Module

1

Thermodynamics

Lecture
3

Basic Concepts of Thermodynamics

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SOME EXCEPTIONAL CASES

Free Expansion with Zero work Transfer

Let us consider a gas in a compartment with an initial pressure P1 and volume V1 that is separated from a vacuum. Let both the compartments be properly insulated so that heat transfer is zero. As the partition is removed, the gas rushes to fill the vacuum. The expansion of gas against a vacuum is known as free expansion.

Let us consider the gas and vacuum together as the system as shown in Fig. 1.18 . We know that work transfer is a boundary phenomena, i.e., work transfer is identified only when work crosses the system boundary. During this free expansion, work done is zero since no work crosses the system boundary.

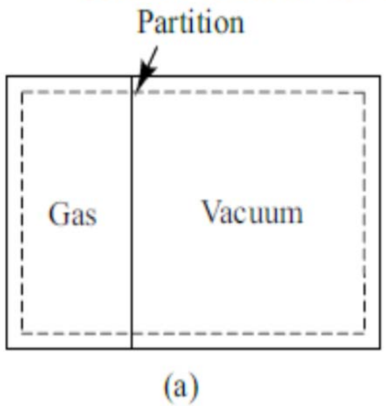

Fig. 1.18: Free Expansion

Summary:

In this module, the basic concepts of thermodynamics are introduced and discussed.

- A system of fixed mass is called a *closed system,* or *control mass,* and a system that involves mass transfer across its boundaries is called an *open system,* or *control volume*.
- The mass-dependent properties of a system are called *extensive properties* and the others *intensive properties*.
- A system is said to be in *thermodynamic equilibrium* if it

maintains thermal, mechanical, phase, and chemical equilibrium.

- Any change from one state to another is called a *process*.

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- A process with identical end states is called a *cycle*.
- During a *quasi-static* or *quasi-equilibrium process*, the system remains practically in equilibrium at all times.
- The state of a simple, compressible system is completely specified by two independent, *intensive properties*.
- *work transfer* is considered as occurring between the system and the surroundings.

MULTIPLE-CHOICE QUESTIONS

1) Work done in an adiabatic process between a given pair of end states depends on

(a) the end states only (b) particular adiabatic process

(c) the value of index n (d) mass of the system

2) Which of the following is true for reversible polytropic process

(a) temperature remains constant (b) entropy remains constant

(c) some heat transfer takes place (d) internal energy remains constant

3) Maximum work done by an expansion of a gas in a closed system is possible when process takes place at constant

(a) pressure (b) temperature

(c) volume (d) entropy

4) A diathermic wall is one in which

(a) prevents thermal interaction (b) permits thermal interaction

(c) encourages thermal interaction (d) discourage thermal interaction

5) An adiabatic wall is one in which

(a) prevents thermal interaction (b) permits thermal interaction

(c) encourages thermal interaction (d) discourages thermal interaction

6) Which of the following have the same unit?

(a) work and power (b) work and energy

(c) power and energy ((d) all of these

7) In a closed system, a gas undergoes a reversible process as per the law P = (–4V + 10) N/m2 and the volume of the gas, V changes from 1 m3 to 2 m3. The work done will be

(a) 10 J output (b) 4 J output

(c) 6 J input (d) 4 J input

8) Work done in a free expansion process is

(a) positive (b) negative

(c) zero (d) maximum

9) Isochoric process is one in which

(a) free expansion takes place

(b) no mechanical work is done by the system

(c) very little mechanical work is done by the system

(d) all parameters remain constant

10) In free expansion process

$a)\ \int \partial W \neq 0, \int PdV = 0$ b) $\int \partial W = 0, \int PdV = 0$

c) $\int \partial W = 0, \int PdV \neq 0$ d) $\int \partial W \neq 0, \int PdV \neq 0$

Solved Problems:

1 kg of fluid initially at 500 kPa with 0.01 m^3 volume undergoes a reversible expansion to volume 0.05 m^3 and pressure 100 kPa according to a linear law. Calculate the work done.

The expansion takes place according to a linear law. Let the pressure and volume relationship is $P = aV + b$

where a and b are constants and can be evaluated from the initial and final conditions.

$$500 = 0.01a + b$$

$$100 = 0.05a + b$$

After solving the above two equations, we get

$$a = -10000, \; b = 600$$

The pressure and volume relationship can be written as

$$P = -10000V + 600$$

Work done is found to be

$$W_{1-2} = \int_{V_1}^{V_2} PdV$$

$$= \int_{0.01}^{0.05} (-10000V + 600)\,dV$$

$$= \left| -10000\frac{V^2}{2} + 600V \right|_{0.01}^{0.05}$$

$$= -5000\left(0.05^2 - 0.01^2\right) + 600(0.05 - 0.01)$$

$$= 12 \text{ kJ}$$

Consider a gas contained in a piston–cylinder assembly as the system. The gas is initially at a pressure of 1000 kPa and occupies a volume of 0.1 m^3. The gas is taken to the final state where pressure is equal to 200 kPa, by the following two different processes.

(i) The volume of the gas inversely proportional to the pressure.

(ii) The process follows the path =constant, where n =1.4.

Calculate the work done by the gas in each case.

Solution

Initial pressure $P_1 = 1000$ kPa

Initial volume $V_1 = 0.1$ m^3

Final pressure $P_2 = 200$ kPa

(i) From the given condition, we get

$$\frac{V_2}{V_1} = \frac{P_1}{P_2}$$

or $$V_2 = \frac{P_1}{P_2} V_1 = \frac{1000}{200} \times 0.1 = 0.5 \text{ m}^3$$

The work done is computed from equation (2.4) to be

$$W_{1-2} = P_1 V_1 \ln \frac{V_2}{V_1}$$

$$= 1000 \times 0.1 \times \ln \frac{0.5}{0.1} = 160.94 \text{ kJ}$$

(ii) From the given condition, we have

$$P_1 V_1^n = P_2 V_2^n$$

or $$1000 \times 0.1^{1.4} = 200 \times V_2^{1.4}$$

or $$V_2 = 0.3157 \text{ m}^3$$

The work done is found from equation (2.7) to be

$$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n-1}$$

$$= \frac{1000 \times 0.1 - 200 \times 0.3157}{1.4 - 1} = 92.15 \text{ kJ}$$

A piston–cylinder device contains 1 kg of fluid at 20 atmospheric pressure. The initial volume is 0.04 m^3. The fluid is allowed to expand reversibly following a process $PV^{1.45} = C$ so that the volume becomes double. The fluid is then cooled reversibly at constant pressure until the piston comes back to the original position. Keeping the position of the piston unaltered, heat is added reversibly to restore the initial pressure. Calculate the cyclic work done. Plot the process in P–V coordinates, given that 1 atmospheric pressure = 101.325 kN/m^2.

The processes are shown in Fig. 2.6.

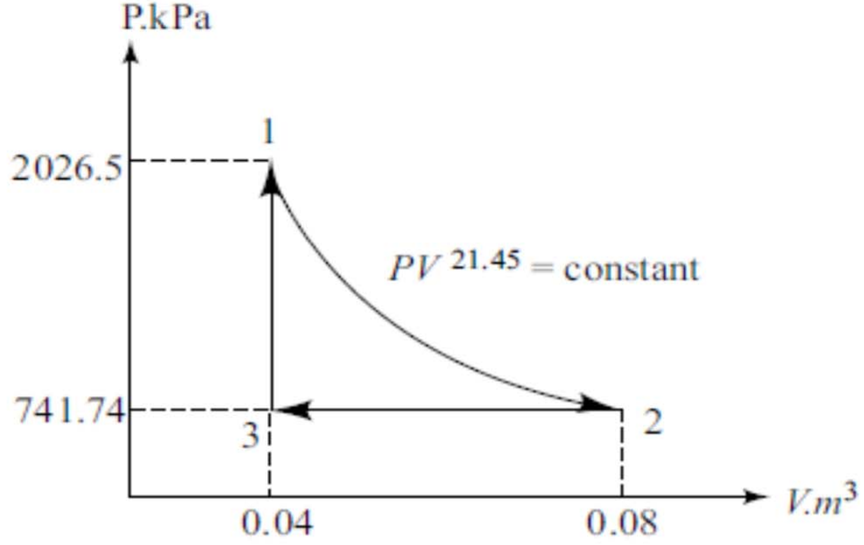

Figure 2.6

From the given data, $P_1 = 20$ atm $= 20 \times 101.325 = 2026.5$ kN/m^2

$$V_1 = 0.04 \text{ m}^3;\ V_2 = 2\ V_1 = 0.08 \text{ m}^3,$$

$$P_1 V_1^n = P_2 V_2^n$$

$$\therefore \quad P_2 = \left(\frac{V_1}{V_2}\right)^n \times P_1 = \left(\frac{1}{2}\right)^{1.45} \times 2026.5 \text{ kPa} = 741.74 \text{ kPa}.$$

The work done during the polytropic expansion 1-2 is

$$\therefore \quad W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n-1} = \frac{2026.5 \times 0.04 - 741.74 \times 0.08}{1.45 - 1} \text{ kJ}$$

$$= 48.27 \text{ kJ}$$

The work done during the constant pressure process 2-3 is

$$W_{2-3} = P_2(V_3 - V_2) = P_2(V_1 - V_2) = 741.74\ (0.04 - 0.08) \text{ kJ}$$

$$= -\ 29.67 \text{ kJ}$$

Since the volume does not change during the process 3-1, the work done $W_{3\text{-}1}$ is zero.

The cyclic work done is $\sum W = W_{1-2} + \mathrm{W}_{2-3} + W_{3-1} = 48.27 - 29.67 + 0 = 18.6$ kJ

EXAMPLE 4–9 Expansion of a Gas against a Spring

A piston-cylinder device contains 0.05 m^3 of a gas initially at 200 kPa. At this state, a linear spring that has a spring constant of 150 kN/m is touching the piston but exerting no force on it. Now heat is transferred to the gas, causing the piston to rise and to compress the spring until the volume inside the cylinder doubles. If the cross-sectional area of the piston is 0.25 m^2, determine (*a*) the final pressure inside the cylinder, (*b*) the total work done by the gas, and (*c*) the fraction of this work done against the spring to compress it.

SOLUTION A sketch of the system and the *P-V* diagram of the process are shown in Fig. 4–32.

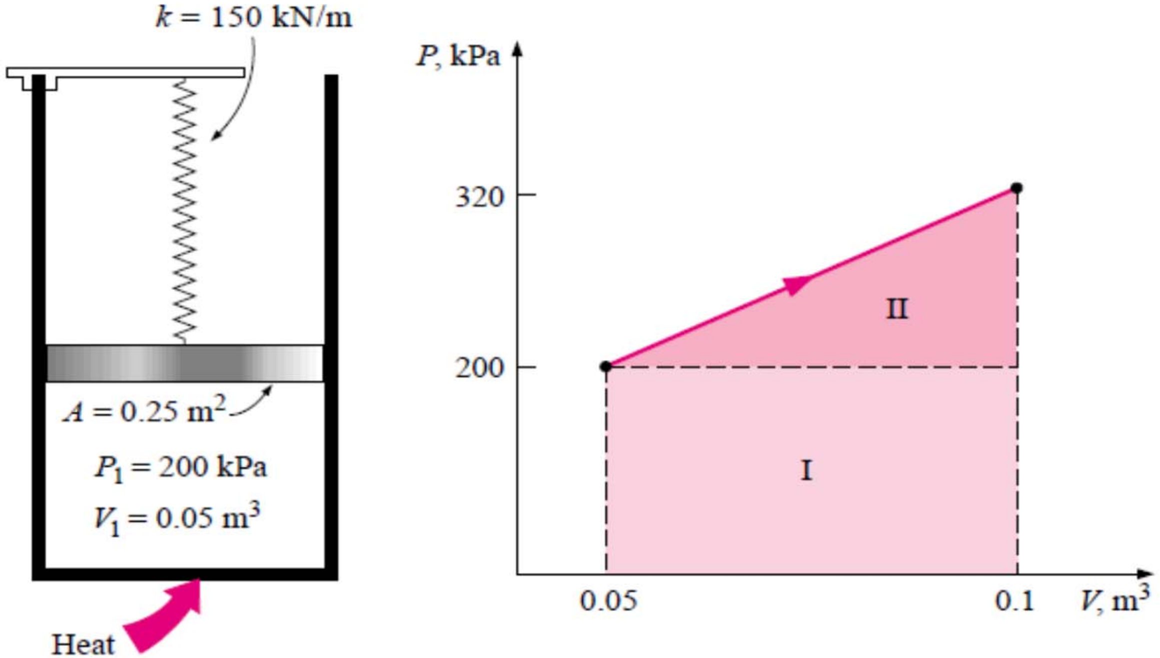

FIGURE 4–32
Schematic and *P-V* diagram for Example 4–9.

Assumptions **1** The expansion process is quasi-equilibrium. **2** The spring is linear in the range of interest.

Analysis (*a*) The enclosed volume at the final state is

$$V_2 = 2V_1 = (2)(0.05 \text{ m}^3) = 0.1 \text{ m}^3$$

Then the displacement of the piston (and of the spring) becomes

$$x = \frac{\Delta V}{A} = \frac{(0.1 - 0.05) \text{ m}^3}{0.25 \text{ m}^2} = 0.2 \text{ m}$$

The force applied by the linear spring at the final state is

$$F = kx = (150 \text{ kN/m})(0.2 \text{ m}) = 30 \text{ kN}$$

The additional pressure applied by the spring on the gas at this state is

$$P = \frac{F}{A} = \frac{30 \text{ kN}}{0.25 \text{ m}^2} = 120 \text{ kPa}$$

Without the spring, the pressure of the gas would remain constant at 200 kPa while the piston is rising. But under the effect of the spring, the pressure rises linearly from 200 kPa to

$$200 + 120 = \mathbf{320\ kPa}$$

at the final state.

(*b*) An easy way of finding the work done is to plot the process on a *P-V* diagram and find the area under the process curve. From Fig. 4–32 the area under the process curve (a trapezoid) is determined to be

$$W = \text{area} = \frac{(200 + 320)\ \text{kPa}}{2}[(0.1 - 0.05)\ \text{m}^3]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = \mathbf{13\ kJ}$$

Note that the work is done by the system.

(*c*) The work represented by the rectangular area (region I) is done against the piston and the atmosphere, and the work represented by the triangular area (region II) is done against the spring. Thus,

$$W_{\text{spring}} = \tfrac{1}{2}[(320 - 200)\ \text{kPa}](0.05\ \text{m}^3)\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = \mathbf{3\ kJ}$$

This result could also be obtained from Eq. 4–26:

$$W_{\text{spring}} = \tfrac{1}{2}k(x_2^2 - x_1^2) = \tfrac{1}{2}(150\ \text{kN/m})[(0.2\ \text{m})^2 - 0^2]\left(\frac{1\ \text{kJ}}{1\ \text{kN}\cdot\text{m}}\right) = 3\ \text{kJ}$$

Assignments:

1) Air of 0.02 m3 at 200 kPa and 30 C is compressed to a volume of 0.002 m3 according to the law PV $PV^{1/3}$ = constant. What is the final temperature and work done during compression?

2) 1 kg of fluid initially at 6 bar with 0.01 m3 volume undergoes the following operations.

(i) reversible expansion to volume 0.05 m3 and pressure 2 bar according to a linear law

(ii) reversible cooling at constant pressure

(iii) reversible compression according to law PV = constant.

This brings the fluid back to initial conditions of 6 bar and 0.01 m3.

Calculate (a) work done in each process. State whether the work is done on or by the fluid, and (b) network of the cycle.

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3) Helium contained in a cylinder fitted with a piston expands reversibly according to the law PV = constant. The initial pressure, temperature and volume are 5 bar, 222 K and 0.055 m3. After expansion, the pressure is 2 bar, calculate the work done during the process.

4) A gas is contained in a cylinder fitted with a piston loaded with a small number of weights. The initial pressure of the gas is 1.3 bar, and the initial volume is 0.03 m3. The gas is now heated until the volume of the gas increases to 0.1 m3. Calculate the work done by the gas in the following processes

(a) pressure remains constant

(b) temperature remains constant

(c) pv = constant during the process.

Show the processes on P-V diagram.

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5) A system contains 0.15 m3 of air at 3.8 bar and 150°C. A reversible adiabatic expansion takes places till the pressure falls to 1.03 bar. Determine the total work done.

6) Air at 300°C and 10 bar expands to 3 bar reversibly following the law $PV^{1.35}$ = constant. Determine the work done per kg of air if Cp = 1kJ/kg-K and C v = 0.714 kJ/kg-K.

Thank You