Course Title:

Fundamental of Thermodynamics and Heat Transfer

Lecture 4 (Week 4):

Energy and Energy Transfer

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Learning Objective of Lecture:

To impart a great deal of knowledge to undergraduate students on the topics:

- ✓ Similarities between Work Transfer and Heat Transfer
- ✓ Differences between Work Transfer and Heat Transfer
- ✓ Expressions for Displacement Work Transfer during different Thermodynamic Processes
- ✓ Power
- ✓ P – V and T – V Diagrams for Piston Cylinder Assembly

2.3. Similarities and Differences between Work Transfer and Heat Transfer

2.3.1. Similarities of Work and Heat:

- Both are forms of energy and are transient type.
- Both are path functions.
- Both have inexact differentials [1].
- Both are boundary phenomenon.
- Both are not thermodynamic properties.
- Both are equal for a cyclic process and their cyclic integral is non-zero.
- Both are physically equivalent and their unit is Joule.

2.3.2. Differences between Work Transfer and Heat Transfer

- Work transfer is the transfer of energy without transfer of mass because of any property difference (pressure, electrical and gravitational potential) other than temperature between the system and surroundings. Whereas heat transfer is the transfer of energy without transfer of mass because of temperature difference between the system and surroundings [2].
- Work is high grade energy, while heat is low grade energy [3].
- Work is ordered motion of molecules in one direction but heat is random motion of molecules.
- Work can be totally converted into heat. Whereas heat cannot be totally converted into work.
- Entropy of the system does not change during work transfer but entropy of the system increases during heat transfer.
- For the displacement work transfer displacement of the system boundary is necessary, while displacement of the system boundary is not necessary for heat transfer.

- Work transfer to a system is taken as negative and work transfer from a system is taken as positive. Heat transfer to a system is taken as positive and heat transfer from a system is taken as negative.

2.4. Expressions for Displacement Work Transfer for Various Quasi-Static Processes

In thermodynamics many problems of interest are expressed in terms of pressure (*P*), temperature (*T*) and volume (*V*) rather than in terms of force (*F*) and distance (*s*). So, it is convenient to express the mathematical relations for displacement work (*P* - *dV* work) in terms of *P*, and *V* as

$$W_{1-2} = \int_1^2 F.ds = \int_1^2 P.A.ds = \int_1^2 P.dV \qquad \ldots\ldots(2.8)$$

where pressure, $P = F/A$ and A is the area of piston on which pressure P is exerted. Equation (2.8) for work done is valid only if the system is closed and the process is quasi-static or reversible.

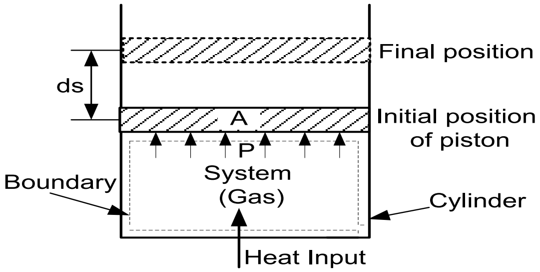


Figure 2.5. Illustration of displacement work transfer

This integral can be evaluated and hence calculations of displacement work can be done, only if we know the relation between *P* and *V* or the path of the process. To illustrate this, let us consider a system with a certain amount of gas having pressure *P* contained in a piston cylinder arrangement as shown in figure 2.5. During a thermodynamic process (e.g. expansion of gas) from initial state 1 to final state 2, the piston is displaced by *ds*. As the cross-sectional area *A* of the piston remains constant, the volumetric displacement of the piston is represented by *dV*. This process can be represented on a *P* - *V* diagram by a path 1 - 2 as shown in figure 2.6. The shaded area (*P.dV*) gives the work done due to small movement ***ds*** of the piston and the total displacement work by the gas during expansion process 1 - 2 is calculated by evaluating total area covered by the process curve on a *P* - *V* diagram with respect to *V* axis using above equation (2.8). The *P* - *V* diagram shows that the work transferred during any thermodynamic process can be determined not only by specifying the initial and final states (which alone does not determine area), but also by knowing the nature of the process curve.

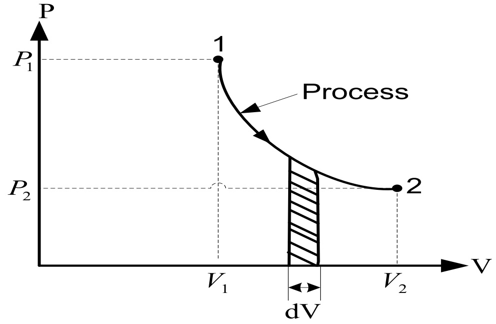


Figure 2.6. Evaluation of displacement work as area under *P* - *V* curve

Some derivations of expressions for work transfer in various thermodynamic quasi - static or quasi- equilibrium processes will be performed below:

2.4.1. Constant Volume (Isochoric) Process

A constant volume process also called an isochoric process is a thermodynamic process during which the volume of a closed system undergoing such a process remains constant. Heating or cooling of a working substance (gas) inside a closed rigid container can be taken as a constant volume or an isochoric process. During an isochoric process, both the pressure and temperature change. The pressure and temperature increase when heat is supplied to the system and decrease when heat is rejected by the system.

As shown in figure 2.7, the area covered by the thermodynamic process curve 1 - 2 on *P-V* diagram for a constant volume heating process is zero. Therefore, work transfer during an isochoric process is zero. This is because there is no displacement (i.e. $dV = 0$) during an isochoric process. So, work transfer during an isochoric process is

$$W_{1-2} = \int_{1}^{2} P.dV = 0 \qquad \text{........(2.9)}$$

On a *P* - *V* diagram as shown as in figure 2.7, an isochoric process appears as a straight vertical line parallel to the axis of pressure.

An ideal Otto cycle is a practical example of an isochoric process where it is assumed that the burning of the petrol - air mixture in an internal combustion engine is instantaneous. There is an increase in the temperature and pressure of the gas inside the cylinder while the volume remains constant.

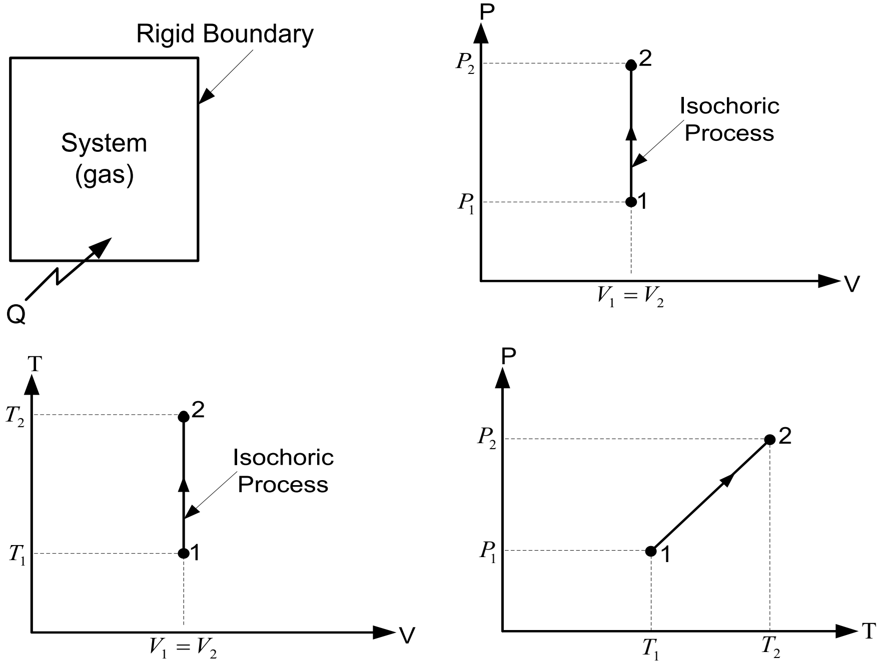


Figure 2.7. Constant volume heating process

2.4.2. Constant Pressure (Isobaric) Process

A constant pressure or an isobaric process is a thermodynamic process in which the pressure remains constant. Expansion or compression of a working substance inside a cylinder with freely moving frictionless piston can be taken as a constant pressure or an isobaric process. During an isobaric process, both the volume and temperature change. The temperature and volume increase when heat is supplied to the system (heating process) and decrease when heat is rejected by the system (cooling process).

As shown in figure 2.8, work transfer during an isobaric process can be calculated as

$$W_{1-2} = \int_{1}^{2} P.dV = P\int_{1}^{2} dV = P[V]_1^2 = P(V_2 - V_1) \qquad \text{……..(2.10)}$$

If the working substance is an ideal gas, applying the ideal gas equation this equation becomes

$$W_{1-2} = mR(T_2 - T_1) \qquad \text{……….(2.11)}$$

where *m* and *R* are the mass and the particular gas constant of the ideal gas respectively.

On a *P* - *V* diagram as shown in figure 2.8, an area below a horizontal line parallel to the axis of volume represents the work transfer during an isobaric process.

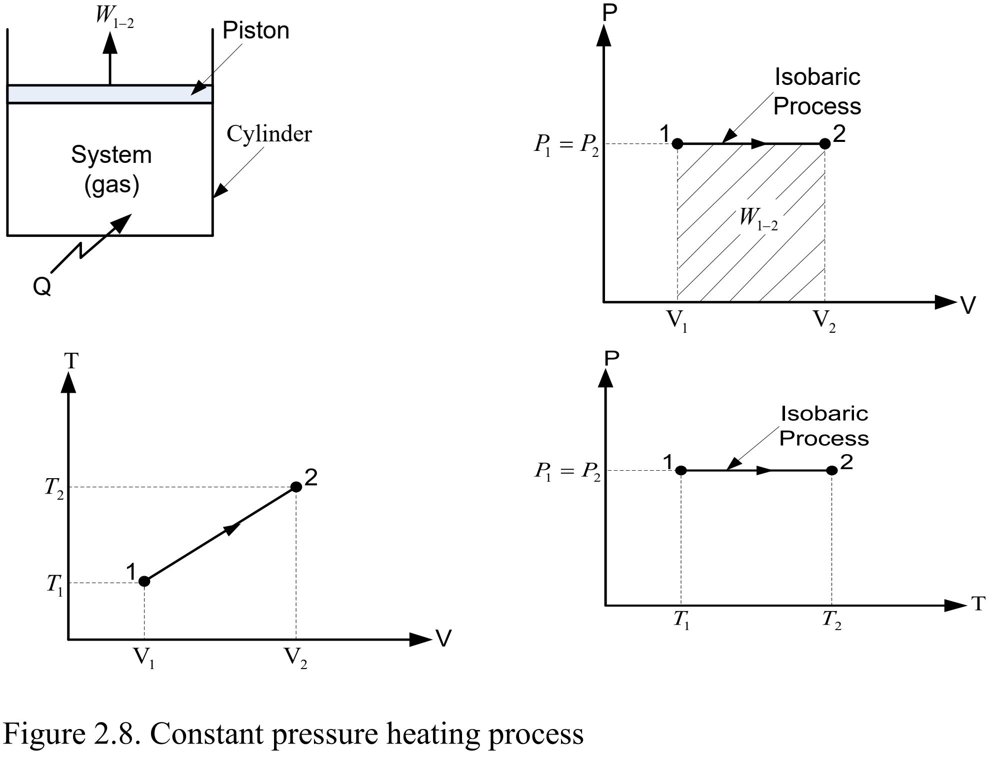


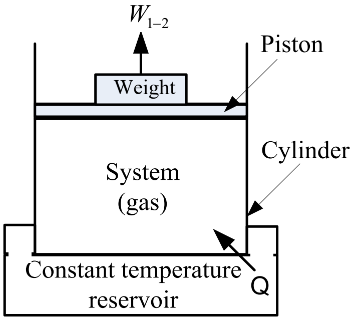
Figure 2.8. Constant pressure heating process

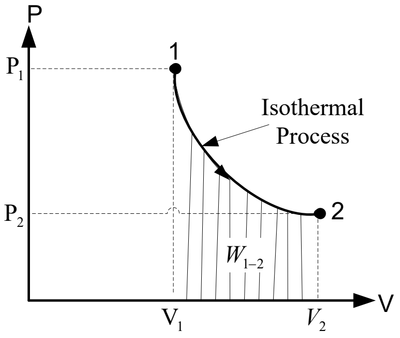
A boiler or steam generator is a practical example of an isobaric process where the outlet temperature of the exiting steam is increased without increasing its associated outlet pressure.

2.4.3. Constant Temperature (Isothermal) Process

A constant temperature or an isothermal process is a thermodynamic process during which the temperature remains constant. If a system with an ideal gas contained in a piston cylinder device is heated under constant temperature, its pressure decreases and volume increases.

An isothermal process can be realized in a piston - cylinder device which is surrounded by a constant temperature reservoir having same temperature as of the system as shown in figure 2.9 [3]. When the piston moves upwards after removing certain weight placed on it, the gas inside the cylinder expands from a high pressure to a low pressure and there is a tendency for its temperature to fall. In an isothermal expansion process heat then flows from the reservoir to the gas until its original temperature is restored. Similarly, in an isothermal compression process heat is removed from the gas (working substance) to the reservoir continuously in order to keep the system temperature at the initial value. It has to be noted that the change occurs slowly enough to allow the system to continually adjust to the temperature of the reservoir through heat exchange and this is possible only when very small amount of weight is removed at a time to make the process quasi-static or quasi-equilibrium.





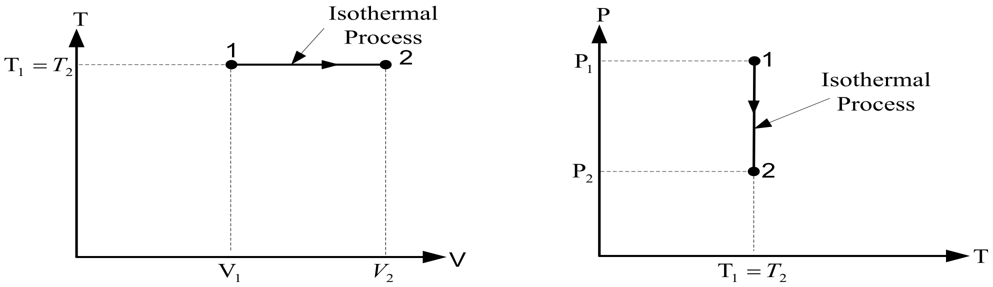


Figure 2.9. Constant temperature expansion process

For the special case of an ideal gas system, the pressure is inversely proportional to the volume of the system if the system kept at the isothermal condition. This means $PV =$ constant. For any intermediate state, it implies

$$PV = P_1V_1 = P_2V_2 \qquad \text{……(2.12)}$$

Work transfer during a constant temperature process is given by

$$W_{1-2} = \int_1^2 P.dV = \int_1^2 \frac{P_1V_1}{V}dV = P_1V_1\int_1^2 \frac{dV}{V} = P_1V_1 \ln(V_2/V_1) \qquad \text{…….(2.13)}$$

$$\Rightarrow \quad W_{1-2} = mRT_1 \ln(V_2/V_1) \qquad \text{…….(2.14)}$$

On a P - V diagram, an area under the relevant pressure - volume isotherm (process curve) for an ideal gas system represents the work transfer during an isothermal process and the isothermal curve (PV = constant) is hyperbolic in character as shown in figure 2.9.

Phase changes such as melting or evaporation of a working substance are examples of an isothermal process.

2.4.4. Adiabatic Process

A process during which a change in the state of the system occurs without exchange of heat with the surroundings is known as an *adiabatic process*. During the adiabatic process, changing variables are pressure, temperature and volume. An adiabatic process can be carried out in a system whose boundaries are perfectly insulated. Such a process may be reversible or irreversible and a reversible adiabatic process is known as isentropic process. For a reversible adiabatic process, the relationship between pressure and volume is described by an equation

$$PV^{\gamma} = constant \qquad \text{……….(2.15)}$$

where $\gamma = c_P/c_V$ is the specific heat ratio.

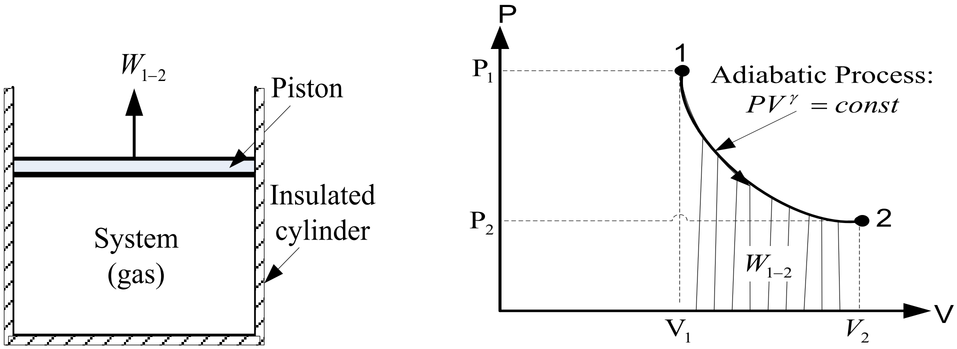


Figure 2.10. Reversible adiabatic process

Then work transfer during an adiabatic process from state 1 to 2 is derived as,

$$W_{1-2} = \int_1^2 PdV = \int_1^2 \frac{P_1{V_1}^{\gamma}}{V^{\gamma}}dV = P_1{V_1}^{\gamma}\int_1^2 \frac{dV}{V^{\gamma}}$$

$$= \frac{P_1{V_1}^{\gamma}}{1-\gamma}\left({V_2}^{1-\gamma} - {V_1}^{1-\gamma}\right)$$

$$= \frac{P_1{V_1}^{\gamma}{V_2}^{1-\gamma} - P_1V_1}{1-\gamma}$$

Putting $P_1{V_1}^{\gamma} = P_2{V_2}^{\gamma}$, and applying equation of state for an ideal gas, we get

$$W_{1-2} = \frac{P_2V_2 - P_1V_1}{1-\gamma} = \frac{mR(T_2 - T_1)}{1-\gamma} \qquad \text{…….(2.16)}$$

2.4.5. Polytropic Process

A *polytropic process* is a thermodynamic process that obeys the pressure - volume relation: $PV^n =$ *constant,* where n is any real number called a *polytropic index* or *exponent* whose value remains constant throughout in any particular process. This equation is used to accurately characterize the thermodynamic processes of certain systems notably the compression or expansion of a gas. However, it can be taken as a generalized equation for different thermodynamic processes namely isochoric, isobaric, isothermal and adiabatic processes which are quasi-static or quasi-equilibrium in operation under ideal working conditions. A polytropic process represents common thermodynamic processes for different values of polytropic index n as given below [2]:

Polytropic index	Relation	Process
(i) When n = o	$P = \text{constant}$	Constant pressure or isobaric
(ii) When $n = 1$	$PV = \text{constant}$	Constant temperature or isothermal
(iii) When $n = \infty$	$PV^n = P^{1/n}V = P^{1/\infty}V$ $= P^0V = \text{constant}$ $\Rightarrow$ V = constant	Constant volume or isochoric
(iv) When $n = \gamma$	$PV^\gamma = \text{constant}$	Adiabatic

This is illustrated on a P - V diagram in figure 2.11 [3]. It may be noted that since specific heat ratio γ is always greater than unity, adiabatic process curve lies between isothermal and isochoric process curves.

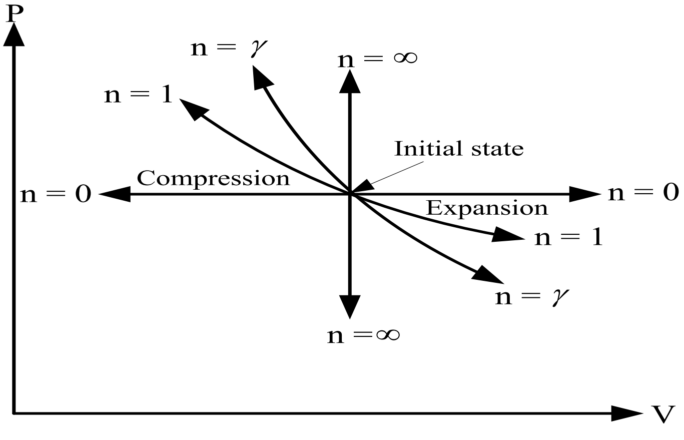


Figure 2.11. Polytropic Process

Pressure-volume relationship for initial, final and any intermediate state during a polytropic process is expressed as

$$P_1V_1{}^n = P_2V_2{}^n = PV^n \qquad \text{.........} (2.17)$$

Pressure at any intermediate state is given as

$$P = \frac{P_1V_1{}^n}{V^n} \qquad \text{.........} (2.18)$$

Work transfer during a polytropic process from state 1 to 2 is calculated as

$$W_{1-2} = \int_1^2 PdV = \int_1^2 \frac{P_1V_1{}^n}{V^n} dV = P_1V_1{}^n \int_1^2 \frac{dV}{V^n}$$

$$= \frac{P_1V_1{}^n}{1-n}\left(V_2{}^{1-n} - V_1{}^{1-n}\right)$$

$$= \frac{P_1V_1{}^nV_2{}^{1-n} - P_1V_1}{1-n}$$

Putting $P_1V_1{}^n = P_2V_2{}^n$, we get

$$W_{1-2} = \frac{P_2V_2 - P_1V_1}{1-n} \qquad \text{........} (2.19)$$

If the working substance is an ideal gas, then by applying the ideal gas equation above equation (2.19) becomes

$$W_{1-2} = \frac{mR(T_2 - T_1)}{1-n} \qquad \text{........} (2.20)$$

2.5. Power

Power is defined as the rate at which energy is transferred across the boundary of a system. For designing of practical instruments or devices it is essential not only to know how much energy is needed to drive a device or how much energy can be obtained from the device, but also we need the rate at which energy can be obtained from the device. In thermodynamics, we deal with two modes of energy transfer: work transfer and heat transfer. Accordingly, there are two types of power namely mechanical power due to work transfer and thermal power due to heat transfer [2].

Mechanical power is defined as the rate of work transfer. Mathematically,

$$\dot{W} = \lim_{\Delta t \to 0} \frac{\delta W}{\Delta t} \qquad \ldots\ldots\ldots\ (2.30)$$

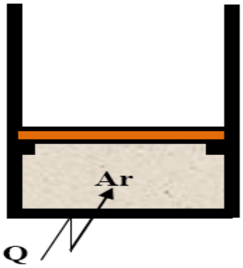
Thermal power is defined as the rate of heat transfer. Mathematically,

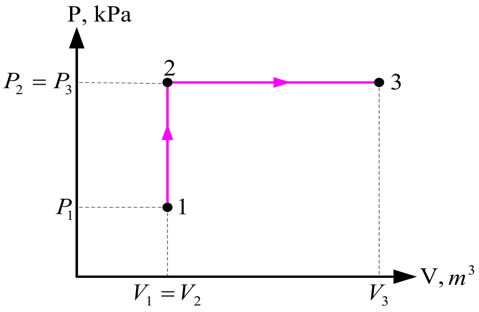
$$\dot{Q} = \lim_{\Delta t \to 0} \frac{\delta Q}{\Delta t} \qquad \ldots\ldots\ldots\ (2.31)$$

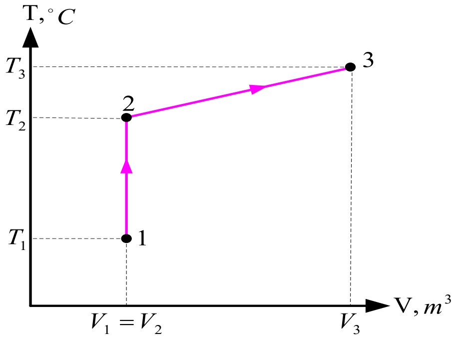
The SI unit of Power is J/s or Watt (W).

2.6. P – V and T – V Diagrams for Different Arrangements of Piston Cylinder Assembly:

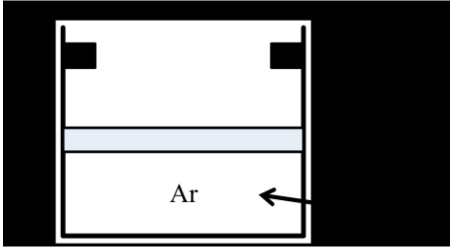
(i) Heat is supplied to a frictionless piston cylinder assembly containing Argon gas shown in the figure below. Initial pressure of the system is less than pressure required to lift the piston. The P – V and T – V diagrams for this heating process are given below:

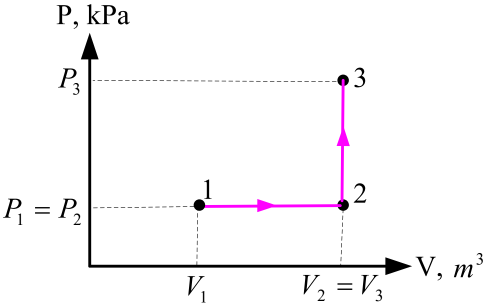


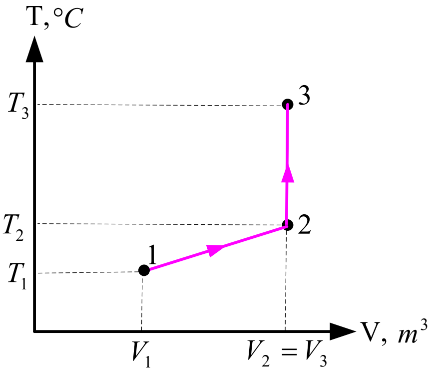




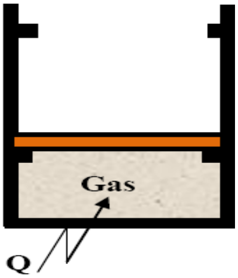
(ii) Heat is supplied to a frictionless piston cylinder assembly containing Argon gas shown in the figure below. The P – V and T – V diagrams for this heating process are given below:

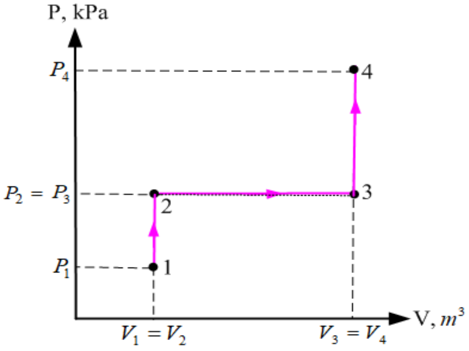


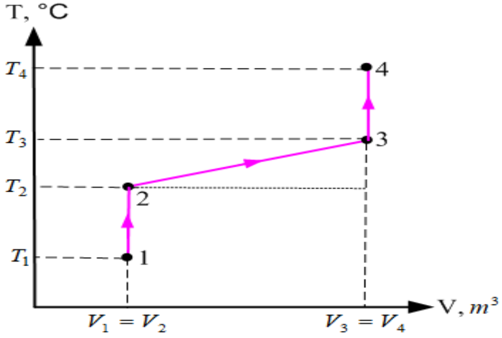




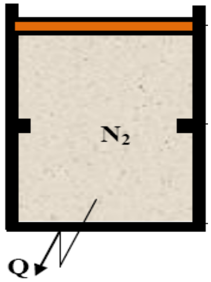
(iii) Heat is supplied to a frictionless piston cylinder assembly containing a gas shown in the figure below. Initial pressure of the system is less than pressure required to lift the piston. The P – V and T – V diagrams for this heating process are given below:

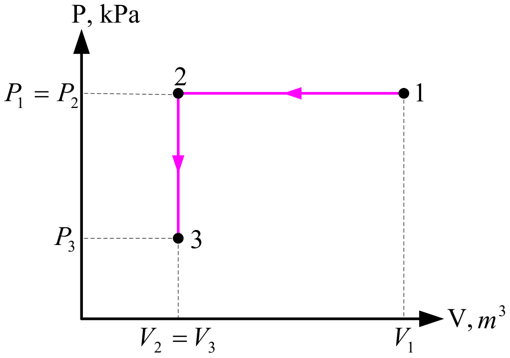


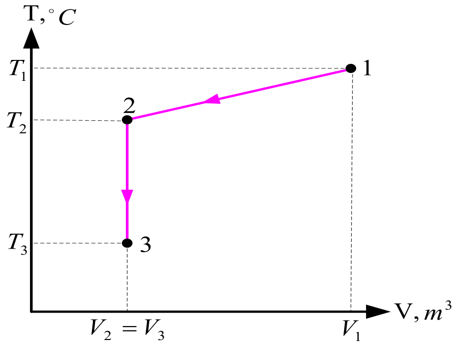




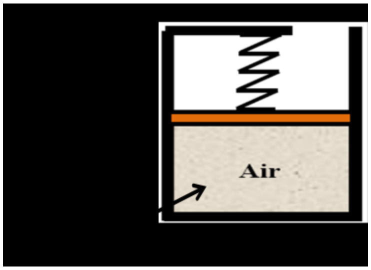
(iv) Heat is lost from a frictionless piston cylinder assembly containing Nitrogen gas shown in the figure below. The P – V and T – V diagrams for this cooling process are given below:

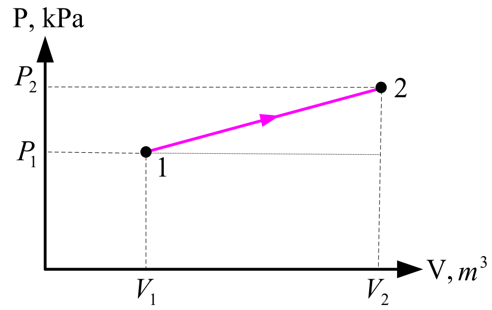




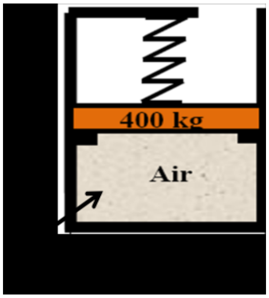


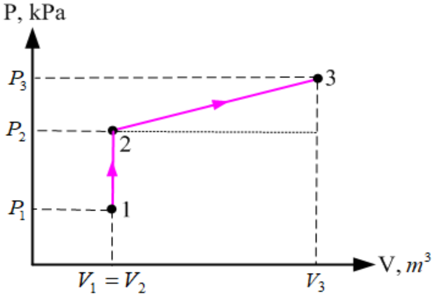
(v) Heat is supplied to a frictionless piston cylinder assembly containing air shown in the figure below. The piston just touches the spring at the initial condition. The P – V and T – V diagrams for this heating process are same as given below:



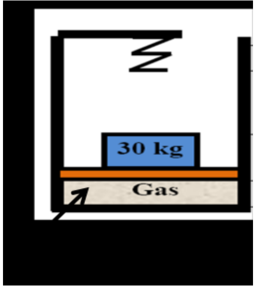


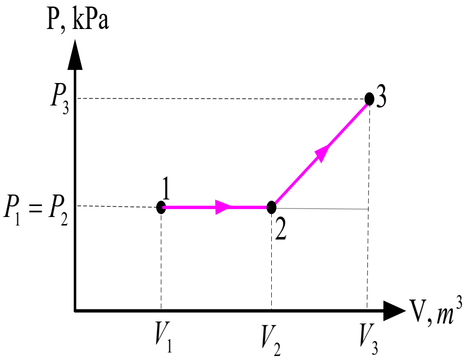
(vi) Heat is supplied to a frictionless piston cylinder assembly containing air shown in the figure below. The piston just touches the spring at the initial condition and rests on the stops. Initial pressure of the system is less than pressure required to lift the piston. The P – V and T – V diagrams for this heating process are same as given below:

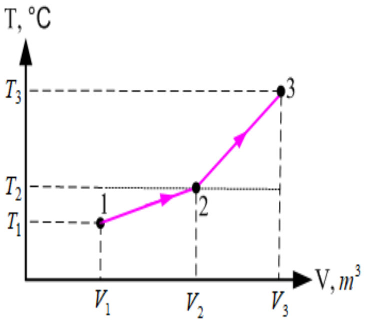




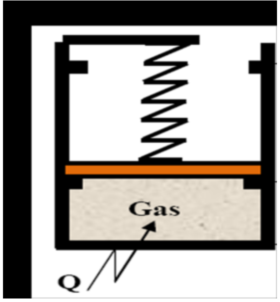
(vii) Heat is supplied to a frictionless piston cylinder assembly containing a gas shown in the figure below. A mass of 30 kg is put on the piston. The P – V and T – V diagrams for this heating process are given below:

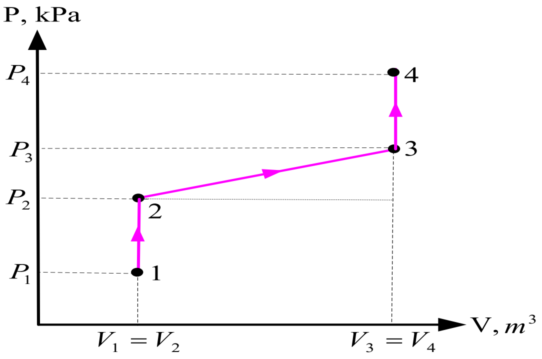






(viii) Heat is supplied to a frictionless piston cylinder assembly containing a gas shown in the figure below. The piston just touches the spring at the initial condition and rests on the stops. Initial pressure of the system is less than pressure required to lift the piston. The P – V and T – V diagrams for this heating process are same as given below:





Lecture Highlights:

- *Similarities* of work and heat are:
  1. Both are forms of energy and are transient type.
  2. Both are path functions.
  3. Both have inexact differentials.
  4. Both are boundary phenomenon.
  5. Both are not thermodynamic properties.
  6. Both are equal for a cyclic process and their cyclic integral is non-zero.
  7. Both are physically equivalent and their unit is Joule.

- *Differences* between *work transfer* and *heat transfer* are:

Work Transfer	**Heat Transfer**
1. It is the transfer of energy without transfer of mass because of any property difference (pressure, electrical and gravitational potential) other than temperature between the system and surroundings.	1. It is the transfer of energy without transfer of mass because of temperature difference between the system and surroundings.
2. Work is high grade energy.	2. Heat is low grade energy.
3. Work is ordered motion of molecules in one direction.	3. Heat is random motion of molecules.
4. Work can be totally converted into heat.	4. Heat cannot be totally converted into work.
5. Entropy of the system does not change during work transfer.	5. Entropy of the system increases during heat transfer.
6. For the displacement work transfer displacement of the system boundary is necessary.	6. Displacement of the system boundary is not necessary for heat transfer.
7. Work transfer to a system is taken as negative and work transfer from a system is taken as positive.	7. Heat transfer to a system is taken as positive and heat transfer from a system is taken as negative.

- *Displacement work*: The magnitude of work transfer during any quasi-equilibrium process is given by the area under the process curve on *P-V* diagram and calculated by the expression

$$W_{1-2} = \int_1^2 P.dV.$$

- Expressions for work transfer for different processes:
  1. For an *isochoric process*: $W_{1-2} = 0$
  2. For an *isobaric process*: $W_{1-2} = P(V_2 - V_1)$
  3. For *isothermal process*: $W_{1-2} = P_1V_1 \ln(V_2/V_1)$
  4. For an *adiabatic process*: $W_{1-2} = \dfrac{P_2V_2 - P_1V_1}{1-\gamma}$

     where γ is the specific heats ratio.

- For a *polytropic process*: $W_{1-2} = \dfrac{P_2V_2 - P_1V_1}{1-n}$ where n is the polytropic index.
- A polytropic process represents common thermodynamic processes for different values of polytropic index n as given below:

Polytropic index	**Relation**	**Process**
(i) When $n = 0$	$P = \text{constant}$	Constant pressure or isobaric
(ii) When $n = 1$	$PV = \text{constant}$	Constant temperature or isothermal
(iii) When $n = \infty$	$V = \text{constant}$	Constant volume or isochoric
(iv) When $n = \gamma$	$PV^{\gamma} = \text{constant}$	Adiabatic

- *Power:* It is defined as a rate of energy transfer and can be classified into thermal power and mechanical power.
  - *Mechanical power* is defined as the rate of work transfer. Mathematically,

$$\dot{W} = \lim_{\Delta t \to 0} \frac{\delta W}{\Delta t}$$

  - *Thermal power* is defined as the rate of heat transfer. Mathematically,

$$\dot{Q} = \lim_{\Delta t \to 0} \frac{\delta Q}{\Delta t}$$

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