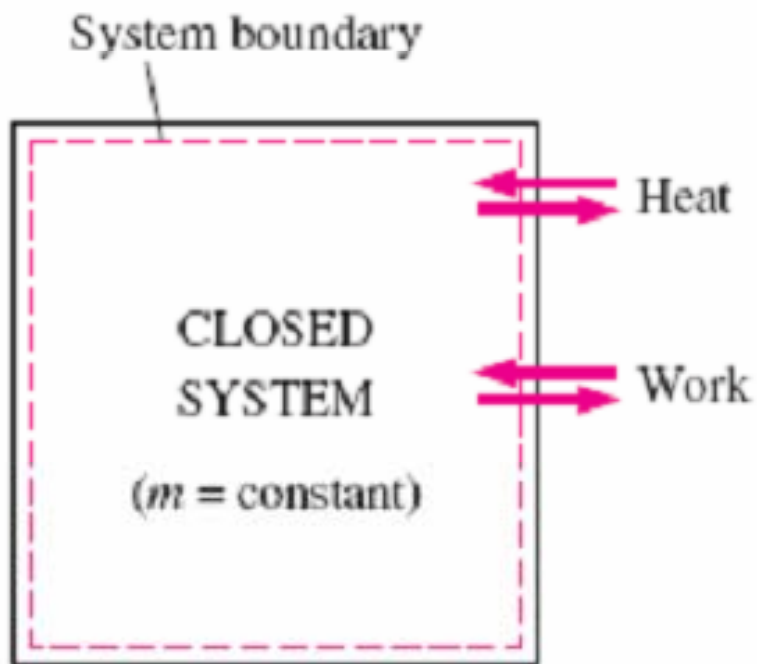


CHAPTER-3

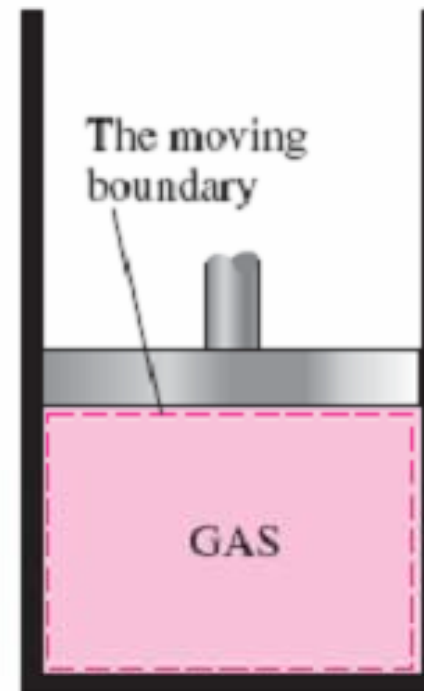
ENERGY TRANSFER BY HEAT, WORK, AND MASS

- The first law of thermodynamics is an expression of the conservation of energy principle.
- Energy can cross the boundaries of a closed system in the form of heat or work, but not in the form of mass.
- Energy transfer across a system boundary due solely to the temperature difference between a system and its surroundings is called heat.
- Work energy can be thought of as the energy expended to lift a weight.

Two examples of closed systems



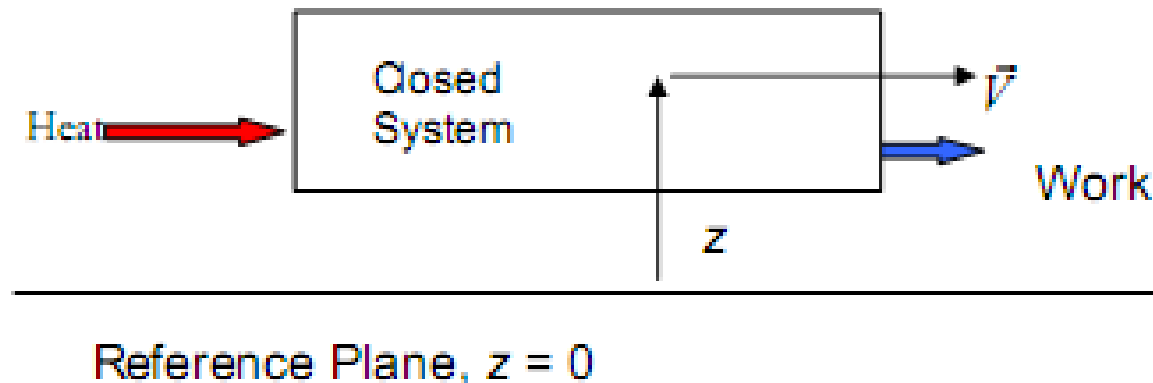
Rigid Tank



Piston Cylinder Device

First Law of Closed System

- A closed system moving relative to a reference plane is shown below where z is the elevation of the center of mass above the reference plane and $\vec{V}$ is the velocity of the center of mass.



- For a closed system, the conservation of energy principle or the first law of thermodynamics is expressed as:-

$$\left(\text{Total energy entering the system} \right) - \left(\text{Total energy leaving the system} \right) = \left(\text{The change in total energy of the system} \right)$$

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

Closed System First Law

- According to classical thermodynamics, we consider the energy added to be net heat transfer to the closed system and the energy leaving the closed system to be net work done by the closed system. So

$$Q_{net} - W_{net} = \Delta E_{system}$$

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

$$W_{net} = (W_{out} - W_{in})_{other} + W_b$$

$$W_b = \int_1^2 P dV$$

➤ Normally the stored energy, or total energy, of a system is expressed as the sum of three separate energies.

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

$$E = \text{Internal energy} + \text{Kinetic energy} + \text{Potential energy}$$

$$E = U + KE + PE$$

➤ U is the sum of the energy contained within the molecules of the system other than the kinetic and potential energies of the system as a whole and is called the internal energy.

➤ The internal energy U is dependent on the:-

- ✓ state of the system
- ✓ mass of the system.

- For a system moving relative to a reference plane, the kinetic energy KE and the potential energy PE are given by:-

$$KE = \frac{1}{2}mv^2 \quad \text{and} \quad PE = mgz$$

- The change in stored energy for any system is

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

- Now the conservation of energy principle, or the first law of thermodynamics for closed systems, is written as

$$Q_{net} - W_{net} = \Delta U + \Delta KE + \Delta PE$$

- If the system does not move with a velocity and has no change in elevation, the conservation of energy equation reduces to

$$Q_{net} - W_{net} = \Delta U$$

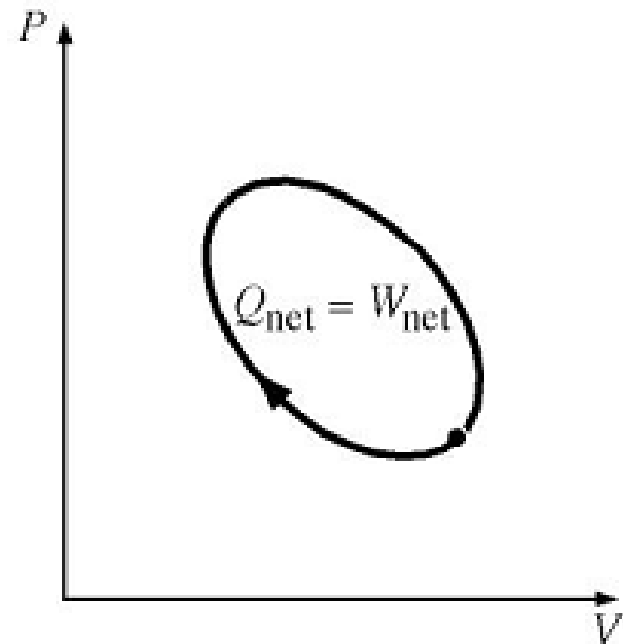
- We will find that this is the most commonly used form of the first law for closed systems.

Closed System First Law for a Cycle

- Thermodynamic cycle is composed of processes that cause the working fluid to undergo a series of state changes through a series of processes such that the final and initial states are identical.
- The change in internal energy of the working fluid is zero for whole numbers of cycles.
- The first law for a closed system operating in a thermodynamic cycle becomes:-

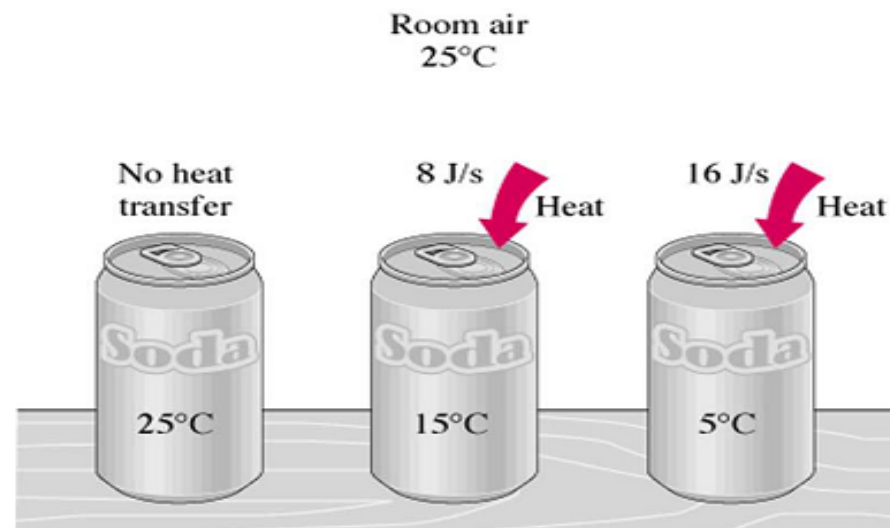
$$Q_{net} - W_{net} = \Delta U_{cycle}$$

$$Q_{net} = W_{net}$$



Heat Transfer

- Heat is the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of temperature difference.
- It is recognized only as it crosses the boundary of a system.
- Heat transfer is not a property.
- Heat transfer between two states is denoted by Q
- A process during which there is no heat transfer is called an adiabatic process.



Heat Transfer

Heat Rate of Heat Transfer

- The rate of heat transfer is the amount of heat transfer per unit time
- It is denoted by $\dot{Q}$ and it can be given by: $\dot{Q} = \frac{dQ}{dt}$
- The unit of $\dot{Q}$ is kJ/s, which is equivalent to kW

Energy Transfer by Work

- Work is an energy interaction between a system and its surroundings.
- Work is the energy transfer associated with a force acting through a distance.

Examples: a rising piston, a rotating shaft, electric wire

- Work is also not a property.
- Since work is a form of energy, it has the units J or kJ.
- Work done during a process between two states is denoted by W .

Power

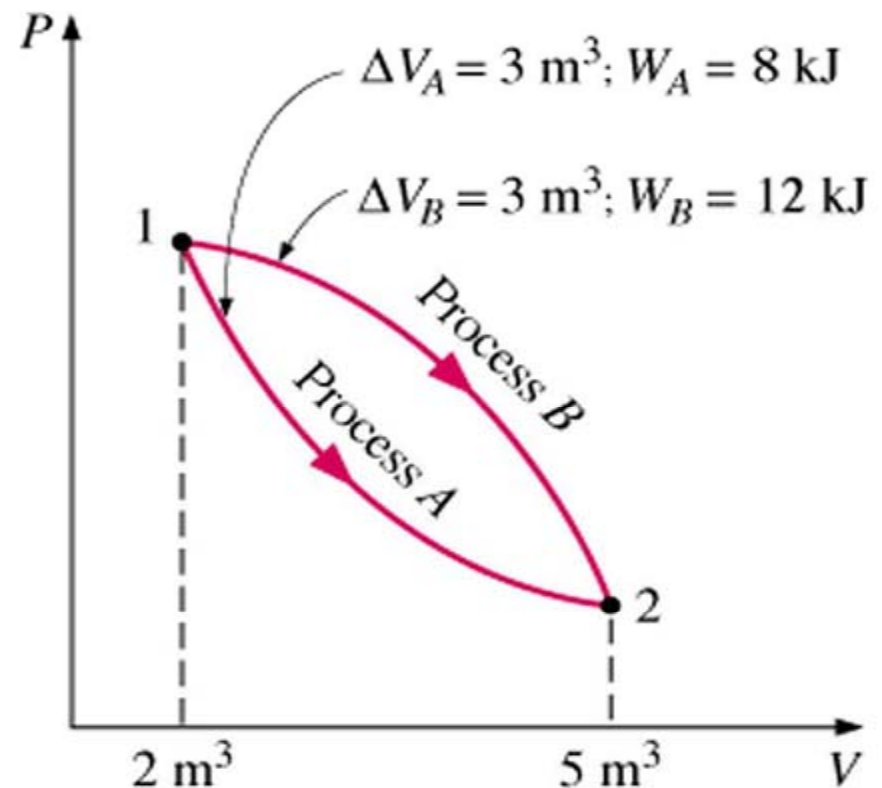
- The work done per unit time is called power and is denoted $\dot{W}$.
- The unit of power and the rate of heat transfer are both kJ/s (or kW)

The General Remarks on Heat and Work

- Heat and work are associated with processes, not a certain state.
- Heat and work are directional quantities.
 - ✓ Complete description of a heat or work interaction requires the specification of both the **magnitude** and **direction**.

Heat Transfer

- Heat and work are path functions, i.e. their magnitudes depend on the path followed during the process as well as the end states.
- On the other hand, properties are point functions, i.e. their magnitudes depend on the end states only.



Heat Transfer

Electrical Work and Power

- Electrons crossing the system boundary do electrical work on the system.
- Electrons in a wire move under the effect of electromotive forces, doing work.
- Electrical power is expressed as: $\dot{W}_e = VI$ (W)
where V is the potential difference and I is the current
- It can also be expressed as: $\dot{W}_e = I^2 R = V^2 / R$
- To calculate electrical work given the electrical power:

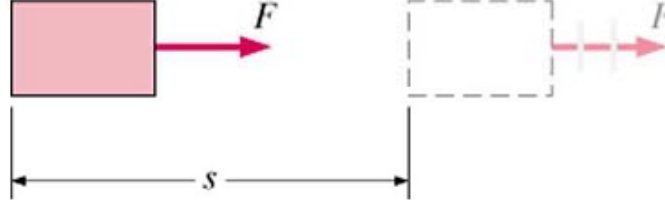
$$W_e = \int_1^2 \dot{W}_e dt = \int_1^2 VI dt$$

- If both V and I remain constant:

$$W_e = VI \Delta t$$

Mechanical Forms of Work

- Generally, the work done is proportional to the force applied (F) and the distance traveled (s):

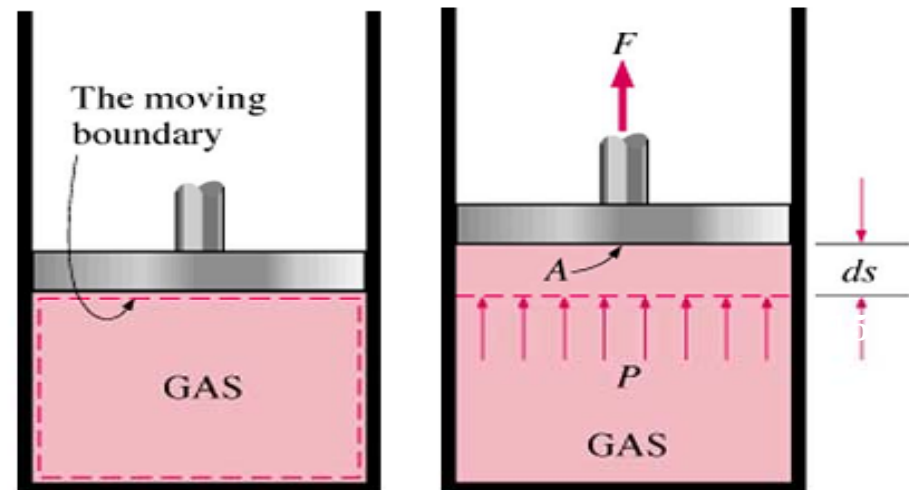
$$W = \int_1^2 F ds$$


Type 1: Moving Boundary Work

- The expansion or compression work associated with the movement of the inner face of the piston is called moving boundary work or simply boundary work.

$$\delta W_b = F ds = PA ds = P dV$$

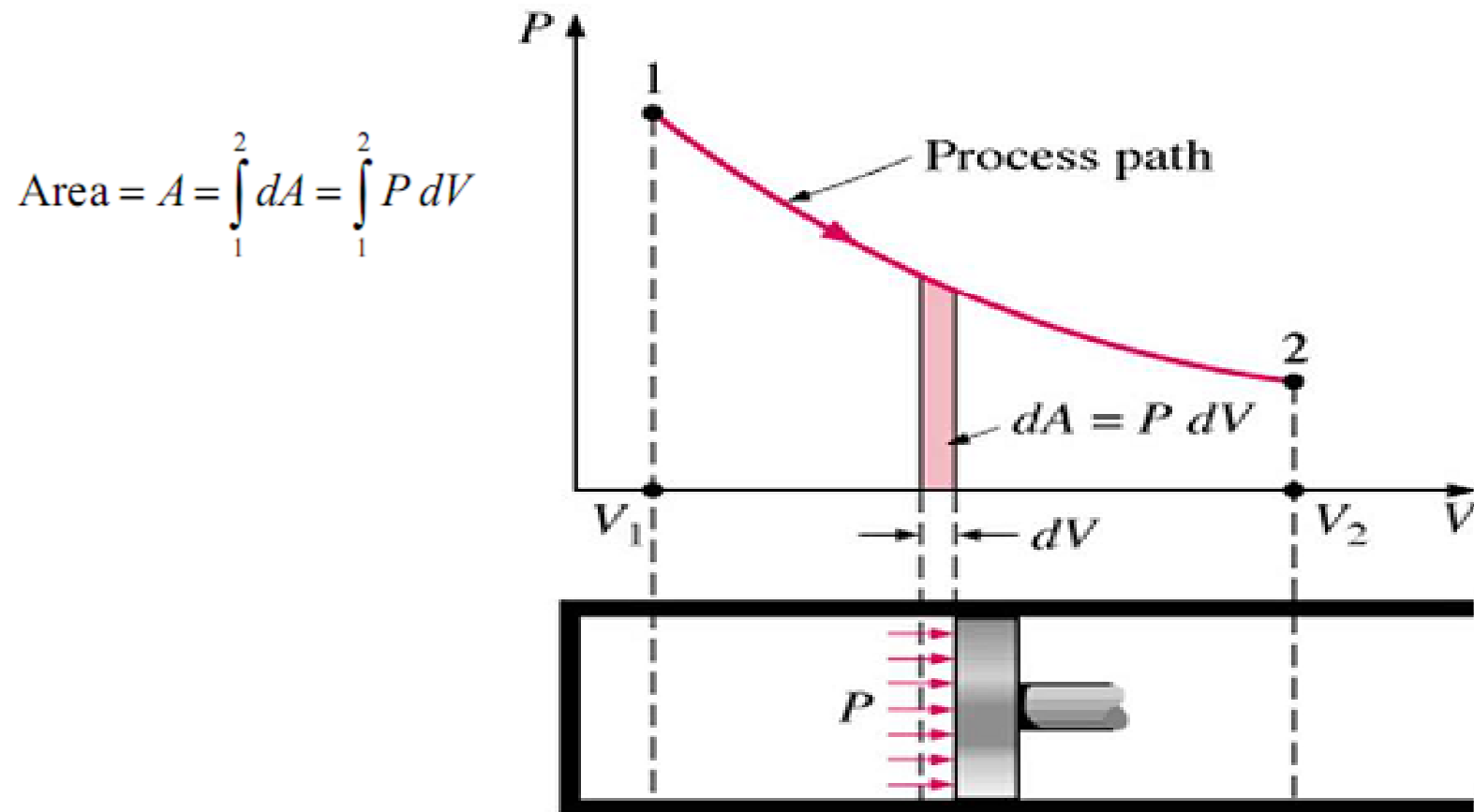
$$\rightarrow W_b = \int_1^2 P dV$$



Mechanical Forms of Work

Expressing Boundary Work on a P-V Diagram

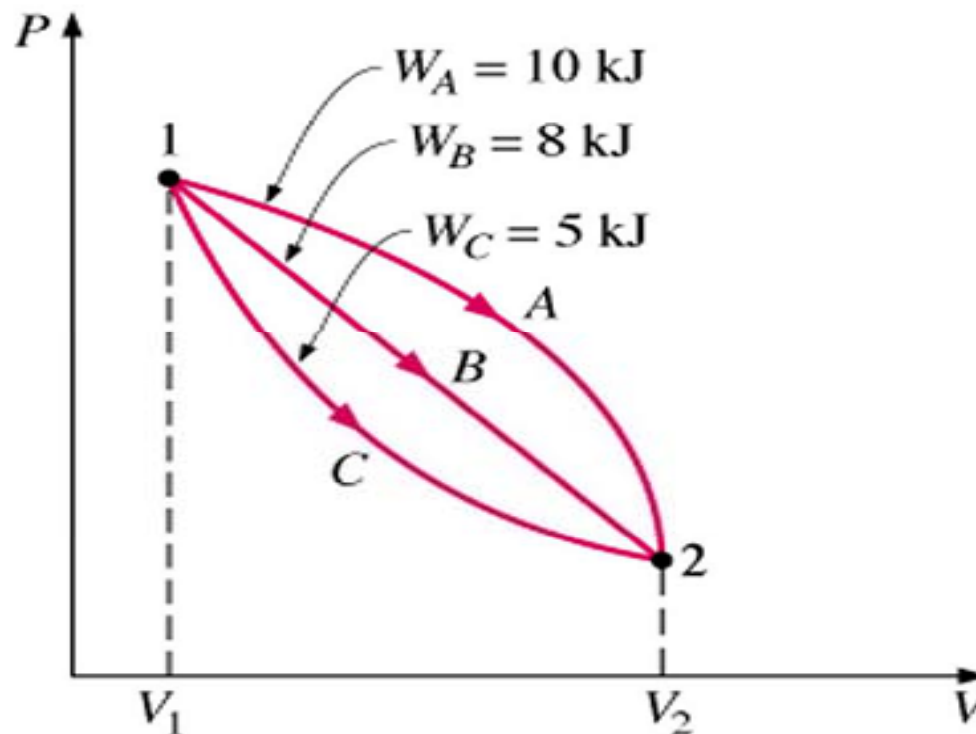
- The area under the process curve on a P-V diagram is equal, in magnitude, to the work done during an expansion or compression process of a closed system.



Mechanical Forms of Work

Expressing Boundary Work on a P-V Diagram

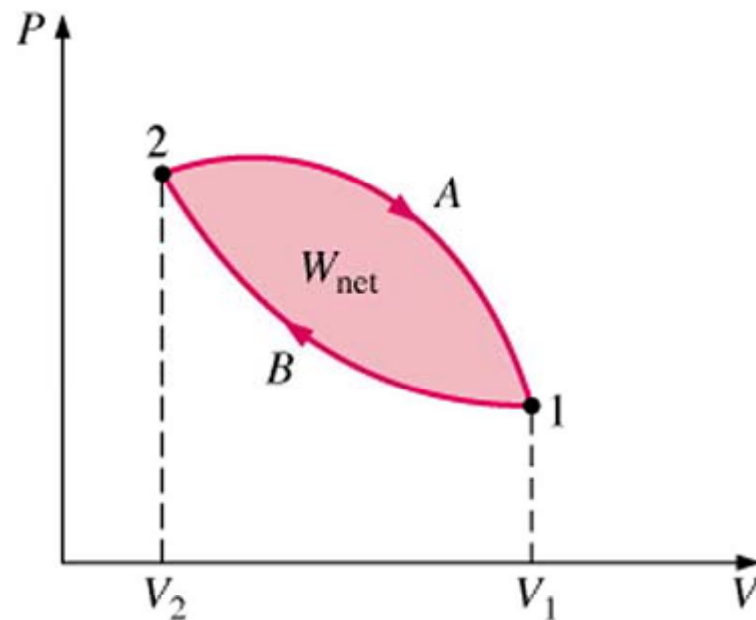
- Since a gas can follow different paths as it expands from state 1 to state 2, each path will have a different area underneath it.
- The work associated with each path will be different because the area under each curve will be different.



Mechanical Forms of Work

The Net Work Done During a Cycle

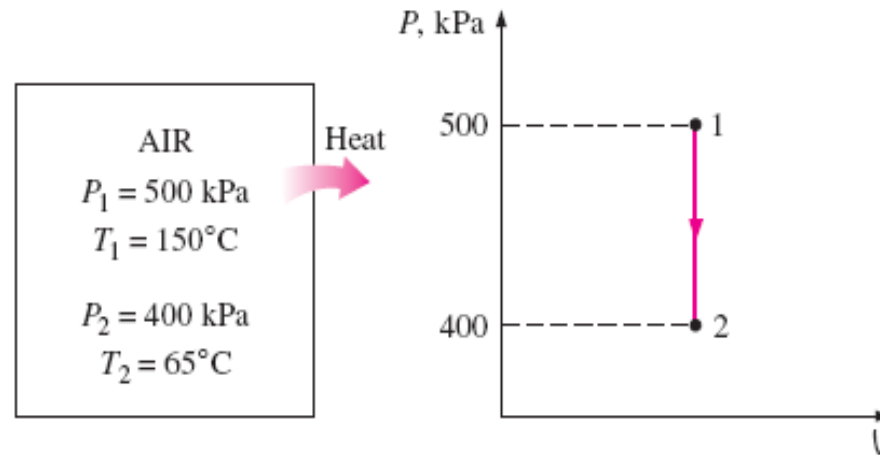
- The work done during a cycle is the area (on a P-V diagram) between the process paths



Mechanical Forms of Work

Some typical process

1. Boundary work at constant volume process.



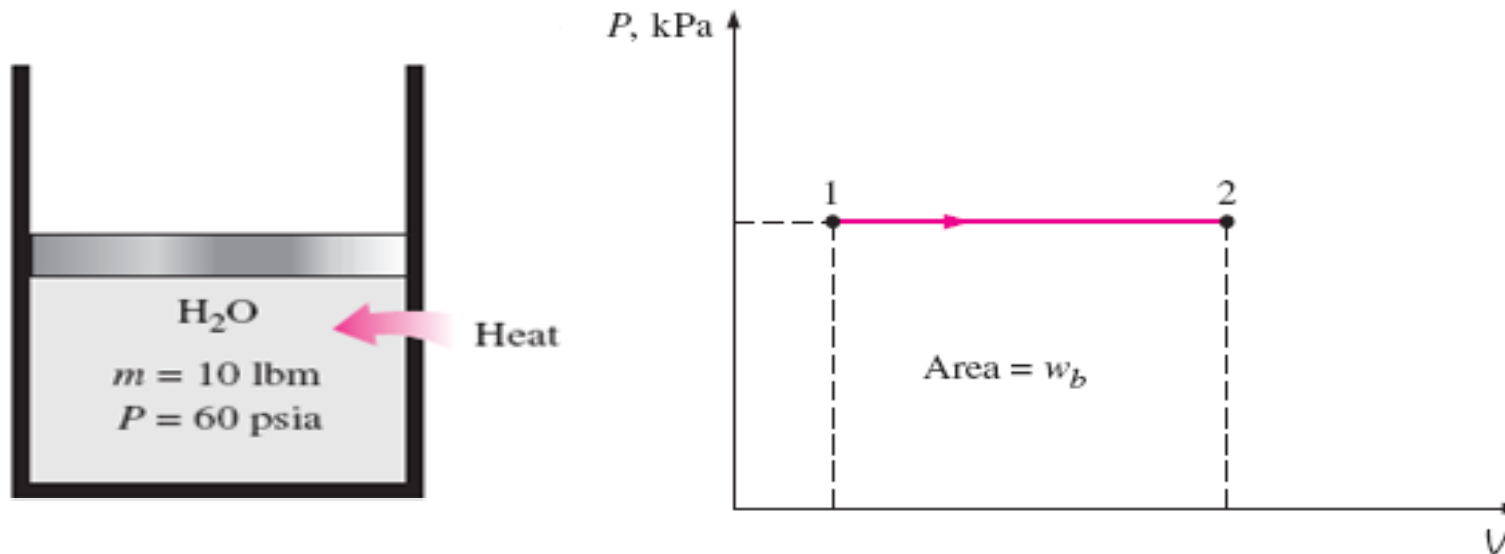
➤ If the volume is held constant, $dv=0$ and the boundary work equation becomes

$$W_b = \int_1^2 P \, dv = 0$$

Mechanical Forms of Work

Some typical process

2. Boundary work at constant pressure



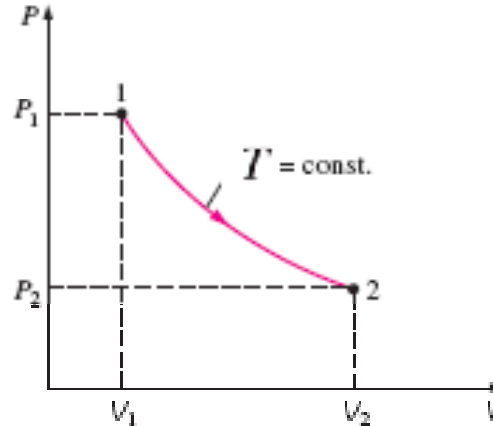
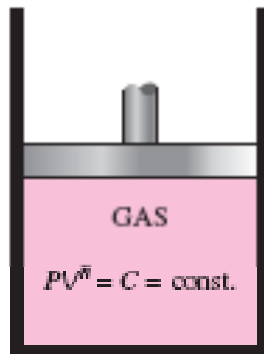
➤ If the pressure is held constant the boundary work equation becomes.

$$W_b = \int_1^2 P dV = P_0 \int_1^2 dV = P_0(V_2 - V_1)$$

Mechanical Forms of Work

Some typical process

3. Boundary work at constant temperature



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

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

$$W_{1 \rightarrow 2} = \int_{V_1}^{V_2} P dV = \int_{V_1}^{V_2} \frac{mRT}{V} dV = mRT \int_{V_1}^{V_2} \frac{dV}{V} = mRT \ln \left(\frac{V_2}{V_1} \right).$$

Mechanical Forms of Work

- **Note:** The above equation is the result of applying the ideal gas assumption for the equation of state.
- For real gases undergoing an isothermal (constant temperature) process, the integral in the boundary work equation would be done **numerically**.

Mechanical Forms of Work

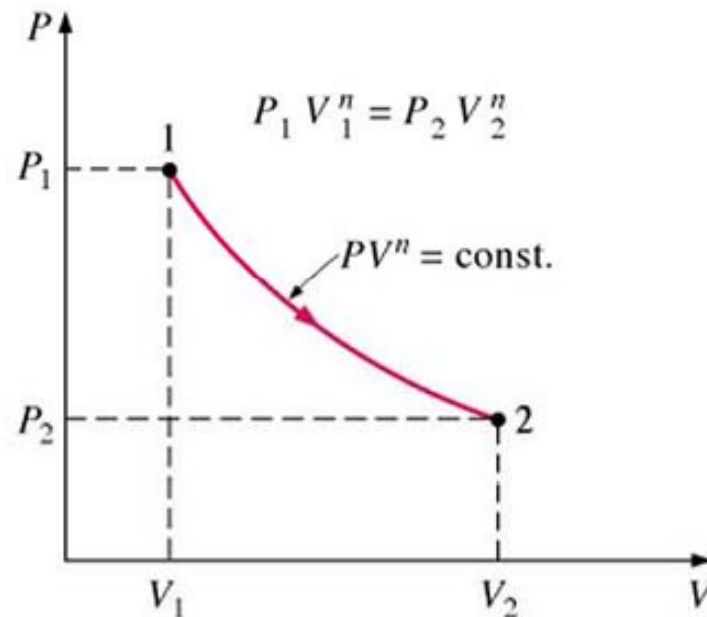
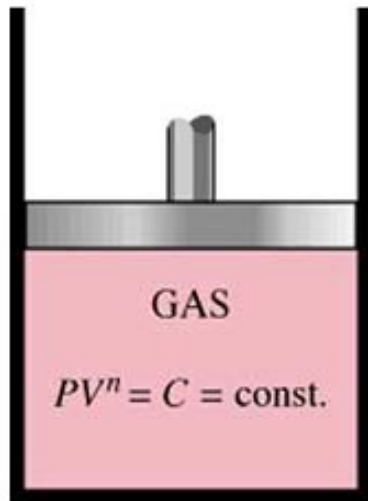
The Polytropic Process

- During actual expansion and compression processes of gases, pressure and volume are sometimes related by:

where n and C are constants $PV^n = C$

- The above equation implies that: $P_1 V_1^n = P_2 V_2^n$

- This kind of process is called a polytropic process



Mechanical Forms of Work

The Polytropic Process

➤ Some of the more common values are given below.

Process	Exponent n
Constant pressure	0
Constant volume	∞
Isothermal & ideal gas	1
Adiabatic & ideal gas	$k = C_P/C_V$

Mechanical Forms of Work

➤ Boundary Work During a Polytropic Process

$$PV^n = C \rightarrow P = CV^{-n}$$

$$W_b = \int_1^2 P dV = \int_1^2 CV^{-n} dV = C \frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{CV_2^{-n}V_2 - CV_1^{-n}V_1}{1-n} = \frac{P_2V_2 - P_1V_1}{1-n}$$

➤ Special Case: Ideal Gas (PV=mRT)

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

➤ Special Case: $n = 1$

$$W_b = \int_1^2 P dV = \int_1^2 CV^{-1} dV = PV \ln\left(\frac{V_2}{V_1}\right)$$

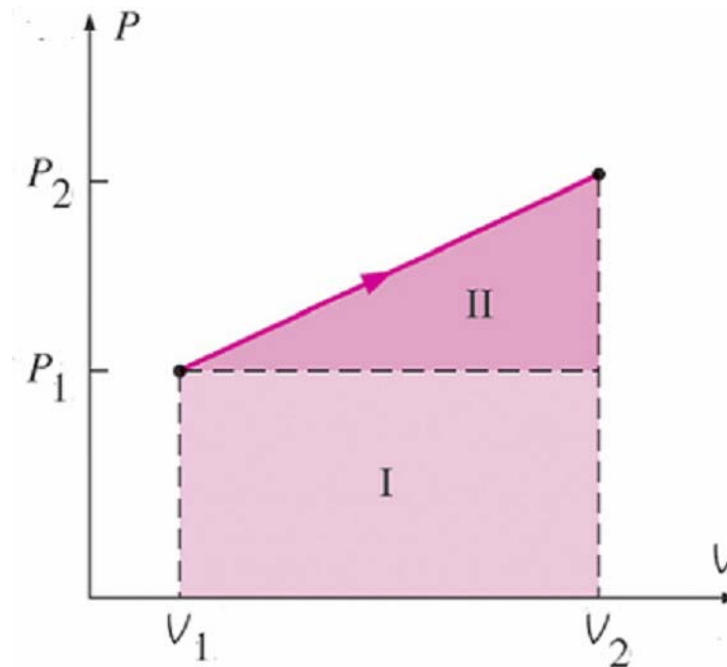
Mechanical Forms of Work

A Linear Process

➤ A Linear Process is of the form:-

$$P = aV + b \quad \text{for constants } a \text{ and } b.$$

➤ The boundary work is:-



$$W_{1 \rightarrow 2} = \frac{1}{2}(P_2 + P_1)(V_2 - V_1)$$

Mechanical Forms of Work

Shaft Work

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

$$T = F \times r \quad \rightarrow \quad F = \frac{T}{r}$$

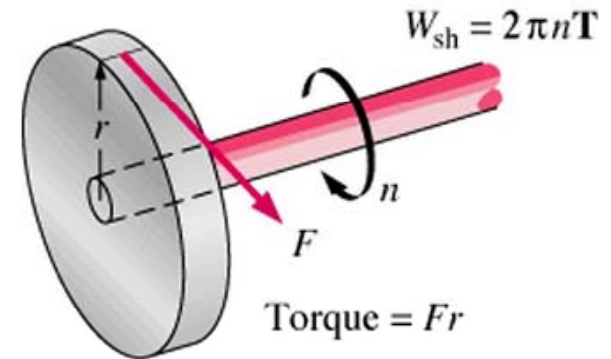
- This force acts through a distance s , which is related to the radius r by:

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

where n is the number of revolutions

- The shaft work will be:

$$W_{\text{sh}} = Fs = \left(\frac{T}{r}\right)(2\pi rn) = 2\pi nT$$



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

$$\dot{W}_{\text{sh}} = 2\pi nT$$

Mechanical Forms of Work

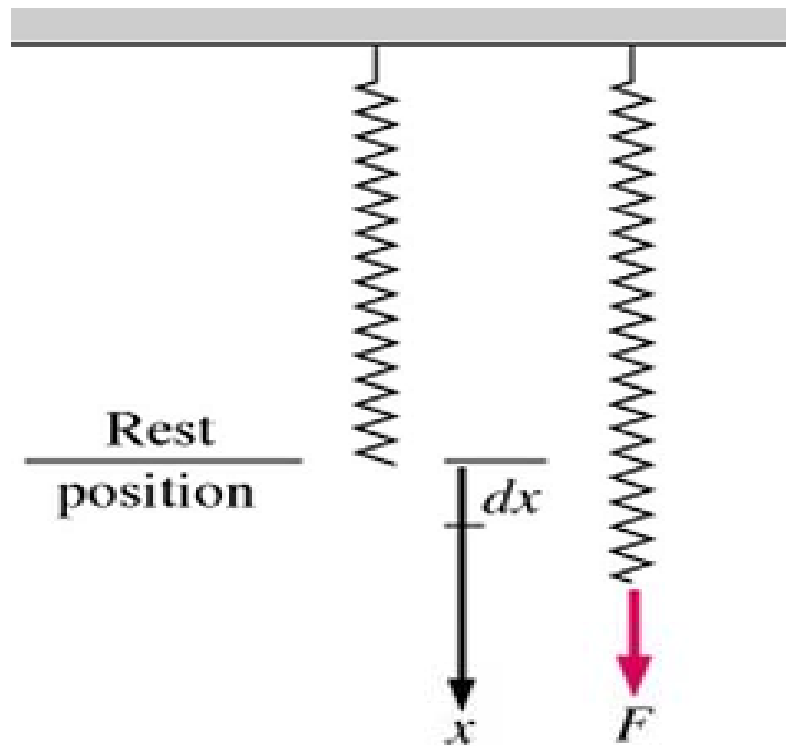
Spring Work

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

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

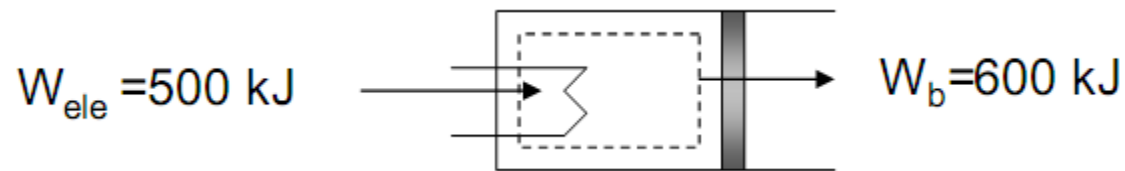
- For linear elastic springs, this force is given as: $F = kx$

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



Example 1

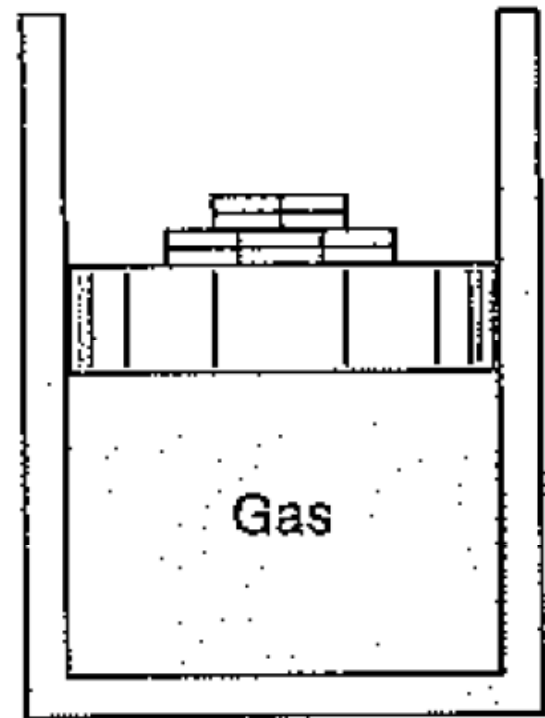
- A fluid contained in a piston-cylinder device receives 500 kJ of electrical work as the gas expands against the piston and does 600 kJ of boundary work on the piston. What is the net work done by the fluid?



Example 2

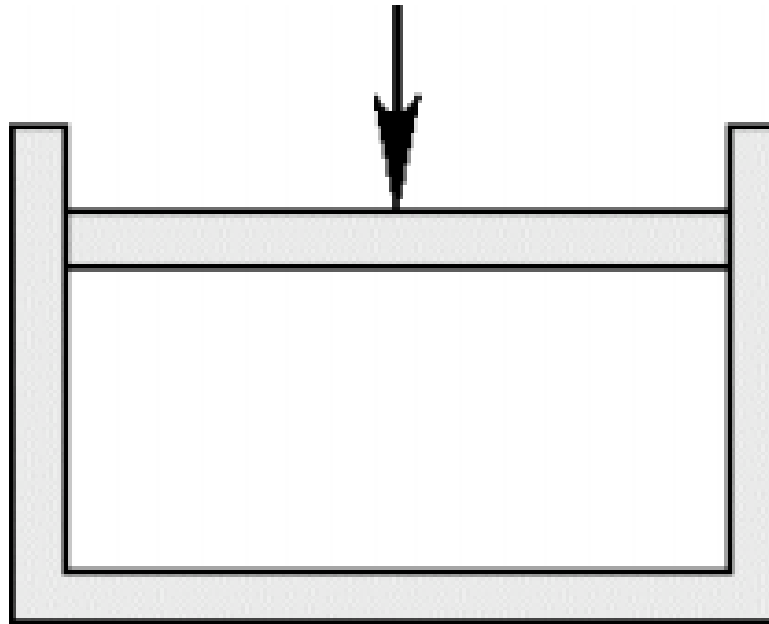
➤ Consider as a system the gas in the cylinder shown; the cylinder is fitted a piston on which a number of small weights are placed. The initial pressure is 200kpa, and the initial volume of the gas is 0.04m^3 . Calculate the work done by the system during this process.

- a) When pressure is constant and volume increase to 0.1m^3 .
- b) When the temperature is constant.
- c) When $PV^{1.3} = \text{constant}$
- d) Volume is constant



Example 3

- An ideal gas is enclosed in a cylinder with a weighted piston as the top boundary. The gas is heated and expands from a volume of 0.04 m^3 to 0.10 m^3 and a constant pressure of 200 kPa . What is the work done by the system?

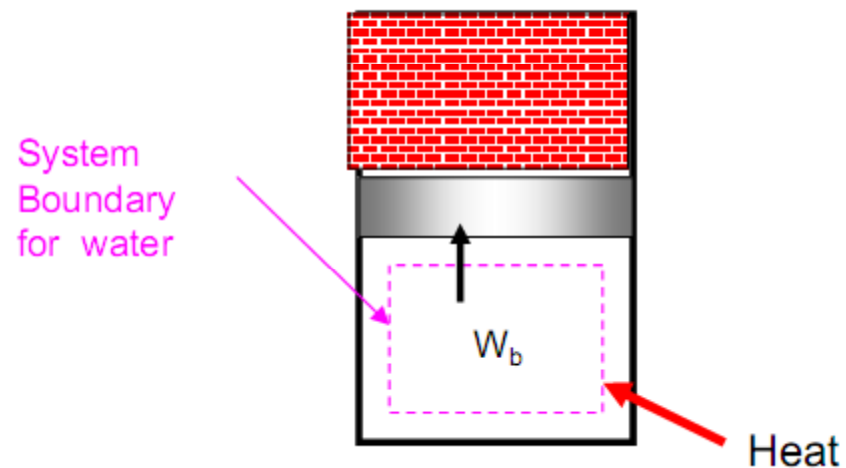


Example 4

- Three kilograms of nitrogen gas at 27°C and 0.15 MPa are compressed isothermally to 0.3 MPa in a piston-cylinder device. Determine the minimum work of compression, in kJ.

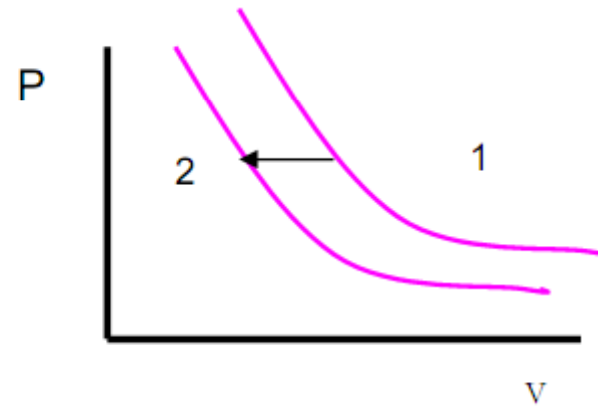
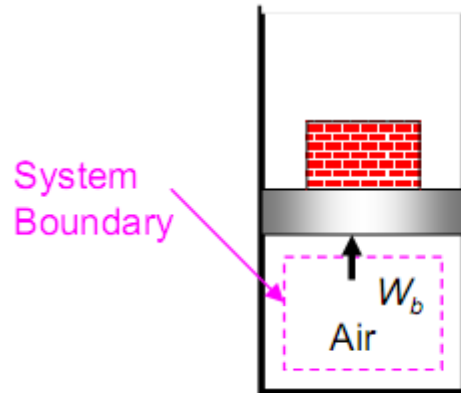
Example 5

- Water is placed in a piston-cylinder device at 20°C , 0.1 MPa . Weights are placed on the piston to maintain a constant force on the water as it is heated to 400°C . How much work does the water do on the piston?



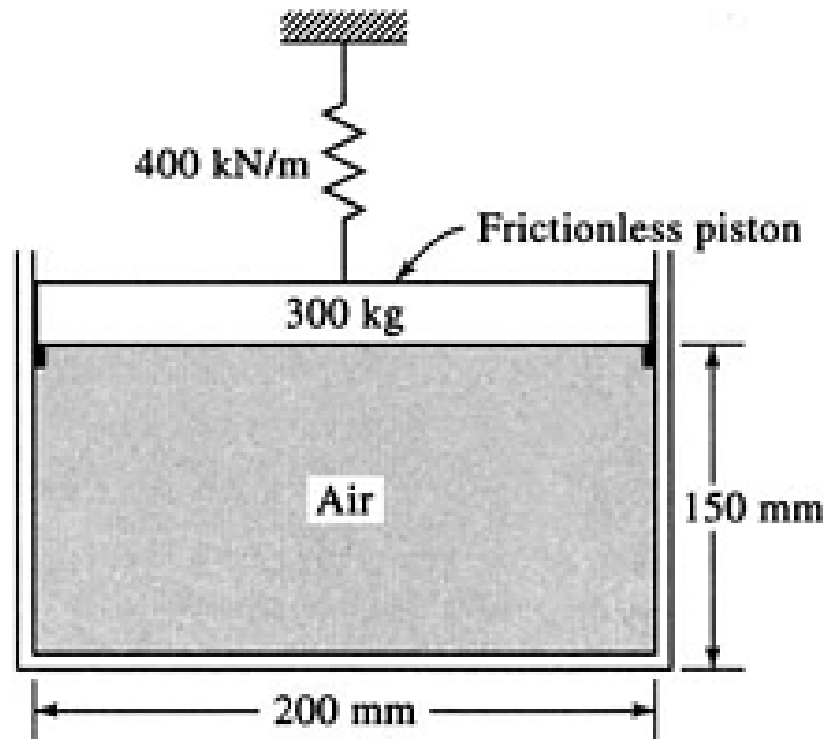
Example 8

- Air undergoes a constant pressure cooling process in which the temperature decreases by 100°C . What is the magnitude and direction of the work for this process?



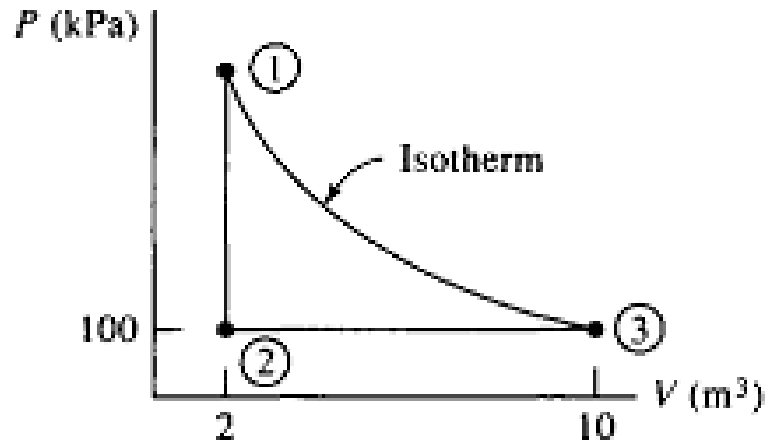
Example 9

- Six g of air is contained in the cylinder shown in Fig. below. The air is heated until the piston raises 50 mm. The spring just touches the piston initially. Calculate (a) the temperature when the piston leaves the stops and (b) the work done by the air on the piston.



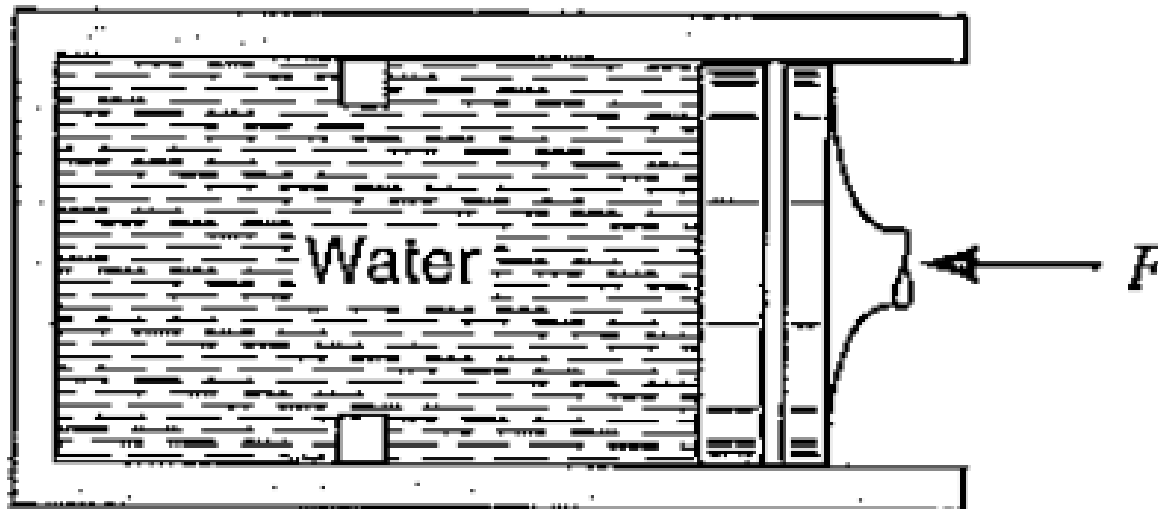
Example 10

- Two kg of air experiences the three-process cycle shown in Fig. below. Calculate the net work.



Example 6

- The piston/cylinder setup shown contains 0.1kg of water at 1000kpa, 500°C. The water is now cooled with a constant force on the piston until it reaches half the initial volume, after this it cools to 25°C while the piston is against the stops. Find the final water pressure and the work in the overall process, and show the process in a p-v diagram.



Example 7

- A cylinder/piston arrangement contains 5kg of water at 100°C with $x=20\%$ and the piston, $m_p = 75\text{kg}$, resting on some stops. The outside pressure is 100kPa , and the cylinder area is $A = 24.5\text{cm}^2$. Heat is now added until the water reaches a saturated vapor state. Find the initial volume, final pressure, work and heat transfer terms and show the p - v diagram.

Example 11

- One kilogram of water is contained in a piston-cylinder device at $100\text{ }^{\circ}\text{C}$. The piston rests on lower stops such that the volume occupied by the water is 0.835 m^3 . The cylinder is fitted with an upper set of stops. When the piston rests against the upper stops, the volume enclosed by the piston-cylinder device is 0.841 m^3 . A pressure of 200 kPa is required to support the piston. Heat is added to the water until the water exists as a saturated vapor. How much work does the water do on the piston?

