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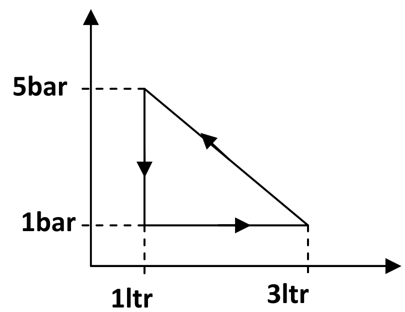
# ENGINEERING THERMODYNAMICS - 1

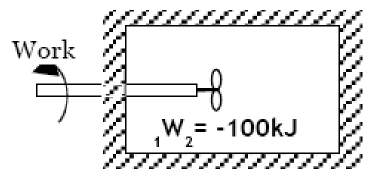
## ASSIGNMENT – 7

## First Law Analysis

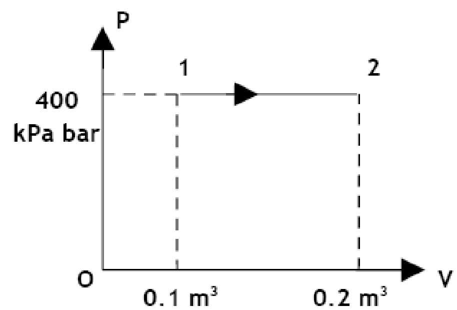
1. Calculate the heat transferred during the cycle as shown in the diagram.




2. Show that the stored energy of an isolated system remains constant.
3. Prove that for a reversible adiabatic process, dh = vdp.
4. An insulated rigid container has 5 kg of air at $30^0$C. A paddle wheel fitted in the container agitates the air and transfers 100kJ of work to this air (Figure). What is the change in the internal energy of the air?




5. Show that the heat added to a closed system in reversible constant pressure process equals the change in enthalpy.
6. A closed system undergoes a reversible constant pressure process as shown in the Figure. If the change in the internal energy during the process is 100kJ, what is the heat transferred during the process.

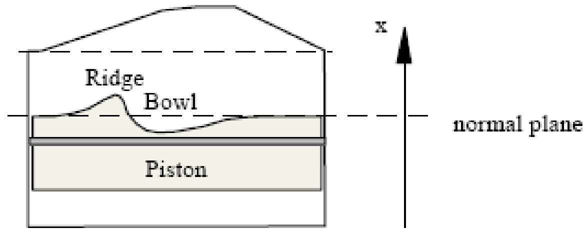



7. During which process executed by a closed system work done is same as heat supplied?
8. Two kg of air is contained in a rigid insulated vessel at 1 bar, $20^0$C. The air is agitated by a fan driven by an electric motor. After some time it is noticed that the air temperature is increased to $30^o$C. What is the work done by the fan on the air inside the vessel?
9. A tank containing nitrogen is heated and stirred by a paddle wheel. The work input to the paddle is 6000 kJ. Heat coming out from the tank is 4000kJ. Determine the change in the internal energy of nitrogen in the tank.
10. State the major assumptions/ restrictions under which following equations are valid (symbols having usual notation)
    (i). $\delta W = P\,dv$
    (ii). $\delta Q - dU = \delta W$

11. During an adiabatic process, a system does 50 kJ of work. What is the change in internal energy of the system?
12. Define enthalpy and show that for a constant pressure process change in enthalpy is equal to net heat transfer.
13. During an adiabatic process, an ideal gas receives 100 kJ of work. The initial internal energy of the gas is 320 kJ. What is the final internal energy?
14. Determine the work done during an adiabatic process if the change in internal energy is -150 kJ.
15. Calculate the work done, the change in internal energy and the heat transferred when 4.5 kg of air is compressed from 1.01 bar, 25$^o$C to 0.54 MPa. The compression occurs according to the process $PV^{1.27}$ = constant.
16. A mass of 8 kg expands within a flexible container so that the P-V relationship is of the form $PV^{1.2}$ = constant. The initial pressure is 1000 kPa and initial volume is 1 $m^3$. The final pressure is 5 k Pa. If the specific internal energy of the gas decreased by 40 kJ/kg, find the heat transfer and its direction.
17. 10 kg of steam at 5 bar, x = 0.85 undergoes a constant pressure process until the temperature becomes 200$^o$C. Determine,
    (a). The work done
    (b). Change in internal energy
    (c). The heat transferred.
18. Steam at 0.51 MPa and 200$^o$C is cooled at constant volume until it becomes dry and saturated. Determine the final pressure, temperature and the heat transferred for 10 kg of steam.
19. 5 kg of saturated liquid water at 6 bar is heated at constant pressure until becomes dry and saturated steam. Determine the work done, the change in internal energy and the heat transferred.
20. A cylinder fitted with a piston has a volume of 0.1 m3 and contains 0.5 kg of steam at 0.4 MPa . Heat is transferred to the steam until the temperature is 300$^o$C, while the pressure remains constant. Determine the heat and work transfer for this process.
21. A rigid tank contains a hot fluid and is cooled while being stirred by a paddle wheel. Initially internal energy of the fluid is 900kJ. During the cooling process the fluid looses 500kJ of energy in the form of heat and the paddle wheel does 100kJ of work on the fluid. Calculate the final internal energy of the fluid.
22. The temperature of 3.5 kg of gas in a rigid container is increased from 25$^o$C to 45$^o$C by heating it. The heat transferred during the process is 38 kJ. The specific heat ratio and molar mass of the gas is 1.42 and 28kg/kmol. Calculate the change in internal energy and work done for the gas treating the gas to be a perfect gas.
23. Starting with the statement of first law for a cyclic process, show that the internal energy is a property of a system.
24. The properties of a certain fluid are related as follows u = 196 + 0.718 T, $P_v$ = 0.287(T+ 273) where u is the specific internal energy (kJ/kg), T is in $^o$C, P is pressure (kN/$m^2$), and v is specific volume ($m^3$/kg). For this fluid, find $C_v$ and $C_p$.
25. A gas of mass 1.5 kg undergoes a quasistatic expansion which follows a relationship P = a + bV, where a and b are constants. The initial and final pressures are 1000 kPa and 200 kPa respectively and the corresponding volumes are 0.20 $m^3$ and 1.20 $m^3$. The specific internal energy of the gas is given by the relation, u = (1.5 Pv –85) kJ/kg, where P is in kPa and v is in $m^3$/kg. Calculate the net heat transfer and the maximum internal energy of the gas attained during expansion.
26. The heat capacity at constant pressure of a certain system is a function of temperature only and may be expressed as $C_p$ = 41.87T+100 J/$^o$C where T is the temperature of the system in $^o$C. The system is heated while it is maintained at a pressure of 1 atmosphere until its volume increases from 2000 $cm^3$ to 2400 $cm^3$

and its temperature increases from 20°C to 100°C. (a) Find the magnitude of heat interaction (b) How much does the internal energy of the system increase?

27. Normally pistons have a flat head, but in diesel engines pistons can have bowls in them and protruding ridges (Figure). Does this geometry influence the work term?




# FIRST LAW ANALYSIS OF AN OPEN SYSTEM

**Introductory Notes**

**Symbols used**:

$\forall$ ⇒*Volume*

*V* ⇒*Velocity*

v ⇒*Specific Volume*

*e* ⇒*total energy per unit mass E/m*

**Conservation of mass principle:** (c.v. : control volume)

(Total mass entering the c.v. during Δt) - (Total mass leaving the c.v. during Δt)
= (Net change in mass within the c.v. during Δt)

OR, $m_{in} - m_{out} = \Delta m_{cv} = m_{final} - m_{initial} (kg)$

In rate form : $\dot{m}_{in} - \dot{m}_{out} = \frac{dm_{cv}}{dt} (kg/s)$

**Note** that while mass is a property of the system, mass flow rate is not a property.

For a system with multiple inlets and outlets : $\Sigma\dot{m}_{in} - \Sigma\dot{m}_{out} = \frac{dm_{cv}}{dt} = \frac{d}{dt}\int_{cv} \rho d\forall$

**Mass balance for a steady flow process:**

$$\frac{dm_{cv}}{dt} = 0$$

$$\Sigma\dot{m}_{in} = \Sigma\dot{m}_{out}$$

For a single inlet and exit: $\dot{m}_{in} = \dot{m}_{out} \Rightarrow \rho_1 V_1 A_1 = \rho_2 V_2 A_2 (kg/s)$

For steady, incompressible flow: $V_1 A_1 = V_2 A_2 (m^3/s)$

**Flow Energy:**

Control volumes involve mass flow across their boundaries and some work is required to push the mass into or out of the control volume. This work is known as the flow work or flow energy.

$W_{flow} = P\forall$

So, the total energy per unit mass of a flowing fluid is :

$e = u + Pv + \frac{V^2}{2} + gz (kJ/kg)$ *,where V=velocity*

$$= h + \frac{V^2}{2} + gz (kJ/kg)$$ *( taking h=u+pv)*

**Energy Analysis for a Control Volume**

$$\dot{E}_i - \dot{E}_e = \frac{dE_{cv}}{dt}$$

$$\Rightarrow \dot{Q}_i + \Sigma \dot{m}_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) = \dot{W}_e + \Sigma \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right) + \frac{dE_{cv}}{dt}$$

At steady state: $\frac{dE_{cv}}{dt} = 0$ So, $\dot{E}_{in} = \dot{E}_{out}$

**Steady Flow Energy Equation (SFEE):**

For a control volume at steady state, the energy balance equation (First law) reduces to

$$\dot{Q} + \Sigma \dot{m}_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) = \dot{W} + \Sigma \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right)$$

where, subscript 'i' implies inlet and 'e' implies exit.

This is called the steady flow energy equation. For a control volume with single inlet and exit, the SFEE is: $\dot{Q} + \dot{m} \left( h_i + \frac{V_i^2}{2} + gz_i \right) = \dot{W} + \dot{m} \left( h_e + \frac{V_e^2}{2} + gz_e \right)$

For Closed system, $\dot{m}_i = \dot{m}_e = 0$

So, the energy equation is $\dot{Q}_i = \dot{W}_e + \frac{dE_{cm}}{dt}$

$$\dot{Q}_i dt = \dot{W}_e dt + dE_{cm}$$

$$\delta q = \delta w + dE_{cm}$$

Integrating over a finite time interval to change the state from 1 to 2

$$\int_1^2 \delta q = \int_1^2 \delta w + \int_1^2 dE_{cm}$$

$$Q_{1\to2} = W_{1\to2} + (E_2 - E_1)$$

Where E = $U + \frac{1}{2} mV^2 + mgz$

And dE = dU, neglecting the changes in kinetic energy and potential energy of the system.

So, $Q_{1\to2} = W_{1\to2} + (U_2 - U_1)$

**Throttling:**

Throttling is a process where there is a significant pressure drop in a flowing fluid when it passes through a flow restricting device such as adjustable valves, capillary tubes, porous plugs. For small throttling devices the process is of a very short duration and as such may be taken as adiabatic.

There are no boundary movements and change in potential and kinetic energies is negligible. So, from the SFEE, we obtain $h_1 \approx h_2 (kJ/kg)$. Thus, throttling is an isenthalpic process. For ideal gases, since h = CpT, so

$T_1 = T_2$ across a throttling process. But for pure substances, taking $h = u + P\,v$ , the sum of internal energy and flow energy remains constant. So $T_1 \neq T_2$

# Assignment Problems

1. Steam with negligible velocity enters a nozzle and flows frictionlessly through it. If the drop in specific enthalpy of the steam is 300 kJ/kg, find out the velocity with which it exits the nozzle. (***774.6 m/s***)
2. Air at 5 bar and 190$^o$C enters a nozzle and leaves from it at 1 bar. The flow through the nozzle is isentropic. Neglecting the inlet velocity and the change in potential energy, find the velocity of air at the exit. (***585 m/s***)
3. In an aircraft engine, compressed air at 3 bar and 450 K enters a combustion chamber in which heat is added at constant pressure to the air. Air is heated thus to 1250 K. Thereafter, it expands through a turbine and comes out of it at 1000 K. Find :
   (a) heat addition in the combustion chamber
   (b) specific work done in the turbine. (***804 kJ/kg, 251.25 kJ/kg***)
4. Air enters a frictionless, adiabatic nozzle with a velocity of 30 m/s and at 5 bar, 18$^o$C. It leaves the nozzle at a pressure of 1 bar. Determine the velocity of air at the nozzle exit. (***465.3m/s***)
5. Air enters a compressor at a rate of 0.72 kg/s and at 1 bar, 290 K. The inlet velocity is 6 m/s. Air leaves from the compressor at 7 bar, 450 K and with a velocity of 2 m/s. Heat transfer from the compressor to its surroundings occur at a rate of 3 kW. Calculate the power input to the compressor. (**118.76 kW**)
6. A gas turbine receives air at 5 bar, 210$^o$C and negligible velocity. Air leaves from the turbine at 1.04 bar and a velocity of 80 m/s. Assume that there is no heat transfer through the turbine wall, the process is frictionless and that change in potential energy is negligible. For these assumptions calculate the power developed by the turbine for a mass flow rate of 5 kg/s. (***861.36 kW***)
7. Steam enters a turbine at 20 bar, 300$^o$C and leaves at 0.1 bar, dryness fraction of 0.9. If the flow is adiabatic and the mass flow rate is 7 kg/s, determine the power developed by the turbine. (***4747.4kW***)
8. Air at a pressure of 1 bar and 25$^o$C enters an insulated diffuser with a velocity of 1000 km/hour. The air velocity is reduced to zero at the diffuser outlet. Considering air as an ideal gas with Cp = 1 kJ/kg $^o$C, determine the temperature of air at the diffuser outlet. (***63.6oC***)
9. Air at 100 kPa and 400 K enters a compressor at the rate of 0.03 kg/s steadily and a heat loss of 15 kJ/kg from the air occurs during the process. Neglecting changes in kinetic and potential energies, calculate the necessary power input to the compressor. Exit temperature from the compressor is 800 K and Cp of air = 1.005 kJ/kg K. (***12.51 kW***)
10. A turbine has 0.5 kg/s of steam entering at 1000 kPa, 250$^o$C and leaving at 250 kPa with quality of 90%. The power output of the shaft is measured at 55 kW. Find the rate of heat transfer to the surrounding, neglecting changes in potential and kinetic energies. (***166.94kW***)
11. An air compressor takes in air at 1 atm , 20$^o$C and discharges into a line having an inside diameter of 1 cm. The average air velocity in the line at a point close to the discharge is 7 m/s and the discharge pressure is 3.5 atm. Assuming that the compression occurs quasistatically, adiabatically and the inlet air velocity is negligible, calculate the work input to the compressor. (***205.56 W***)
12. Steam enters a turbine operating at steady state with a mass flow rate of 4600 kg/hr. The turbine develops a power of 1000 kW. The steam enters at 60 bar, 400$^o$C and leaves at 0.1 bar, 90% quality. Neglecting changes in kinetic and potential energies for the steam, calculate the heat transferred from the turbine to it's surroundings. (***62.92 kW***)

13. Air at 105 m/s, density of 1.25 kg/$m^3$ enters a gas turbine through an inlet area of 0.05 $m^2$. The air stream exits from the turbine at 135 m/s and 0.67 kg/$m^3$. During the flow process, the air loses 27 kJ/kg of heat and it's specific enthalpy comes down by 145 kJ/kg. Determine:
• the mass flow rate of the air through the turbine.
• turbine exit area.
• the power developed by the turbine. (***6.56 kg/s, 0.073 m2, 750.75 kW***)

14. A water heater operating at steady state has two inlets and one exit. At the first inlet, water vapor enters at $P_1$ = 7 bar, $T_1$ = 200°C with mass flow rate of 40 kg/s. At the second inlet, liquid water at $P_2$ = 7 bar, $T_2$ = 40°C enters through an area of 25 $cm^2$. At the exit, saturated liquid at 7 bar comes out with a volumetric flow rate of 0.06 $m^3$/s. Determine the mass flow rates at the second inlet and the exit in kg/s and the velocity at the second inlet in m/s. (***14.15 kg/s, 54.15 kg/s, 5.7 m/s***)

15. A throttling calorimeter is used to measure the quality of wet steam at 20 bar. The steam is throttled through a throttle valve and the pressure an temperature in the calorimeter are recorded to be 1 bar and 130°C. Calculate the quality of the initial steam at 20 bar. (***0.967***)

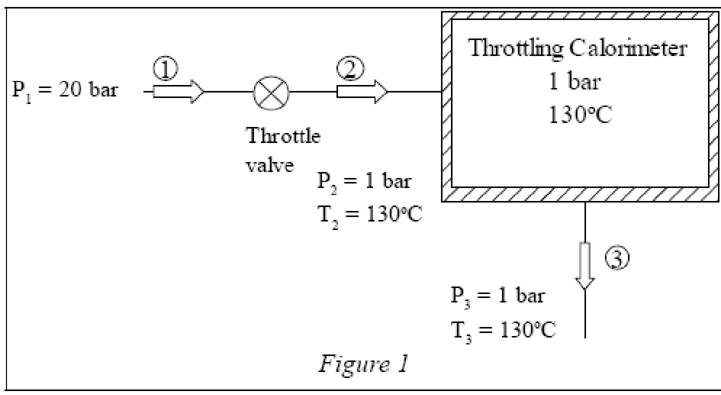


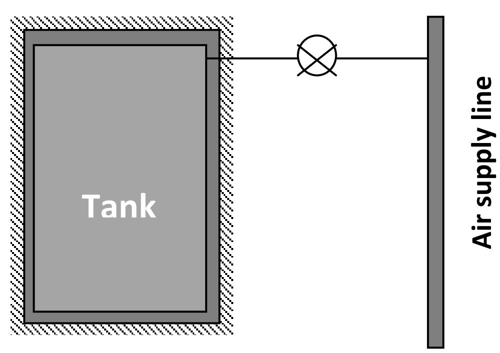
*Figure 1*

16. A de-super heater is an equipment where superheated steam is converted to saturated steam by cooling it with a spray of water. In a certain de-super heater, steam enters at 1.5 bar, 125°C and leaves as saturated steam at 1.5 bar. The water sprayed enters at 30°C. Mass flow rate of superheated steam is 5000 kg/hour. Assuming the de-super heater is insulated and the changes in kinetic and potential energies are negligible, calculate the mass flow rates of the sprayed water and the saturated steam.
(***54.72 kg/hour, 5054.72 kg/hour***)

17. A compressor delivers an air flow rate of 2.33 $m^3$/s at 0.276 MPa, 43°C which is heated at this pressure to 430°C and finally expanded in a turbine which delivers a power output of 1860 kW. During the expansion, there is a heat transfer of 0.09 MJ/s to the surroundings. Calculate the turbine exhaust temperature if changes in kinetic and potential energies are negligible. (***156.33°C***)

18. An evacuated 150-L tank is connected to a line flowing air at room temperature, 25°C, and 8MPa pressure. The valve is opened, allowing air to flow into the tank until the pressure inside is 6 MPa. At this point the valve s closed. This filling process occurs rapidly and is essentially adiabatic. The tank is then placed in storage where it eventually returns to room temperature. What is the final pressure?

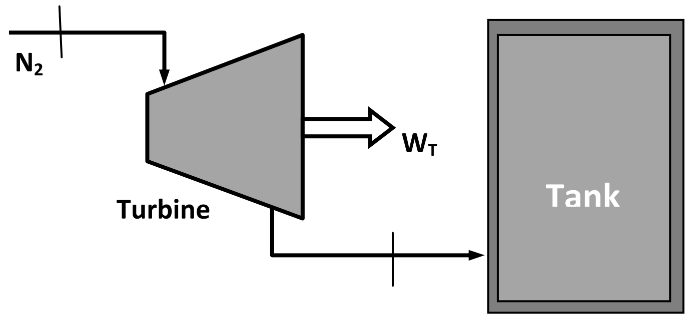
19. A 25-L tank, shown in fig. that is initially evacuated is connected by a valve to an air supply line flowing air at 20°C and 800 kPa. The valve is opened, and air flows into the tank until the pressure reaches 600 kPa. Determine the final temperature and mass inside the tank, assuming the process is adiabatic. Develop an expression for the relation between the

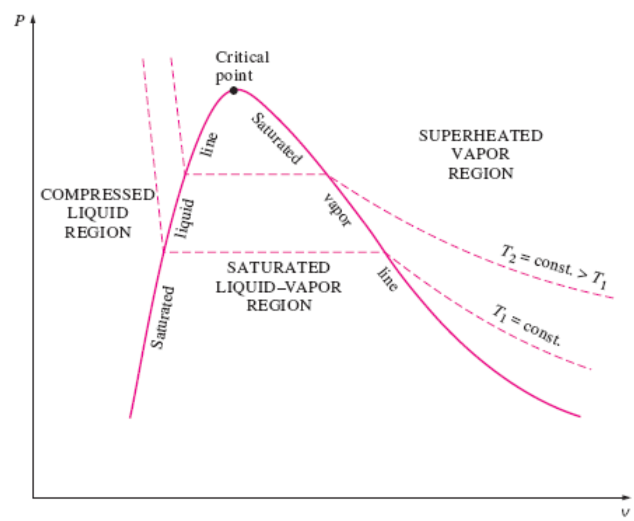


line temperature and the final temperature using constant specific heats.

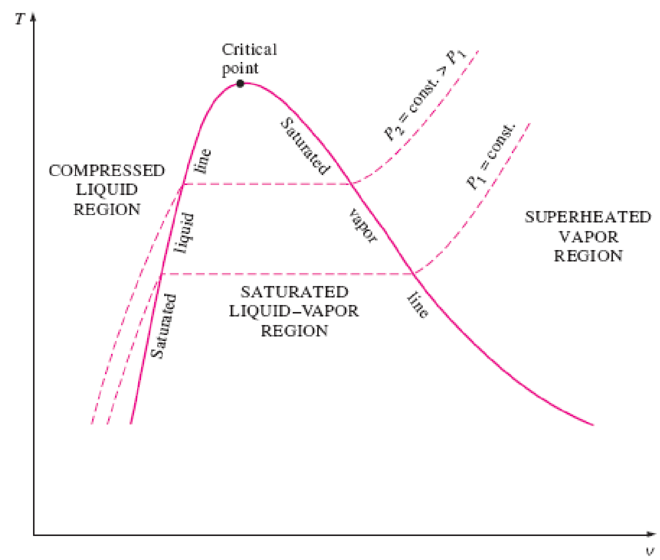
20. A rigid 100-L tank contains air at 1 MPa and 200°C. A valve on the tank is now opened, and air flows out until the pressure dropsto100 kPa. During this process, heat is transferred from a heat source at 200°C, such that when the valve is closed, the temperature inside the tank is 50°C. Calculate the heat transferred from the tank during this process.

21. A nitrogen line, at 300 K and 0.5 Mpa, shown in fig. is connected to a turbine that exhausts to a closed initially empty tank of 50 $m^3$. The turbine operates to a tank pressure of0.5 MPa, at which point the temperature is 250 K. Assuming the entire process is adiabatic, determine the turbine work.




*P-v Diagram of a pure substance*




*T-v diagram of a pure substance*