Slide 1

First Law of Thermodynamics

Zeroth Law of Thermodynamics

- Two bodies in ***thermal equilibrium*** with a ***third body*** are in thermal equilibrium with ***each other***

First Law of Thermodynamics

- ***Mass Conservation:*** For a closed system, mass of the system is constant
- ***Energy Conservation:*** Although energy assumes various forms, the total quantity of energy is constant, with the consequence that when energy disappears in one form, it appears simultaneously in others

Slide 2

- ***Sign Conventions for heat and work transfer***
  - Heat added to a system is positive
  - Work done by a system is positive
- ***First Law of Thermodynamics for a process***

  $\delta Q - \delta W = dE$

  δQ denotes the elemental (heat) energy transfer across the system boundaries due to temperature differences

  δW the elemental (work) energy in transit across the boundaries (e.g., the piston weight lifted due to the expansion of the system)

  dE the energy change in the system. The "E" includes internal energy U (=TE+VE+RE etc.) which resides in the matter, kinetic energy KE and potential energy PE.

  For a vertical displacement of z_1 to z_2, change in PE = $mg(z_2-z_1)$

  For a velocity change from v_1 to v_2, change in $KE=m(v_2^2- v_1^2)/2$

  - For a ***stationary*** system, $\delta Q - \delta W = dU$

Slide 3

- ***Uncoupled and Coupled Systems***
  - If two or more interactions (heat and work transfer) affect the same energy mode, the system is a *coupled* one; otherwise, it is *uncoupled*
  - ***Example of uncoupled system:*** Motion of a body on a frictionless inclined plane (changes in KE and PE affected by work transfer only)
  - ***Example of coupled system:*** Motion of a car on a rough inclined surface (change in internal energy affected by both heat and work transfer)

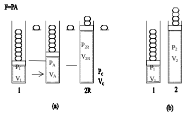
Slide 4

- ***First Law for Non-cyclic Process***
  - $Q_{12} - W_{12} = E_2 - E_1$
- ***Caratheodory's Theorem***
  - The work performed during all adiabatic processes ($Q_{12} = 0$) between two given states is the same. Hence, $W_{12} = E_2 - E_1 = \Delta E$.
- ***Poincare Theorem*** $\oint \delta Q = \oint \delta W$
  - For a cyclic process, net heat transfer and net work transfer are equal, i.e.
- ***First Law for Rate Processes***

$$\oint \delta Q = \oint \delta W$$

$$\dot{Q} - \dot{W} = dE/dt$$

Slide 5



- ***Quasiequilibrium Process***
  - Departure from equilibrium is infinitesimally small during the process (Fig. (a))
  - Work transfer during the process can be calculated by integrating along the path as the intermediate states are known
- ***Non-quasiequilibrium Process***
  - Large departure from equilibrium (Fig. (b))
  - Work transfer during the process calculated in terms of energy change between initial and final states
- **Refer to Example 1 in Example_2.pdf**

Slide 6

- ***First Law in Enthalpy Form***
  - Enthalpy defined as $H = U + pV$
  - For negligible changes in KE and PE, first law becomes

  $\delta Q - \delta W = dU = d(H - pV)$

  For quasiequilibrium process, $\delta W = pdV + \delta W_{other}$

  For $\delta W_{other} = 0$, $\delta Q - \delta W' = dH$, where $\delta W' = -Vdp$

For *isobaric* processes, $\delta Q_p = dH$

For *isometric* processes, $\delta Q_v = dU$

Refer to Examples 2 and 3 in Example_2.pdf

Slide 7

- ***Internal Energy and Enthalpy***
  - $\Delta U = U(T,p) - U(T_{ref},p_{ref})$
  - $\Delta H = H(T,p) - H(T_{ref},p_{ref})$
  - Generally, $U(T_{ref},p_{ref}) = 0$; hence, $H(T_{ref},p_{ref}) = p_{ref}V(T_{ref}, p_{ref})$
  - For *ideal gases*, $u = u(T)$ and $h = h(T)$.

    $h(T) = u(T) + pV = u(T) + RT$
- ***Specific Heats at Constant Volume and Pressure***
  - Sp. Heat at constant pressure, $C_p = (\partial h/\partial T)_p$
  - Sp. Heat at constant volume, $C_v = (\partial u/\partial T)_p$
  - For *ideal gases*, $C_v = C_v(T)$ and $C_p = C_p(T)$.

    $C_p = dh/dT$; $C_v = du/dT$ and $C_p - C_v = R$

Slide 8

- ***Reversible Adiabatic Process for an Ideal Gas***
  - From 1st Law: $\delta Q - \delta W = dU$
  - For reversible process, $\delta W = pdV$
  - For ideal gas, $dU = C_v dT$
  - For adiabatic reversible process for an ideal gas, $C_v dT = - pdV$
  - Using $C_p - C_v = R$ and $C_p/C_v = k$, we obtain:

    $pV^k = \text{constant}$

Slide 9

- ***First Law for Open Systems***
  - In open systems, mass crosses the system boundary (also known as the control surface cs which encloses a control volume c.v).
  - In addition to heat and work interactions with the environment, interactions also occur through an exchange of constituent species between the system enclosure and its environment. Consequently the mass contained within the system may change.
  - Examples:

    Turbine with rigid walls (fixed control volume)
    Automobile engine cylinders (deformable control volume)
  - Lagrangian analysis (fixed mass basis) of energy balance difficult
  - Eulerian analysis (fixed volume basis) adopted for mass and energy conservation

Slide 10

- ***Mass Balance for a Control Volume***
  - ***Non-steady state***: $dm_{c.v}/dt = \dot{m}_i - \dot{m}_e$
  - ***Steady state***: $dm_{c.v}/dt = 0$
  - ***Elemental form***: $dm_{c.v} = dm_i - dm_e$
  - ***Closed System***: m = constant
- ***Energy Balance for a Control Volume***
  - ***Non-steady state:*** $\dot{Q}_{cv} - \dot{W}_{cv} = \dot{m}_i h_{T,i} - \dot{m}_e h_{T,e}$
  - ***Steady state:*** $\dot{Q}_{cv} - \dot{W}_{cv} = dE_{cv}/dt + \dot{m}_i h_{T,i} - \dot{m}_e h_{T,e}$
  - ***Elemental form:*** $\dot{Q}_{cv}dt - \dot{W}_{cv}dt = dE_{cv} + \dot{m}_i h_{T,i}dt - \dot{m}_e h_{T,e}dt$
  - ***Closed system:*** $\dot{Q}_{cv} - \dot{W}_{cv} = dE_{cv}/dt$
  - ***Unit mass basis (steady state):*** $q_{cv} - w_{cv} = h_{T,i} - h_{T,e}$

  e_T= h + KE + PE (*methalpy*); $q_{cv} = \dot{Q}_{cv}/\dot{m}; w_{cv} = \dot{W}_{cv}/\dot{m}$

- **Refer to Examples 4 through 7 of Example_2.pdf**

Slide 11

Example

- As liquid water flows steadily through an adiabatic valve the pressure decreases from P_1 = 51 bar to P_2 = 1 bar. If the inlet water temperature is 25ºC, what is the exit temperature? Assume that the specific volume of water is temperature independent and equal to 0.001 m³/kg, and that u = cT, where c = 4.184 kJ kg⁻¹ K⁻¹. Neglect effects due to the kinetic and potential energies.

Solution

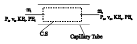
Mass conservation implies that $dm_{c.m.}/dt = 0$. Therefore, = = . Furthermore, $dE_{c.v}/dt = 0$, and = = 0. Applying Eq. (50), $\Delta e_T = 0$.

Since $e_T = h + ke + pe$, this implies that $h_2 = h_1$. A process during which the enthalpy is unchanged (i.e., $h_2 = h_1$) is called a throttling process. Furthermore, since $v_2 = v_1 = v$, and $u_2 + P_2v_2 = u_1 + P_1v_1$ (as a consequence of $h_2 = h_1$),

$$c\,(T_2 - T_1) = -v(P_2 - P_1), \text{ i.e.,}$$

$T_2 - T_1 = (0.001 \times (51-1)\text{ bar} \times 100\text{ kPa bar}^{-1}) \times (4.184\text{ kJ kg}^{-1}\text{K}^{-1}) = 1.2$ K, and $T_2 = (298 + 1.2) = 299.2$ K.

Slide 12



A fluid flows through a capillary tube with an inlet velocity V_i and exit velocity V_e. Apply the mass and energy conservation equations for steady flow and simplify the expression.

Mass conservation implies that $\dot{m}_i = \dot{m}_e = \dot{m}$. From energy conservation $dE_{c.v}/dt = 0$, and $\dot{W}_{CV} = 0$ so that

$$-\Delta e_T = 0, \text{ i.e., } q_{c.v} - \Delta e_T = 0. \qquad \text{(A)}$$

For an adiabatic system, Eq. (A) assumes the form

$$\Delta(h + ke) + \Delta pe = 0, \text{ or } (h + ke) + pe = \text{Constant.} \quad \text{(B)}$$

The sum (h + ke) is called the stagnation enthalpy and is commonly used in fluid dynamics analyses. If u is a function of temperature alone, e.g., as for an ideal gas or incompressible liquid , Δu = 0 and Δh = Δ (Pv). In this case,

$$(Pv + ke) + pe = \text{Constant, or } P/\rho + V^2/2 + gZ = \text{Constant.} \quad \text{(C)}$$

Slide 13

Multiple Inlets and Exits

$dm_{cv}/dt = \sum_i \dot{m}_i - \sum_i \dot{m}_e$

$\dot{Q}_{cv} - \dot{W}_{cv} = dE_{cv}/dt + \sum_i \dot{m}_i h_{T,i} - \sum_i \dot{m}_e h_{T,e}$

- ***Non-reacting Multicomponent Systems***
  - $dm_{k,cv}/dt = \dot{m}_{k,i} - \dot{m}_{k,e}$
  - $dm_{cv}/dt = \Sigma\, dm_{k,cv}/dt = \sum_i \dot{m}_i - \sum_i \dot{m}_e$

    $dE_{cv}/dt = \dot{Q}_{cv} - \dot{W}_{cv} + 3\dot{N}_{k,i}\bar{e}_{k,T,i} - 3\dot{N}_{k,e}\bar{e}_{k,T,e}$

Slide 14

- ***Mass Conservation Equation in Integral Form***

  $\dot{m}_i = -\int_{A_i} \rho\mathbf{V}.d\mathbf{A}$ $\qquad$ $\dot{m}_e = \int_{A_e} \rho\mathbf{V}.d\mathbf{A}$

  $$\frac{d}{dt}\left(\int_{CV} \rho dV\right) = -\int_{A_i} \rho\mathbf{V}.d\mathbf{A} + \int_{A_e} \rho\mathbf{V}.d\mathbf{A} = -\oint_{CS} \rho\mathbf{V}.d\mathbf{A}$$

- ***Mass Conservation Equation in Differential Form***
  - Using *Gauss Divergence Theorem*,

    $\oint_{CS} \rho\mathbf{V}.d\mathbf{A} = -\int_{CV} \nabla.(\rho\mathbf{V})dV$

  For fixed control volume, $\frac{d}{dt}\left(\int_{CV} \rho dV\right) = \int_{CV} \left(\frac{\partial\rho}{\partial t}\right) dV$

  Hence, $\int_{CV} \left(\frac{\partial\rho}{\partial t}\right) dV + \int_{CV} \nabla.(\rho\mathbf{V}) dV = 0$

  Shrinking CV to an infinitesimal volume, $\frac{\partial\rho}{\partial t} + \nabla.(\rho\mathbf{V}) = 0$

Slide 15

- ***Energy Equation in Integral Form***
  - Net methalpy inflow into the control volume = $-\oint_{CS} \rho e_T \mathbf{V}.d\mathbf{A}$
  - For a rigid control surface, work done $\dot{W}_{CV} = \int_{CV} \dot{w}'''_{CV} dV$
  - Heat transferred to control volume $\dot{Q}_{CV} = -\oint_{CS} \mathbf{q}.d\mathbf{A}$
  - Hence the energy equation equation becomes

    $$\frac{d}{dt}\left(\int_{CV} \rho e dV\right) = -\oint_{CS} \rho e_T \mathbf{V}.d\mathbf{A} + \oint_{CS} \mathbf{q}.d\mathbf{A} - \int_{CV} w'''_{CV} dV$$

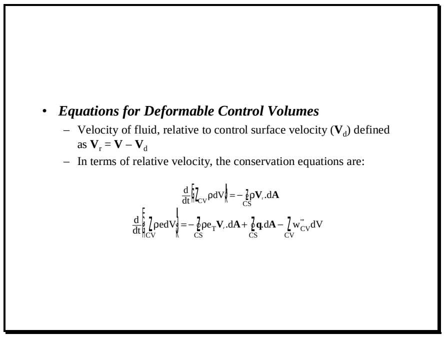
- ***Energy Equation in Differential Form***
  - Using Gauss Divergence Theorem, as before, and shrinking the control volume to an infinitesimal volume,

    $$\frac{\partial(\rho e)}{\partial t} + \nabla.(\rho e_T \mathbf{V}) = -\nabla.\mathbf{q} - w'''_{CV}$$

  - For negligible changes in KE and PE, no work and heat transfer by conduction (Fourier) only, the equation becomes

    $$\frac{\partial(\rho h)}{\partial t} + \nabla.(\rho h \mathbf{V}) = \nabla.(\lambda\nabla T) + \frac{\partial p}{\partial t}$$

Slide 16

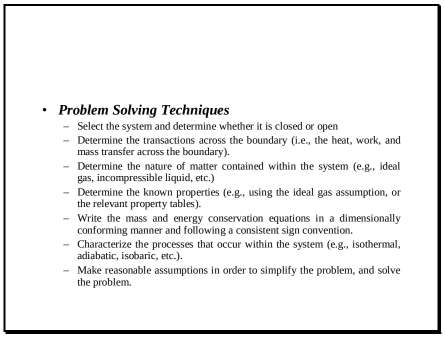


- ***Equations for Deformable Control Volumes***
  - Velocity of fluid, relative to control surface velocity ($\mathbf{V}_d$) defined as $\mathbf{V}_r = \mathbf{V} - \mathbf{V}_d$
  - In terms of relative velocity, the conservation equations are:

$$\frac{d}{dt}\left\{\int_{CV} \rho dV\right\} = -\oint_{CS} \rho \mathbf{V}_r.d\mathbf{A}$$

$$\frac{d}{dt}\left\{\int_{CV} \rho e dV\right\} = -\oint_{CS} \rho e_T \mathbf{V}_r.d\mathbf{A} + \oint_{CS} \mathbf{q}.d\mathbf{A} - \int_{CV} w'''_{CV} dV$$

Slide 17



- ***Problem Solving Techniques***
  - Select the system and determine whether it is closed or open
  - Determine the transactions across the boundary (i.e., the heat, work, and mass transfer across the boundary).
  - Determine the nature of matter contained within the system (e.g., ideal gas, incompressible liquid, etc.)
  - Determine the known properties (e.g., using the ideal gas assumption, or the relevant property tables).
  - Write the mass and energy conservation equations in a dimensionally conforming manner and following a consistent sign convention.
  - Characterize the processes that occur within the system (e.g., isothermal, adiabatic, isobaric, etc.).
  - Make reasonable assumptions in order to simplify the problem, and solve the problem.