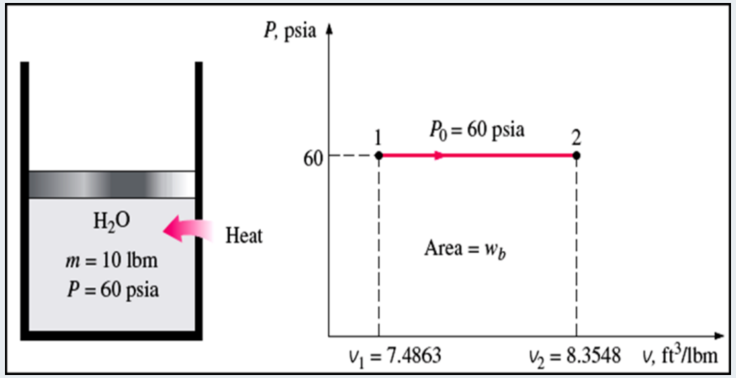
6. Some Typical Processes

Cont…

ii. Boundary work at constant pressure

- In a **constant pressure process**, the pressure (P) remains unchanged while the system's volume changes.
- This is a common scenario in thermodynamic processes, such as the expansion or compression of a gas under constant atmospheric pressure.



$$W_b = \int_1^2 P dV = P\int_1^2 dV = P(V_2 - V_1)$$

Figure 6: Boundary work at constant pressure
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6. Some Typical Processes Cont…

iii. Boundary work at constant Temperature

If the temperature of an ideal gas system held constant, then the equation of state provides the pressure volume relation.

$$P = \frac{mRT}{V}$$

$$W_b = \int_1^2 P dV \qquad W_b = \int_1^2 \frac{mRT}{V} dV$$

$$mRT = C = PV$$

$$W_b = C \int_1^2 \frac{dV}{V} \qquad W_b = C \, ln \frac{V_2}{V_1}$$

$$W_b = mRT \, ln \frac{V_2}{V_1} = P_1 V_1 ln \frac{V_2}{V_1}$$

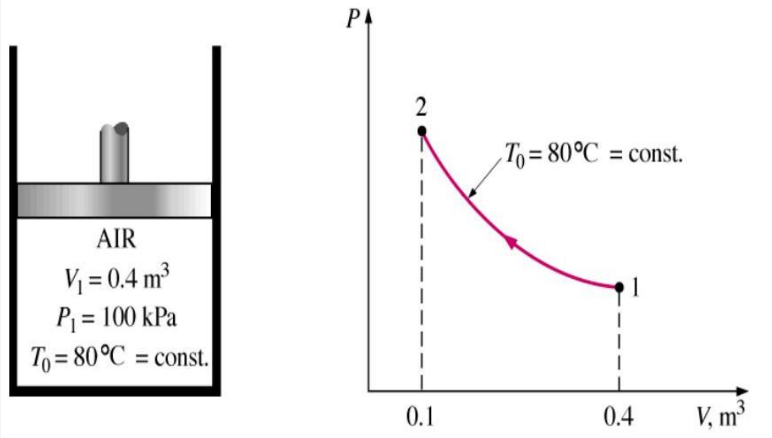


Figure 7: Boundary work at constant temperature
url: https://slideplayer.com/slide/15258439/92/images/7/Constant+temperature%2C+ideal+gas.jpg

6. Some Typical Processes Cont…

iv. Polytropic Process

- During actual expansion and compression processes of gases, pressure and volume are often related by $PV^n = C$. where n and C are constants.
- This equation describes a wide range of thermodynamic processes by varying the value of n.
- It's used to analyze real-world systems like gas compressors, turbines, and engines.
- The polytropic process encompasses other familiar processes as specific case [4]:

  n=0: Constant pressure process (P=constant).

  n=1: Isothermal process (T=constant).

  n=∞: Constant volume process (V=constant).

  n=γ (ratio of specific heats): Adiabatic process

6. Some Typical Processes **Cont…**

Polytropic Process

$$W_b = \int_1^2 PdV \text{ , } PV^n = C \quad \text{and,} \quad P = CV^{-n}$$

$$W_b = \int_1^2 CV^{-n}\,\mathrm{dV} = \mathrm{C}\left[\frac{V_2{}^{-n+1} - V_1{}^{-n+1}}{-n+1}\right] = \frac{P_2V_2 - P_1V_1}{1-n}$$

$$W_b = \frac{mR(T_2 - T_1)}{1-n}$$

For the special case of *n* = 1, the system is isothermal process and the boundary work becomes

$$W_b = \int_1^2 PdV = \int_1^2 CV^{-n}dV = PV\ln\frac{V_2}{V_1}$$

6. Some Typical Processes Cont…

v. Spring Work

- **Spring work** refers to the work done when a spring is either stretched or compressed from its equilibrium position.
- If the spring is stretched or compressed, the work is stored as potential energy in the spring.
- The direction of the force determines whether the work is **positive or negative**:

  Positive work: External force stretches or compresses the spring.

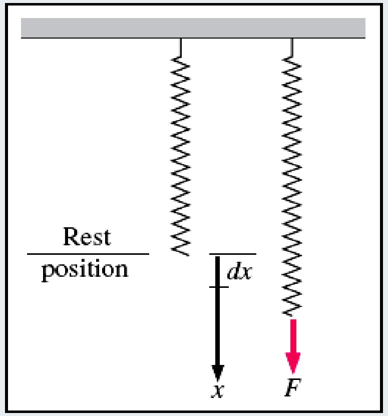
  Negative work: The spring itself does work while returning to its equilibrium position.

6. Some Typical Processes

Cont…

Spring Work

- Springs follow **Hooke's Law**, which states that the force required to stretch or compress a spring is proportional to the displacement (x) [5].
- When the length of the spring changes by a differential amount *dx* under the influence of a force *F*, the work done is



$$\delta W_{spring} = \int_1^2 F dx$$

$$F = kx$$

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

Figure 8: Spring work
url: https://slideplayer.com/slide/14310633/89/images/32/When+the+length+of+the+spring+changes+by+a+differential+amount+dx+under+the+influence+of+a+force+F%2C+the+work+done+is.jpg

7. The First Law for a Closed System

The general energy balance equation

$$E_{in} - E_{out} = \Delta U + \Delta KE + \Delta PE$$

It can be more explicitly expressed as:

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

Therefore, for a closed system where mass never crosses the boundary of the system, the energy balance reduces to:

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

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

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

Where, $Q_{net,in} = Q_{in} - Q_{out}$ *and,* $W_{net,out} = W_{out} - W_{in}$

7. The First Law for a Closed System **Cont…**

For closed systems undergoing cyclic processes, the initial and final states are identical and the energy balance equation becomes:

$$\Delta E_{system} = E_2 - E_1 = 0$$

$$E_{in} - E_{out} = 0$$

$$E_{in} = E_{out}$$

$$W_{net,out} = Q_{net,in} = Q_{in} - Q_{out}$$

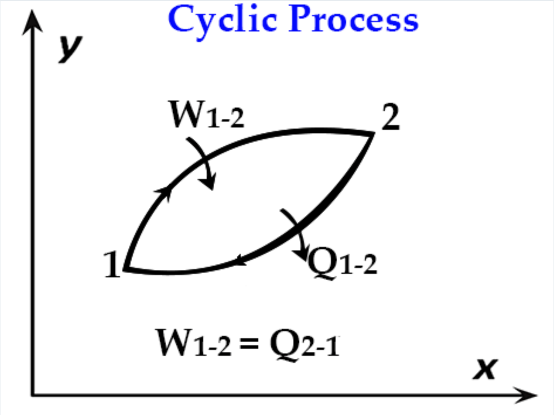


Figure 9: Cyclic Process
url:https://blogger.googleusercontent.com/img/b/R29vZ2xl/AVvXsEhkh5h8_t8lo_f4j_WBmTC1TWJCDr2_JSaslO-y1ZK2Qque9pwvFAJZ7AVH64sO9h1BmGLb1oug3pwLls615ylbsTLu9tswyhbt_M7onIfrEvto2rSjoR7nQxqnTp2vZBvYhIB0eqr-LrU/s1600/Cyclic+process.png

7. The First Law for a Closed System Cont…

If the closed system consists of internal energy, kinetic energy and potential energy, the total energy of the system becomes:

$$E_{in} - E_{out} = \Delta U + \Delta KE + \Delta PE$$

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

$$(Q_{net,in} - W_{net,out}) = (U_2 - U_1) + (m\frac{{V_2}^2 - {V_1}^2}{2}) + mg(z_2 - z_1)$$

If the change in kinetic and potential energies are negligible,

$(Q_{net,in} - W_{net,out}) = (U_2 - U_1)$ or, $Q_{net,in} = (U_2 - U_1) + W_{net,out}$

Summary

- The First Law of Thermodynamics is introduced and its significance in energy conservation is explained.
- Energy of a system can be grouped into microscopic and macroscopic forms.
- In thermodynamics, energy transfer mechanisms for closed systems are heat transfer and work, and for open systems, in addition to heat transfer and work, there is a mass transfer.
- Boundary work is the work associated with a moving boundary.
- Typical processes of boundary work are at constant volume, constant pressure, constant temperature, polytropic process and spring work.
- Application of energy conservation equations to closed systems without mass transfer, with examples like piston-cylinder devices.

References

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Thank you !