CHAPTER-4

FIRST LAW OF THERMODYNAMICS

ENERGY BALANCE

- The net change(increase or decrease) in the ***total energy*** of the system during a process is equal to:

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix}-\begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix}=\begin{pmatrix}\text{The change in total}\\ \text{energy of the system}\end{pmatrix}$$

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

- referred to as the ***energy balance*** and is applicable for any kind of system undergoing any kind of process.

- Note that energy is a property, and the value of a ***property does*** not change unless the ***state of the system change***.

ENERGY BALANCE

- The energy change of a system is ***zero*** if the state of the system does not change during the process.
- Energy can exist in numerous forms such as:-
  - Internal energy (Sensible, latent, chemical, nuclear) U;
  - Kinetic energy KE;
  - Potential Energy PE;
  - Electric Energy E;
  - Magnetic M.
- For ***compressible*** systems, ***electric***, ***magnetic*** and ***surface tension*** energy are negligible.

$$E = Internal\ energy + Kinetic\ energy + Potential\ energy$$

$$E = U + KE + PE$$

ENERGY BALANCE

- The ***change in total energy*** of a system during a process is the sum of the changes in U, PE and KE.

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

$$\Delta U = m\left(u_2 - u_1\right)$$

$$\Delta KE = \frac{1}{2} m\left(V_2^2 - V_1^2\right)$$

$$\Delta PE = mg\left(z_2 - z_1\right)$$

- Most systems encountered in practice are ***stationary***, that is, they do not involve any change in their ***velocity*** or ***elevation*** during a process.

$$\Delta E = \Delta U$$

- Energy can be transferred to or from a system in ***three*** forms:- ***heat***, ***work*** and ***mass.***

ENERGY BALANCE

- The net transfer of a quantity is equal to the difference between the amounts transferred in and out.
- The energy balance can be written more explicitly as:-

$$\Delta E_{system} = E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass\ in} - E_{mass\ out})$$

  - Heat is zero for adiabatic process,
  - Work is zero for systems that involve no work interactions,
  - Energy transport with mass is zero for closed systems.

ENERGY BALANCE

- Energy balance for any system undergoing any kind of process can be expressed more compactly as:-

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

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$

$$\delta E_{in} - \delta E_{out} = dE_{system}$$

- In the rate form

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}$$

ENERGY BALANCE

- For **closed** system undergoing a **cycle**

$$\Delta E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass\ in} - E_{mass\ out})$$

=0 (cyclic)

=0 (closed)

$$W_{net} = Q_{net} \Rightarrow \oint \delta W = \oint \delta Q$$

ENERGY BALANCE

- The first law or energy balance relation in that case for a closed system becomes

$$Q - W = \Delta E_{system}$$

Summary

- Generally $Q - W = \Delta E \Rightarrow Q - W = \Delta U + \Delta KE + \Delta PE$
- Stationary system $Q - W = \Delta U$
- Differential $\delta q - \delta w = de$

ENERGY BALANCE

Closed systems undergoing a process

- When a system undergoes a process, a change in state of a system will be:
- For path AB

$$\int_1^2 \delta Q_A + \int_1^2 \delta Q_B = \int_1^2 \delta W_A + \int_1^2 \delta W_B$$

- For path AC

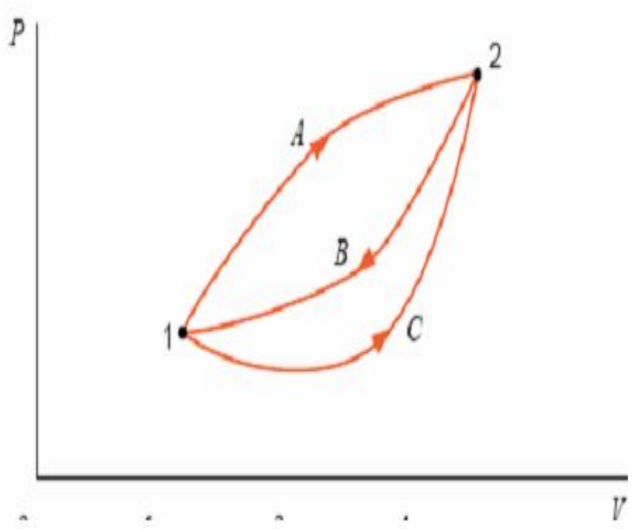
$$\int_1^2 \delta Q_A + \int_1^2 \delta Q_C = \int_1^2 \delta W_A + \int_1^2 \delta W_C$$

- Subtracting the two equation will get

$$\int_1^2 \delta Q_B - \int_1^2 \delta Q_C = \int_1^2 \delta W_B - \int_1^2 \delta W_C$$

- Rearranging the above equation

$$\int_1^2 (\delta Q - \delta W)_B = \int_1^2 (\delta Q - \delta W)_C$$



ENERGY BALANCE

- The resulting equation indicates that the expression $(\delta Q - \delta W)$ is **independent of the path.**
- The given expression, an energy term represents a **property**.
- It represents a change in energy of the system and denoted by dE:-

$$\delta Q - \delta W = dE$$

$$\delta Q = dE + \delta W$$

- Integration of the above equation will give

$$Q_{1-2} = (E_2 - E_1) + W_{1-2}$$

- Equation above is therefore the expression for the **first law of thermodynamics for a closed** system undergoing a process.

ENERGY BALANCE

- The total energy is a combination of **internal energy**, **kinetic**, **potential energy.**

$$E = U + PE + KE$$

- The individual terms that makes up the properties must be a property themselves, hence

$$dE = dU + dPE + dKE$$

- The first law becomes

$$\delta Q = dU + dPE + dKE + \delta W$$

- Integrating the above equation gives

$$Q_{1-2} = (U_2 - U_1) + m\left(\frac{V_2^2 - V_1^2}{2}\right) + mg(Z_2 - Z_1) + W_{1-2}$$

- For negligible changes in KE and PE

$$Q_{1-2} = (U_2 - U_1) + W_{1-2}$$

ENERGY BALANCE

- The first law as a rate equation

$$\frac{\delta Q}{dt} = \frac{dU}{dt} + \frac{dKE}{dt} + \frac{dPE}{dt} + \frac{\delta W}{dt}$$

$$\dot{Q} = \dot{E} + \dot{W}$$

INTERNAL ENERGY AND ENTHALPY

A. Internal energy

- The internal energy includes some complex forms of energy show up due to **translation**, **rotation** and **vibration** of molecules, electronics spin and rotation.
- Designated by U- extensive; u-intensive $u = \frac{U}{m}$
- If we take two phases as liquid and vapor at a given **saturation pressure** and **temperature**, then

$$U = U_f + U_g$$

$$mu = m_f u_f + m_g u_g \qquad u = \frac{m_f}{m} u_f + \frac{m_g}{m} u_g$$

$$u = (1 - x)u_f + xu_g$$

$$u = u_f + xu_{fg}$$

INTERNAL ENERGY AND ENTHALPY

Example

- A vessel of $5m^3$ contains liquid and vapor water with a mixture specific volume of 0.003155 m^3/kg at 0.1 Mpa. Heat is transferred until the pressure reaches 22.09 Mpa. Determine the:-
  a. volume and mass of liquid and vapor initially
  b. heat transfer.

INTERNAL ENERGY AND ENTHALPY

B. Enthalpy

- Is another **extensive** property which has a unit of energy.
- Denoted by H and is defined as

$$H = U + PV$$

- Per unit mass of the system

$$h = \frac{H}{m} \quad \text{specific enthalpy}$$

$$h = u + pv$$

- Consider a piston-cylinder assembly where we have a **continuous supply of heat so that the boundary changes**.

INTERNAL ENERGY AND ENTHALPY

- For the process

$$Q_{1-2} = (U_2 - U_1) + W_{1-2}$$

- If we are assuming, the process is at **constant pressure**.

$$W_{1-2} = \int PdV = PV_2 - PV_1$$

$$Q_{1-2} = (U_2 - U_1) + PV_2 + PV_1$$

$$Q_{1-2} = (U_2 + PV_2) - (U_1 + PV_1)$$

$$Q_{1-2} = H_2 - H_1$$

- If we take two phase at a given saturation state

$$H = H_f + H_g$$

- Following the same procedure as for internal energy

$$h = h_f + xh_{fg}$$

INTERNAL ENERGY AND ENTHALPY

Example

- 10L of water is contains is a piston-cylinder arrangement initially at 2Mpa and quality of 10%. It is heated slowly to 300^0C. Determine
  a) the work done,
  b) the heat input,

SPECIFIC HEAT

- It is an **intensive** property. SI unit (kJ/kgC; kJ/kgK; kJ/kmolK)
- A substance that will enables us to compare **the energy storage capability of various substances**.

Defined

- The energy required to raised the temperature of one kilogram of a substance by one degree centigrade.
- Where the substance may be solid, liquid or gaseous phase:

$$c = \frac{1}{m}\left(\frac{\delta Q}{\delta T}\right)$$

SPECIFIC HEAT

- This energy(heat) is dependant on the type of process executed.
- In engineering thermodynamics, we focus on two types of specific heat.

A. Constant Volume process

- The boundary work is zero and the specific heat is identified by subscript v.
- From first law of thermodynamics for closed systems:-

$$\delta Q - \delta W = dU$$

$$\delta q = du \text{ but } \quad \delta q = C_v \Delta T$$

$$du = C_v \Delta T \qquad C_v = \left(\frac{du}{dT}\right)_v$$

- Change in internal energy with temperature at constant volume.

SPECIFIC HEAT

B. Constant Pressure process

- From first law of thermodynamics

$$\delta Q - \delta W = dU$$

$$\delta Q = du + \delta W = du + PdV$$

$$\delta Q = du + \delta W = d(U + PV)$$

$$\delta q = dh \text{ but } \delta q = C_p dt$$

$$C_p = \left(\frac{dh}{dT}\right)_p$$

- Change in enthalpy with temperature at constant pressure.

INTERNAL ENERGY,ENTHALPY AND SPECIFIC HEAT

A. IDEAL GAS

- From the ideal gas equation

$$Pv = RT$$

- **Experimental observation shows that** U=U(T)
- Combining $h = u + Pv \;\; and \; Pv = RT$

$$h = u + RT \Rightarrow h = h(T)$$

- From the specific heat relation

$$C_v = \left(\frac{du}{dT}\right)_v \qquad \int_1^2 du = \int_1^2 C_v\,(T)dT$$

$$u_2 - u_1 = \int_1^2 C_v\,(T)dT$$

INTERNAL ENERGY,ENTHALPY AND SPECIFIC HEAT

- Taking average value of specific heat for **narrow temperature**:-

$$u_2 - u_1 = C_{ave,v}(T_2 - T_1)$$

- And

$$\int_1^2 dh = \int_1^2 C_p(T)\, dT = h_2 - h_1$$

$$h_2 - h_1 = C_{ave,p}(T_2 - T_1)$$

- Hence

$$\Delta u = C_v \Delta T$$

$$\Delta h = C_p \Delta T$$

INTERNAL ENERGY,ENTHALPY AND SPECIFIC HEAT

Relation of specific heat for ideal gases

- It can be obtained by differentiating the relation

$$dh = C_p dT \; ; du = C_v dT$$

$$h = u + pv = u + RT$$

=0 (R=constant)

$$C_p dT = C_v dT + R dT + T dR$$

$$C_p = C_v + R \quad \left({}^{kJ}/_{kg\,K} \right)$$

$$\bar{C}_p = \bar{C}_v + \bar{R}_u \quad \left({}^{kJ}/_{kmol\,K} \right)$$

- Where

$$\bar{R}_u = 8.314 \, {}^{kJ}/_{kmol}$$

INTERNAL ENERGY,ENTHALPY AND SPECIFIC HEAT

- We introduce other ideal gas property called **specific heat ratio** K, defined as

$$K = \frac{C_p}{C_v} \; ; \quad C_p = C_v + R$$

$$C_v = \frac{R}{K+1} ; \quad C_p = \frac{KR}{K-1}$$

B. Solid and Liquid (incompressible substance)

- The specific volume is constant during a process

$$C_p = C_v = C$$

- A substance whose specific volume(density) is constant is called an **incompressible substance**.

INTERNAL ENERGY,ENTHALPY AND SPECIFIC HEAT

- INTERNAL ENERGY

$$\int_1^2 du = \int_1^2 C_v\, dT$$

$$u_2 - u_1 = \int_1^2 C(T)dT = C_{avg}\,(T_2 - T_1)$$

- ENTHALPY

=0(v=constant)

$$h = u + pv \Rightarrow dh = du + pdv + vdp$$

- Integrating will give

$$\Delta h = \Delta u + v\Delta p = C_{avg}\Delta T + v\Delta p$$

- For **solids**, the term $v\Delta p$ is insignificant

$$\Delta h = \Delta u = C_{avg}\Delta T$$

INTERNAL ENERGY,ENTHALPY AND SPECIFIC HEAT

- For **liquid**

I. Constant pressure process

=0(p=constant)

$$\Delta h = \Delta u + v\Delta p = C_{avg}\Delta T + v\Delta p$$

$$\Delta h = \Delta u = C_{avg}\Delta T$$

II. Constant temperature process

=0(T=constant)

$$\Delta h = \Delta u + v\Delta p = C_{avg}\Delta T + v\Delta p$$

$$\Delta h = v\Delta p$$

Thermodynamics Solution Method

1. Sketch the system and show energy interactions across the boundaries.
2. Determine the property relation. Is the working substance an ideal gas or a real substance? Begin to set up and fill in a property table.
3. Determine the process and sketch the process diagram. Continue to fill in the property table.
4. Apply conservation of mass and conservation of energy principles.
5. Bring in other information from the problem statement, called physical constraints, such as the volume doubles or the pressure is halved during the process.
6. Develop enough equations for the unknowns and solve.

Example

1. A rigid tank contains nitrogen at 27°C. The temperature rises to 127°C by heat transfer to the system. Find the heat transfer and the ratio of the final pressure to the initial pressure.

2. Air is expanded isothermally at 100°C from 0.4 MPa to 0.1 MPa. Find the ratio of the final to the initial volume, the heat transfer, and work.

Example

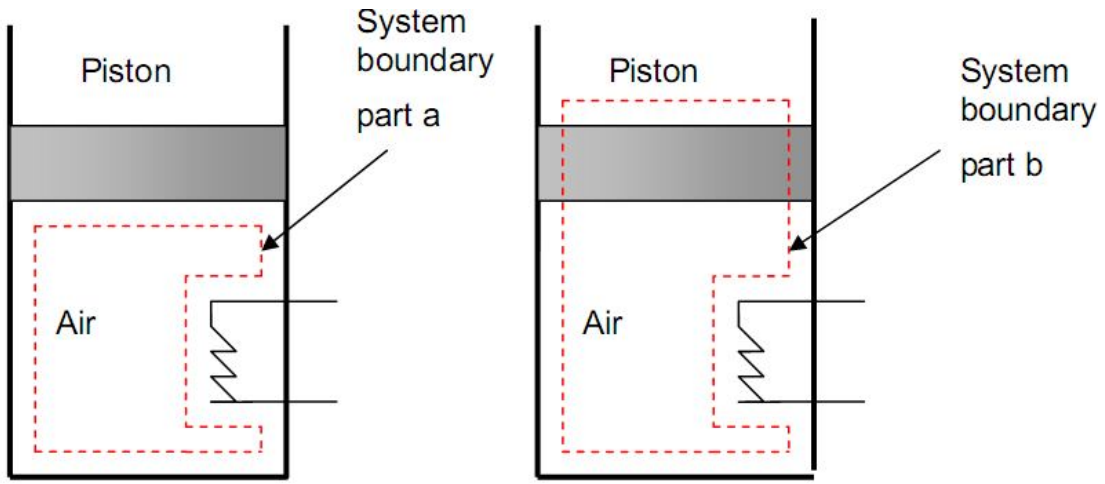
3. A two-liter bottle of your favorite beverage has just been removed from the trunk of your car. The temperature of the beverage is 35°C, and you always drink your beverage at 10°C.

A. How much heat energy must be removed from your two liters of beverage?

B. You are having a party and need to cool 10 of these two-liter bottles in one-half hour. What rate of heat removal, in kW, is required? Assuming that your refrigerator can accomplish this and that electricity costs 8.5 cents per kW-hr, how much will it cost to cool these 10 bottles?

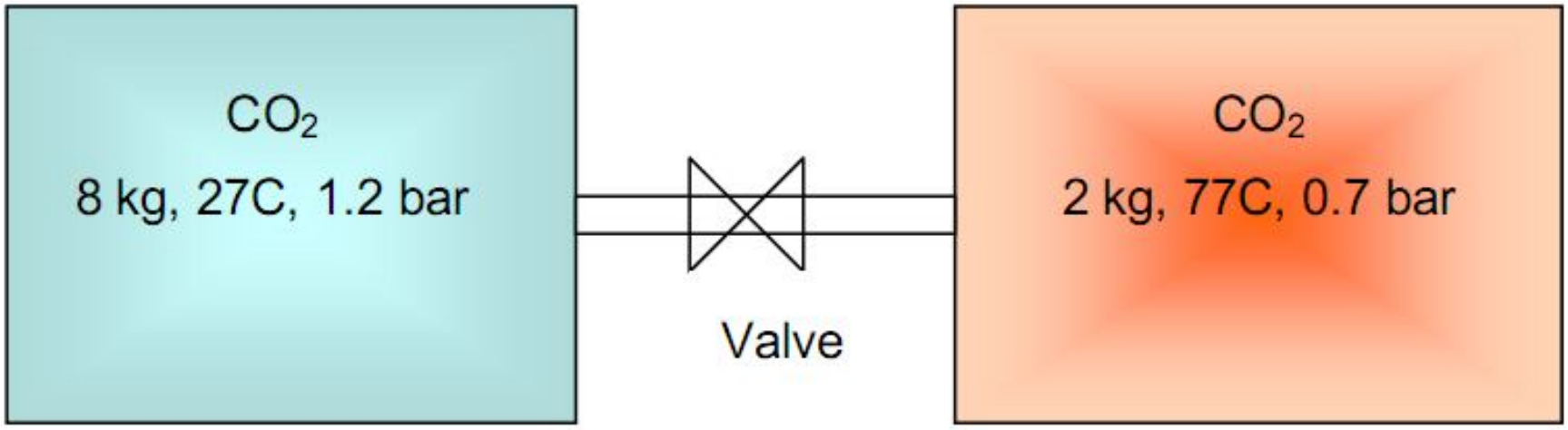
Example

4. Air is contained in a vertical piston-cylinder assembly fitted with an electrical resistor. The atmospheric pressure is 100 kPa and piston has a mass of 50 kg and a face area of 0.1 m^2 . Electric current passes through the resistor, and the volume of air slowly increases by 0.045 m^3 . The mass of the air is 0.3 kg and its specific energy increases by 42.2 kJ/kg. Assume the assembly (including the piston) is insulated and neglect the friction between the cylinder and piston, g = 9.8 m/s^2.Determine the heat transfer from the resistor to air for a system consisting a) the air alone, b) the air and the piston.



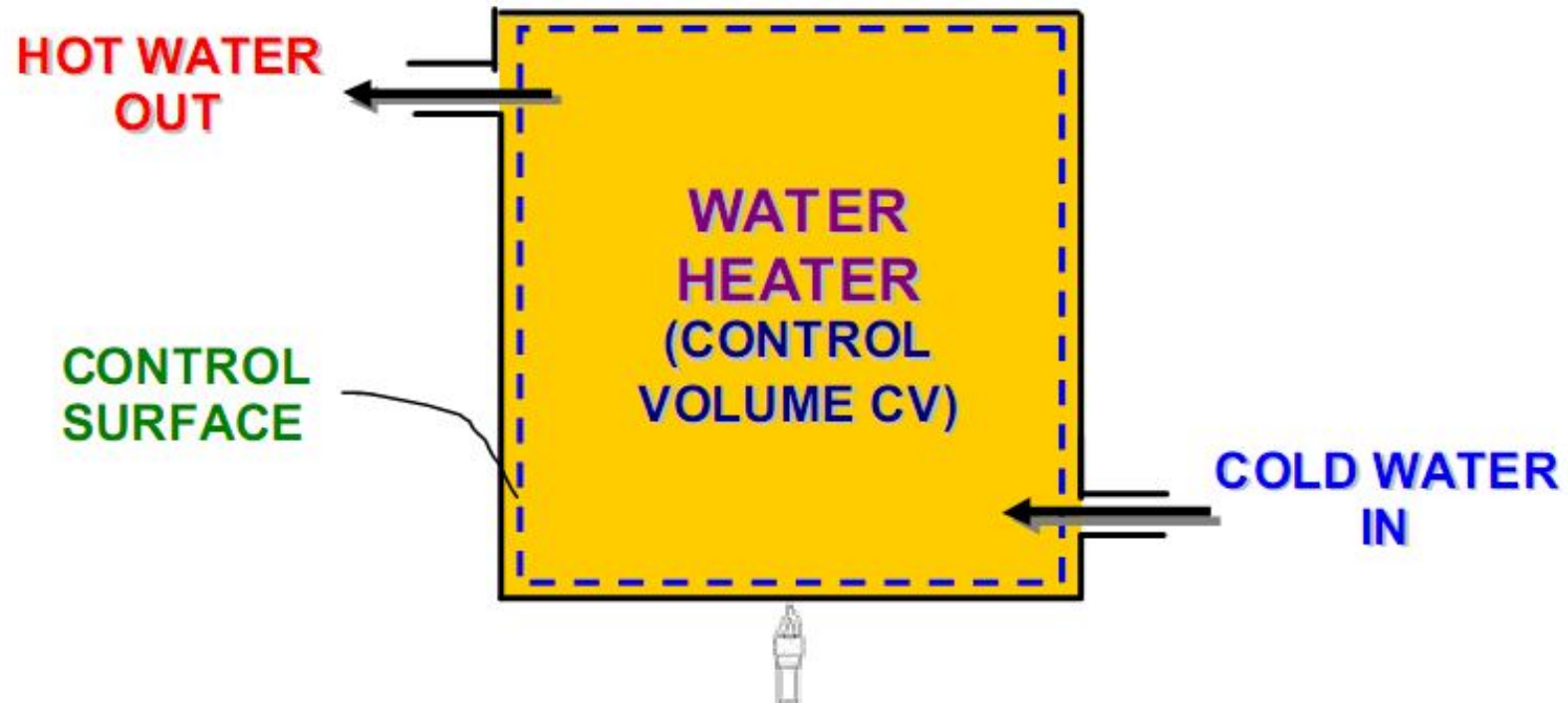
Example

5. Two tanks are connected by a valve. One tank contains 2 kg of CO_2 at 77°C and 0.7 bar. The other tank has 8 kg of the same gas at 27°C and 1.2 bar. The valve is opened and gases are allowed to mix while receiving energy by heat transfer from the surroundings. The final equilibrium temperature is 42°C. Using ideal gas model, determine a) the final equilibrium pressure b) the heat transfer for the process.

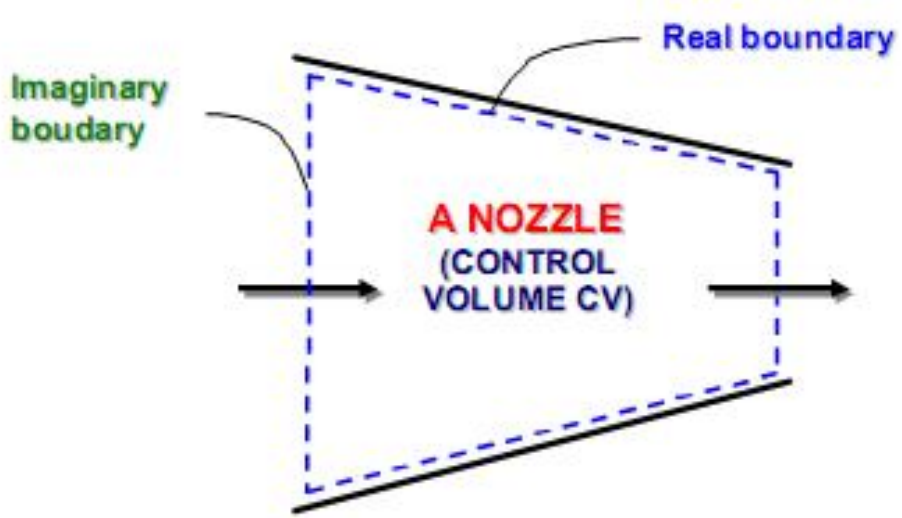


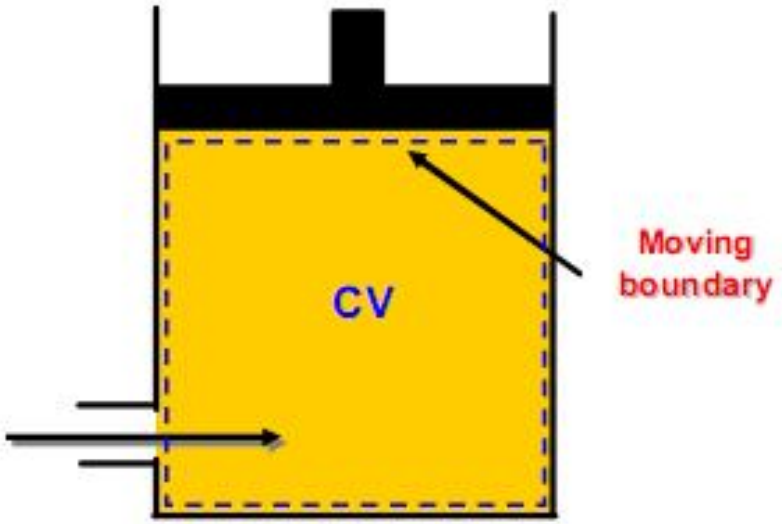
The first law of thermodynamics for control volumes

- In general, any arbitrary region in space can be selected as a control volume.
- The boundaries of a control volume are called a **control surface** and they can be **real** or **imaginary**.



The first law of thermodynamics for control volumes





The first law of thermodynamics for control volumes

- The terms **steady** and **uniform** are used extensively in this chapter and thus it is important to have a clear understanding of their meanings.
- The term **steady** implies no change with time. The opposite of steady **unsteady**, or **transient**.
- The term **uniform**, however, implies no change with location over a specific region.

The first law of thermodynamics for control volumes

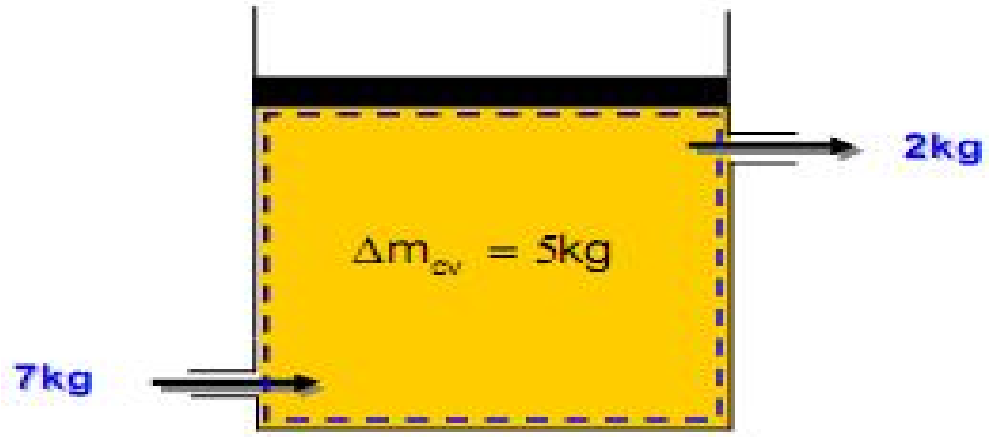
Conservation of mass principle:-

- The conservation of mass is one of the most fundamental principles in nature.

$$\left[\begin{array}{c}\text{Total mass}\\ \text{entering}\\ \text{CV}\end{array}\right] - \left[\begin{array}{c}\text{Total mass}\\ \text{Leaving}\\ \text{CV}\end{array}\right] = \left[\begin{array}{c}\text{Net change}\\ \text{in mass within}\\ \text{CV}\end{array}\right]$$

$$\sum m_i - \sum m_e = \Delta m_{cv}$$

Inlet Exit



The first law of thermodynamics for control volumes

- The mass flow rate through a differential area can be expressed as:

$$\dot{m} = \rho v_n dA$$

- Where V_n = the velocity component normal to dA.
- The mass flow rate through the entire cross-sectional area of the pipe or duct is obtained by integration:

$$\dot{m} = \int_A \rho v_n dA \qquad (kg/s)$$

$$\dot{m} = \rho v_{av} A \qquad (kg/s)$$

- V_{av} = average fluid velocity normal to A, m/sec

The first law of thermodynamics for control volumes

- The volume of the fluid flowing through a cross-section per unit time is called **the volume flow rate** and is give by

$$\dot{V} = \int_A v_n \, dA = v_{av} A \qquad (m^3 / s)$$

- The mass and volume flow rates are related by

$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}$$

The first law of thermodynamics for control volumes

- The **conservation of mass principle** for a general steady-flow system with **multiple inlets** and **exits** can be expressed in the rate form as:-

$$\left(\begin{array}{c}\text{Total mass}\\ \text{entering CV}\\ \text{per unit time}\end{array}\right) = \left(\begin{array}{c}\text{Total mass}\\ \text{leaving CV}\\ \text{per unit time}\end{array}\right)$$

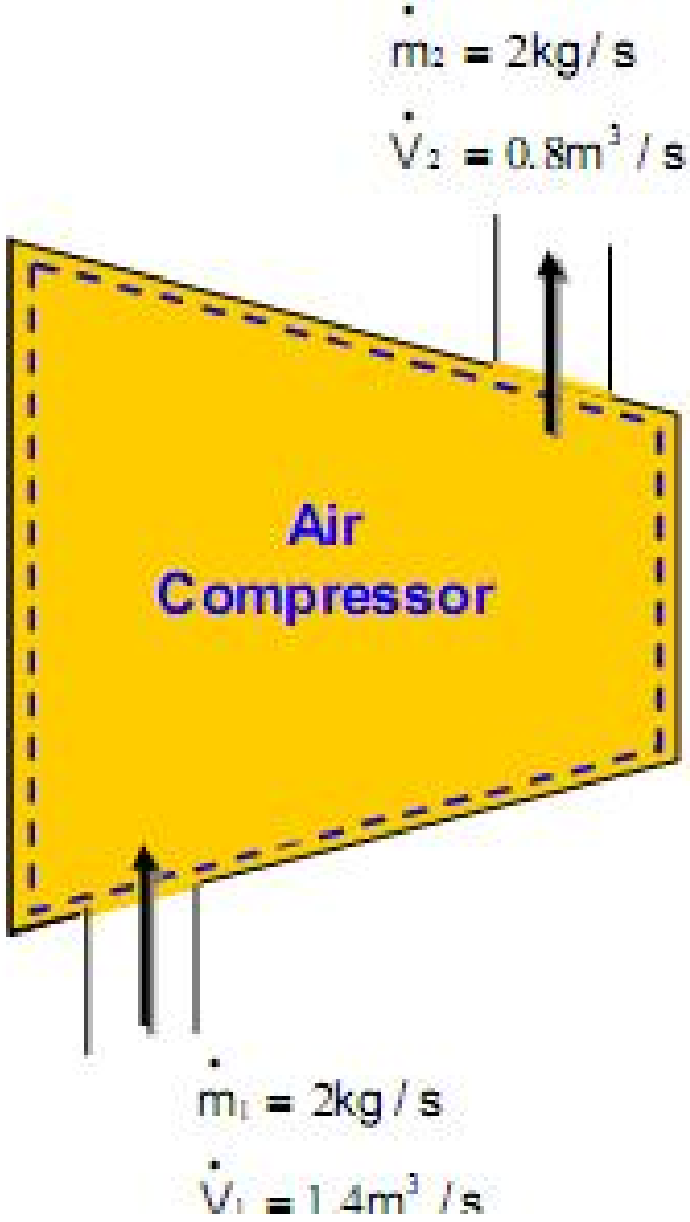
$$\sum \dot{m}_i = \sum \dot{m}_e \qquad (kg/s)$$

- For devices with only **one inlet** and **one outlet:**

$$\dot{m}_1 = \dot{m}_2 \qquad (kg/s)$$

$$\rho_1 v_1 A_1 = \rho_2 v_2 A_2$$

The first law of thermodynamics for control volumes



During a steady-flow process, volume flow rates are not necessarily conserved

The first law of thermodynamics for control volumes

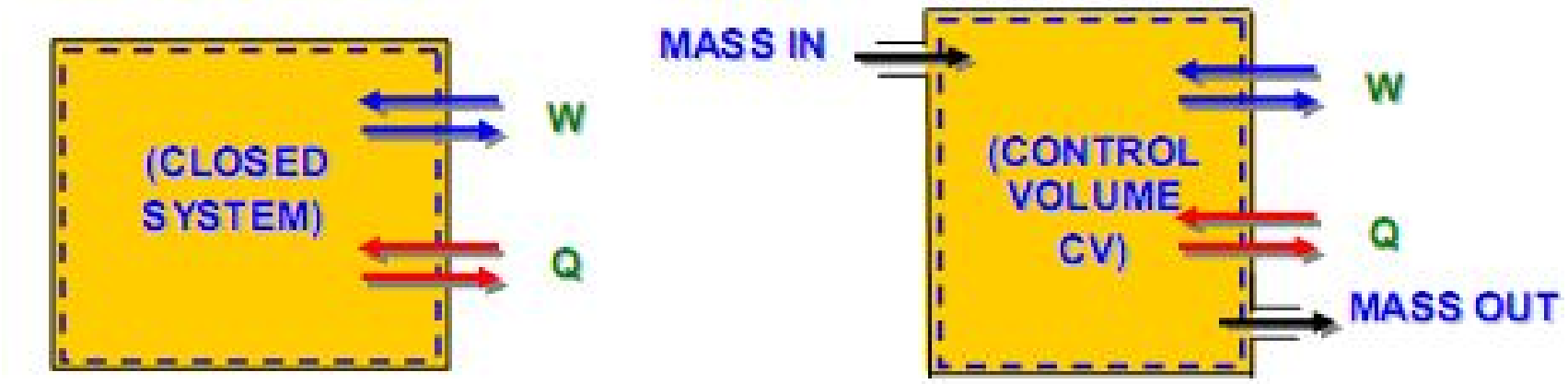
Conservation of energy principle:-

- The change in the energy of a **closed system** during a process is equal to the **net heat** and **work** transfer across the system boundary. This was expressed as

$$Q - W = \Delta E$$

- For **control volumes**, however, an additional mechanism can change the energy of a system: mass flow in and out of the control volume.
- When mass enters a control volume, the energy of the control volume increases because the entering mass carries some energy with it.

The first law of thermodynamics for control volumes

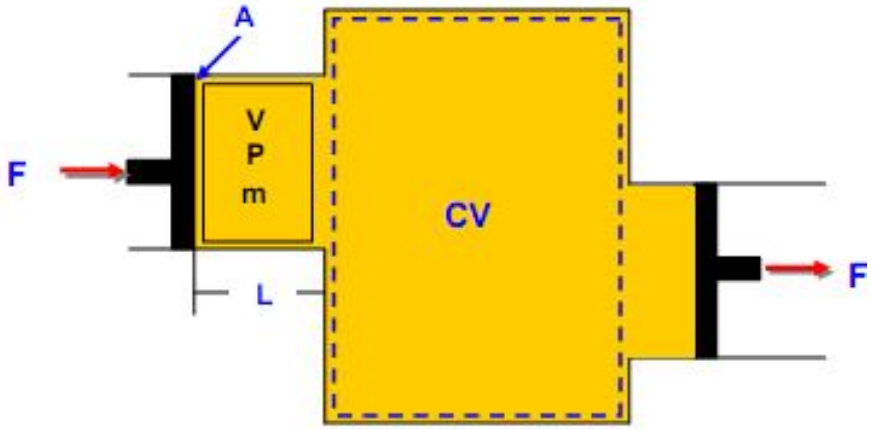


- The energy required to push fluid into or out of a control volume is called **the flow work** or **flow energy**.

The first law of thermodynamics for control volumes

Flow work

- Unlike closed systems, 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** and is necessary for maintaining a **continuous flow** through a control volume.



$$F = PA$$

$$W_{flow} = FL = PAL = PV \quad (kJ)$$

$$w_{flow} = P\upsilon \quad (kJ/kg)$$

The first law of thermodynamics for control volumes

- Total energy of a flowing fluid:-

$$e = u + ke + pe = u + \frac{v^2}{2} + gz \qquad (kJ/kg)$$

- The fluid entering or leaving a control volume possesses an additional form of energy-**the flow energy** Pv.
- The total energy of a flowing fluid on a **unit-mass basis** become:-

$$\theta = Pv + e = Pv + (u + ke + pe)$$

The first law of thermodynamics for control volumes

- The combination P*v*+u has been previously defined as **enthalpy** h. So the above relation reduces to:-

$$\theta = h + ke + pe = h + \frac{v^2}{2} + gz \qquad (kJ/kg)$$

The steady-flow process

- A large number of engineering devices such as **turbines**, **compressors**, and **nozzles** operate for long periods of time under the same conditions, and they are classified as steady-flow devices.

The first law of thermodynamics for control volumes

- The conservation of energy principle for a general steady-flow system with multiple inlets and exists can be expressed verbally as

$$\left[\begin{array}{c}\text{Total energy}\\ \text{crossing boundary}\\ \text{as heat and work}\\ \text{per unit time}\end{array}\right] = \left[\begin{array}{c}\text{Total energy}\\ \text{transport out of}\\ \text{CV with mass}\\ \text{per unit time}\end{array}\right] - \left[\begin{array}{c}\text{Total energy}\\ \text{transport into}\\ \text{CV with mass}\\ \text{per unit time}\end{array}\right]$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e \theta_e - \sum \dot{m}_i \theta_i$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e \left(h_e + \frac{v_e^2}{2} + g z_e \right) - \sum \dot{m}_i \left(h_i + \frac{v_i^2}{2} + g z_i \right)$$

For each exit

For each inlet

The first law of thermodynamics for control volumes

- For single-stream(one-inlet, one-outlet) the mass flow rate through the entire **control volume remains constant**.
- The conservation of energy for single stream steady flow-systems becomes:

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1)\right] \quad (kW)$$

$$\dot{Q} - \dot{W} = \dot{m}[\Delta h + \Delta ke + \Delta pe] \quad (kW)$$

$$q - w = h_2 - h_1 + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1) \quad (kJ/kg)$$

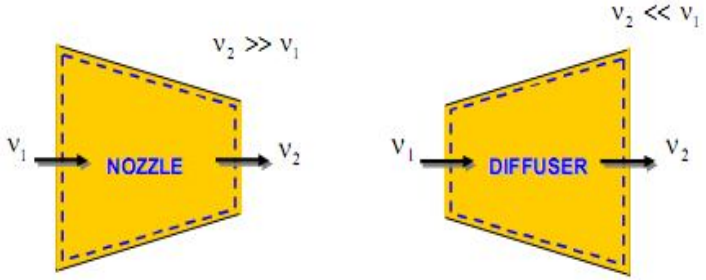
$$q - w = \Delta h + \Delta ke + \Delta pe \quad (kJ/kg)$$

$$q - w = \Delta h \quad (kJ/kg)$$

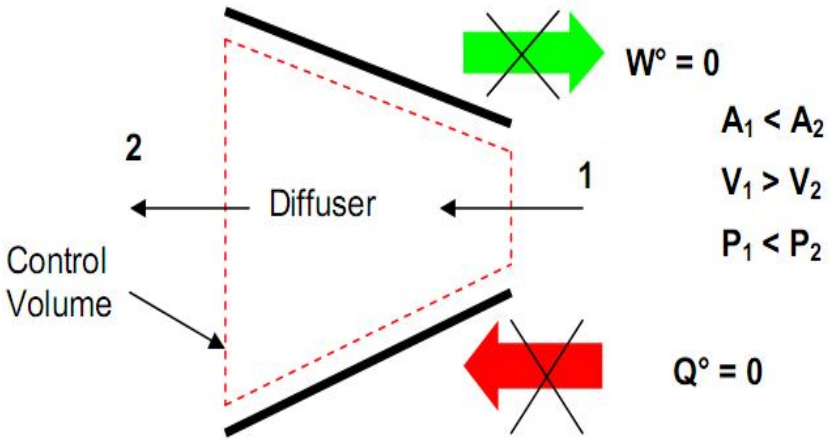
The first law of thermodynamics for control volumes

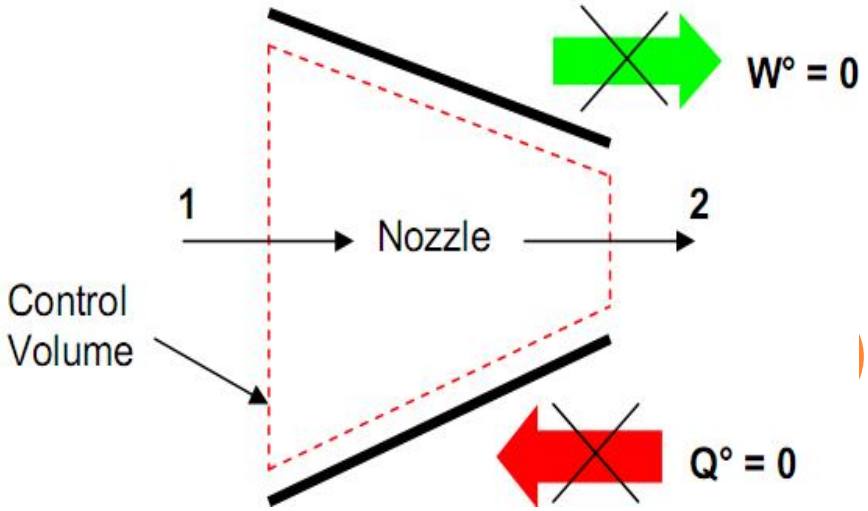
Some steady-flow engineering devices.

1. Nozzles and diffusers



- Nozzles and diffusers are commonly utilized in **jet engines**, **rockets**, **spacecraft**, and even **garden hoses**.
- A nozzle is a device that **increases the velocity of a fluid** at the expense of pressure.
- A diffuser is a device that **increases the pressure of a fluid** by slowing it down.





The first law of thermodynamics for control volumes

- The relative importance of the terms appearing in the energy equation for nozzles and diffusers is as follows:

$$\dot{Q} \approx 0, \dot{W} = 0, \Delta h \neq 0, \Delta ke \neq 0, \Delta pe = 0$$

$$\cancel{q}^{0} - \cancel{w}^{0} = \Delta h + \Delta ke + \cancel{\Delta pe}^{0} \qquad (kJ/kg)$$

$$0 = \Delta h + \Delta ke \qquad (kJ/kg)$$

$$0 = h_2 - h_1 + \frac{v_2^2 - v_1^2}{2} \qquad (kJ/kg)$$

For ideal gases $$0 = C_p(T_2 - T_1) + \frac{v_2^2 - v_1^2}{2} \qquad (kJ/kg)$$

The first law of thermodynamics for control volumes

Example

1. Steam at 0.4Mpa, 300^0C enters on adiabatic nozzle with a low velocity and leaves at 0.2Mpa with a quality of 90%. Find the exit velocity in m/sec.
2. Steam enters a converging-diverging nozzle operating at steady state with P_1 =0.05MPa, T_1 = 400°C and a velocity of 10m/s. The steam flows through the nozzle with negligible heat transfer and no significant change in potential energy. At the exit, P_2=0.01MPa, and the velocity is 665 m/s. The mass flow rate is 2 kg/s. Determine the exit area of the nozzle, in m^2.

The first law of thermodynamics for control volumes

2. Turbines and Compressors

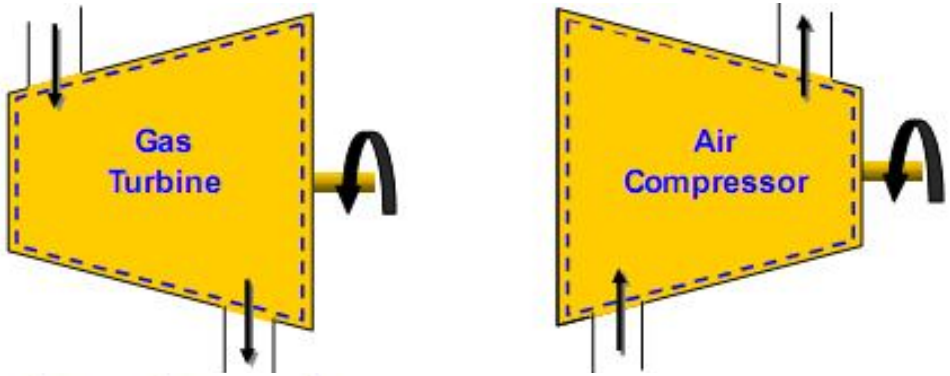
- In steam, gas or hydroelectric power plants, the device that drives the electric generator is the turbine.
- As the fluid passes through the turbine, **work is done against the blades**, which are attached to the shaft.
- As a result, the shaft rotates, and the turbine produces work.
- The work done in a turbine is **positive** since it is done by the fluid.

The first law of thermodynamics for control volumes

- **Compressor**, as well as **pumps** and **fans**, are devices used to **increase the pressure of a fluid**.
- Work is supplied to these devices from an external source through a rotating shaft.
- The work term for compressor is **negative** since work is done on the fluid.
- A compressor is capable of compressing the **gas** to very high pressures.
- Pumps work very much like compressor except that they handle **liquids** instead of gases.

The first law of thermodynamics for control volumes

- For turbines and compressors, the relative magnitudes of the various terms appearing in the energy equation are as follows.



$$\dot{Q} \approx 0, \dot{Q} \neq 0, \dot{W} \neq 0, \Delta h \neq 0, \ \Delta ke = 0, \ \Delta pe = 0$$

$$q - w = \Delta h + \cancel{\Delta ke}^{\,0} + \cancel{\Delta pe}^{\,0} \qquad (kJ/kg)$$

$$q - w = \Delta h \qquad (kJ/kg)$$

$$q - w = h_2 - h_1 \qquad (kJ/kg)$$

For ideal gases $q - w = C_p(T_2 - T_1) \qquad (kJ/kg)$

The first law of thermodynamics for control volumes

Example

- High pressure air at 1300^0K flows into an air craft gas turbine and undergoes a steady-state, steady flow adiabatic process to the turbine exit at 660^0K. Calculate the work done per unit mass of air flowing through the turbine. Use Cp@300^0K= 1.005kJ/kgK.

Ideal-gas specific heats of various common gases (*Continued*)

(*b*) At various temperatures

Temperature, K	c_p kJ/kg · K	c_v kJ/kg · K	k	c_p kJ/kg · K	c_v kJ/kg · K	k	c_p kJ/kg · K	c_v kJ/kg · K	k
	Air			*Carbon dioxide, CO_2*			*Carbon monoxide, CO*		
250	1.003	0.716	1.401	0.791	0.602	1.314	1.039	0.743	1.400
300	1.005	0.718	1.400	0.846	0.657	1.288	1.040	0.744	1.399
350	1.008	0.721	1.398	0.895	0.706	1.268	1.043	0.746	1.398
400	1.013	0.726	1.395	0.939	0.750	1.252	1.047	0.751	1.395
450	1.020	0.733	1.391	0.978	0.790	1.239	1.054	0.757	1.392
500	1.029	0.742	1.387	1.014	0.825	1.229	1.063	0.767	1.387
550	1.040	0.753	1.381	1.046	0.857	1.220	1.075	0.778	1.382
600	1.051	0.764	1.376	1.075	0.886	1.213	1.087	0.790	1.376
650	1.063	0.776	1.370	1.102	0.913	1.207	1.100	0.803	1.370
700	1.075	0.788	1.364	1.126	0.937	1.202	1.113	0.816	1.364
750	1.087	0.800	1.359	1.148	0.959	1.197	1.126	0.829	1.358
800	1.099	0.812	1.354	1.169	0.980	1.193	1.139	0.842	1.353
900	1.121	0.834	1.344	1.204	1.015	1.186	1.163	0.866	1.343
1000	1.142	0.855	1.336	1.234	1.045	1.181	1.185	0.888	1.335

TABLE A–17

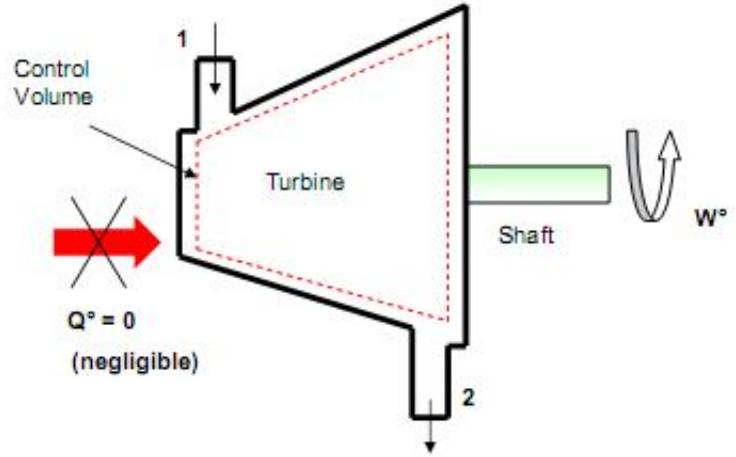
Ideal-gas properties of air

T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg · K	T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg · K
200	199.97	0.3363	142.56	1707.0	1.29559	580	586.04	14.38	419.55	115.7	2.37348
210	209.97	0.3987	149.69	1512.0	1.34444	590	596.52	15.31	427.15	110.6	2.39140
220	219.97	0.4690	156.82	1346.0	1.39105	600	607.02	16.28	434.78	105.8	2.40902
230	230.02	0.5477	164.00	1205.0	1.43557	610	617.53	17.30	442.42	101.2	2.42644
240	240.02	0.6355	171.13	1084.0	1.47824	620	628.07	18.36	450.09	96.92	2.44356
250	250.05	0.7329	178.28	979.0	1.51917	630	638.63	19.84	457.78	92.84	2.46048
260	260.09	0.8405	185.45	887.8	1.55848	640	649.22	20.64	465.50	88.99	2.47716
270	270.11	0.9590	192.60	808.0	1.59634	650	659.84	21.86	473.25	85.34	2.49364
280	280.13	1.0889	199.75	738.0	1.63279	660	670.47	23.13	481.01	81.89	2.50985
285	285.14	1.1584	203.33	706.1	1.65055	670	681.14	24.46	488.81	78.61	2.52589
290	290.16	1.2311	206.91	676.1	1.66802	680	691.82	25.85	496.62	75.50	2.54175
295	295.17	1.3068	210.49	647.9	1.68515	690	702.52	27.29	504.45	72.56	2.55731
298	298.18	1.3543	212.64	631.9	1.69528	700	713.27	28.80	512.33	69.76	2.57277
300	300.19	1.3860	214.07	621.2	1.70203	710	724.04	30.38	520.23	67.07	2.58810
305	305.22	1.4686	217.67	596.0	1.71865	720	734.82	32.02	528.14	64.53	2.60319
310	310.24	1.5546	221.25	572.3	1.73498	730	745.62	33.72	536.07	62.13	2.61803
315	315.27	1.6442	224.85	549.8	1.75106	740	756.44	35.50	544.02	59.82	2.63280
320	320.29	1.7375	228.42	528.6	1.76690	750	767.29	37.35	551.99	57.63	2.64737
325	325.31	1.8345	232.02	508.4	1.78249	760	778.18	39.27	560.01	55.54	2.66176
330	330.34	1.9352	235.61	489.4	1.79783	780	800.03	43.35	576.12	51.64	2.69013

The first law of thermodynamics for control volumes

Example

- Steam enters a turbine at steady state with a mass flow rate of 4600 kg/h. The turbine develops a power output of 1000 kW. At the inlet the pressure is 0.05 MPa, the temperature is 400°C, and the velocity is10 m/s. At the exit, the pressure is 10 kPa, the quality is 0.9, and the velocity is 50 m/s. Calculate the rate of heat transfer between the turbine and surroundings, in kW.



The first law of thermodynamics for control volumes

Example

- Nitrogen gas is compressed adiabatically in a compressor from 0.1Mpa,25^0C to 250^0C. If the mass flow rate is 0.2kg/s, determine the work done on the Nitrogen in kJ/kg. Assume nitrogen is ideal gas and use Cp=1.039kJ/kgk. What is the power input to the compressor.

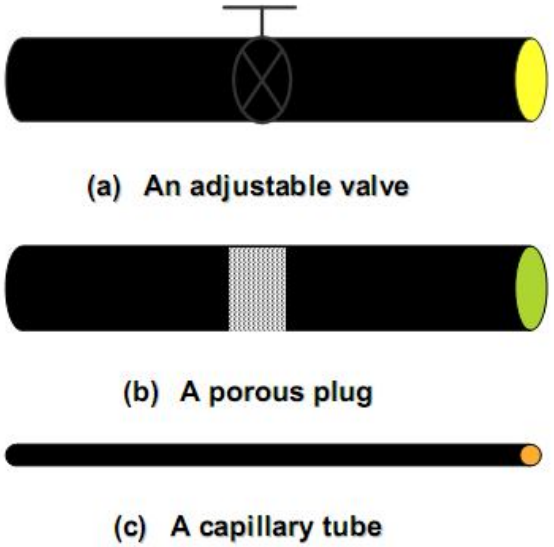
The first law of thermodynamics for control volumes

3. Throttling valves

- Throttling valves are any kind of flow-restricting devices that cause a significant **pressure drop in the fluid**.
- Some familiar examples are ordinary **adjustable valves**, **capillary tubes** and **porous plugs**.
- The pressure drop in the fluid is often accompanied by a **large drop in temperature**, and for that reason throttling devices are commonly used in **refrigeration** and **air-conditioning applications**.

The first law of thermodynamics for control volumes

- But in the case of an **ideal gas** h= h(T), and thus the temperature has to remain constant during a throttling process.



$$\dot{Q} \approx 0,\ \dot{W} = 0, \Delta h \neq 0,\ \Delta ke = 0,\ \Delta pe = 0$$

$$\cancel{q}^{0} - \cancel{w}^{0} = \Delta h + \cancel{\Delta ke}^{0} + \cancel{\Delta pe}^{0} \qquad (kJ/kg)$$

$$0 = \Delta h \qquad (kJ/kg)$$

$$h_2 \approx h_1 \qquad (kJ/kg)$$

The first law of thermodynamics for control volumes

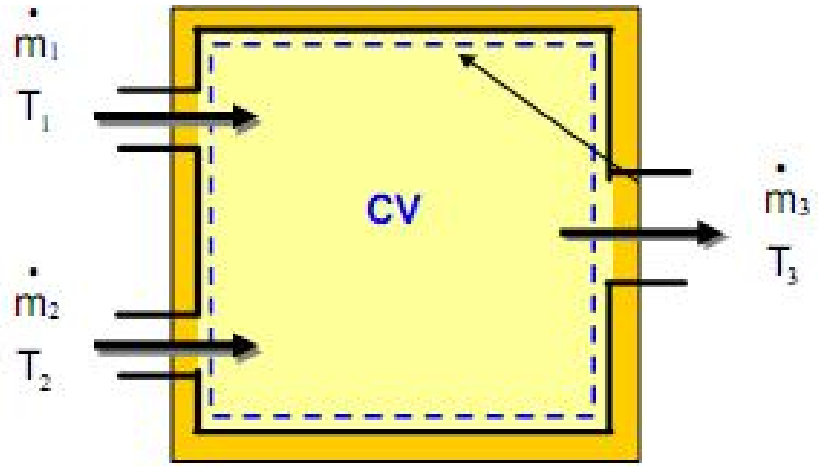
Example

- One way to determine the quality of saturated steam is to throttle the steam to a low enough pressure that it exists as a superheated vapor. Saturated steam at 0.4Mpa is throttled to 0.1Mpa, 100^0C. Determine the quality of the steam at 0.4Mpa.

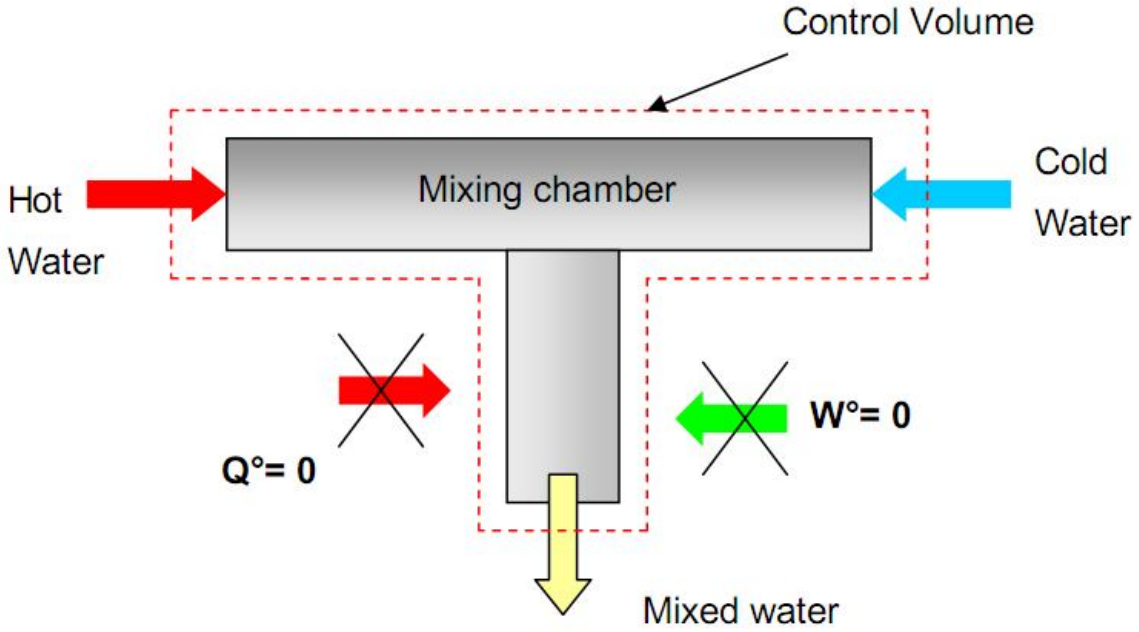
The first law of thermodynamics for control volumes

4. A-Mixture chambers

- In engineering applications, mixing two streams of fluids is not a rare occurrence.
- This section where the mixing process takes place is commonly referred to as a mixing chamber.
- An ordinary **T-elbow** or **y-elbow** in a shower, for example, serves as the mixing chamber for the cold-water and hot-water streams.



The first law of thermodynamics for control volumes



$$\cancel{\dot{Q}}^{0} - \cancel{\dot{W}}^{0} = \sum \dot{m}_e \left(h_e + \cancel{\frac{v_e^2}{2}}^{0} + \cancel{gz_e}^{0} \right) - \sum \dot{m}_i \left(h_i + \cancel{\frac{v_i^2}{2}}^{0} + \cancel{gz_i}^{0} \right)$$

For each exit — For each inlet

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

The first law of thermodynamics for control volumes

Example

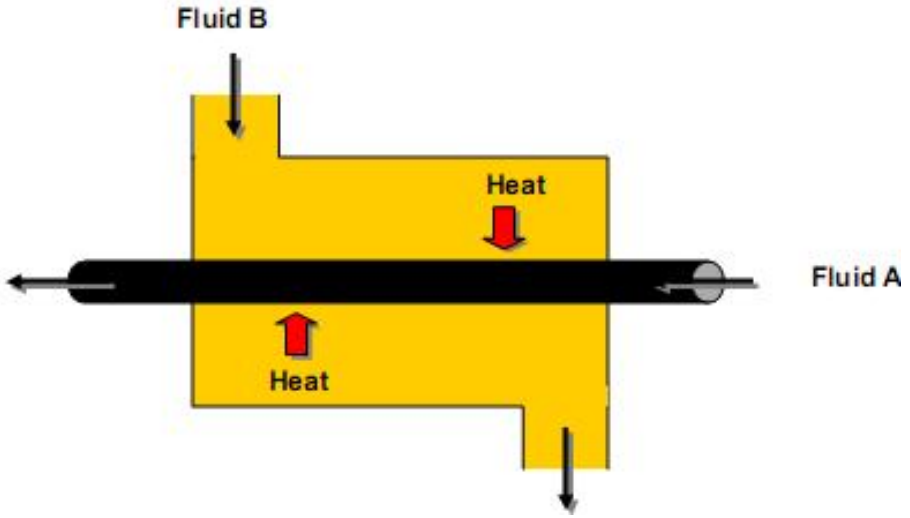
- Steam at 0.2 MPa, 300^{0}C, enters a mixing chamber and is mixed with cold water at 20^{0}C, 0.2 MPa, to produce 20 kg/s of saturated liquid water at 0.2 MPa. What are the required steam and cold water flow rates?



The first law of thermodynamics for control volumes

4. B. Heat exchangers

- Heat exchangers are devices where two moving fluid streams exchange heat without mixing.
- Heat exchangers are widely used in various industries, and they come in various designs.
- The simplest form of a heat exchanger is a double-tube (also called tube and shell) heat exchanger.



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- Under steady operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant.

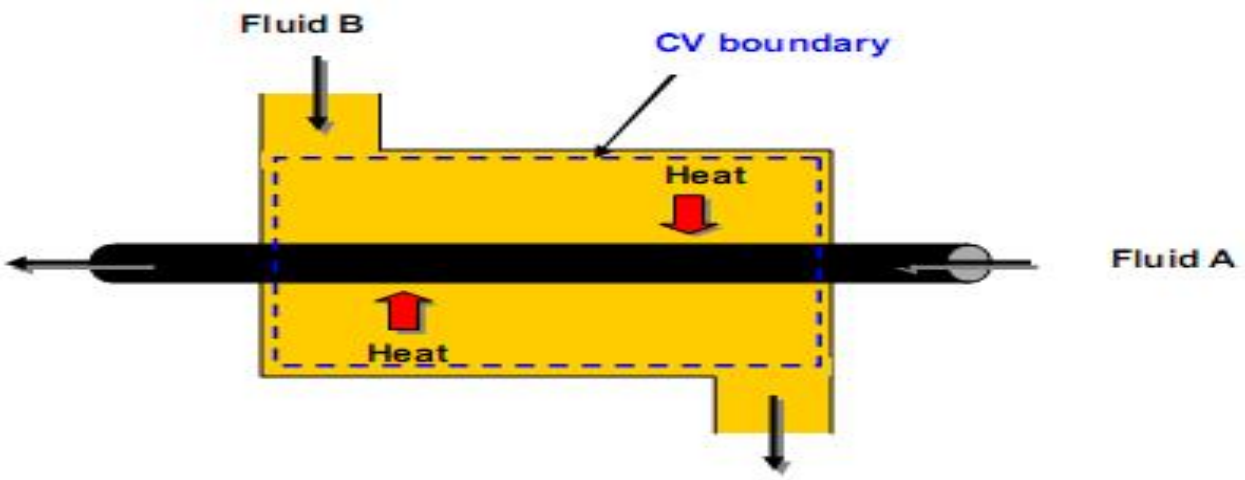
$$\dot{Q} \approx 0,\ \dot{W} = 0, \Delta h \neq 0,\ \Delta ke = 0,\ \Delta pe = 0$$

$$\dot{Q}^{\,0} - \dot{W}^{\,0} = \sum \dot{m}_e \left(h_e + \frac{v_e^{2\,0}}{2} + g z_e \right)^{0} - \sum \dot{m}_i \left(h_i + \frac{v_i^{2\,0}}{2} + g z_i \right)^{0}$$

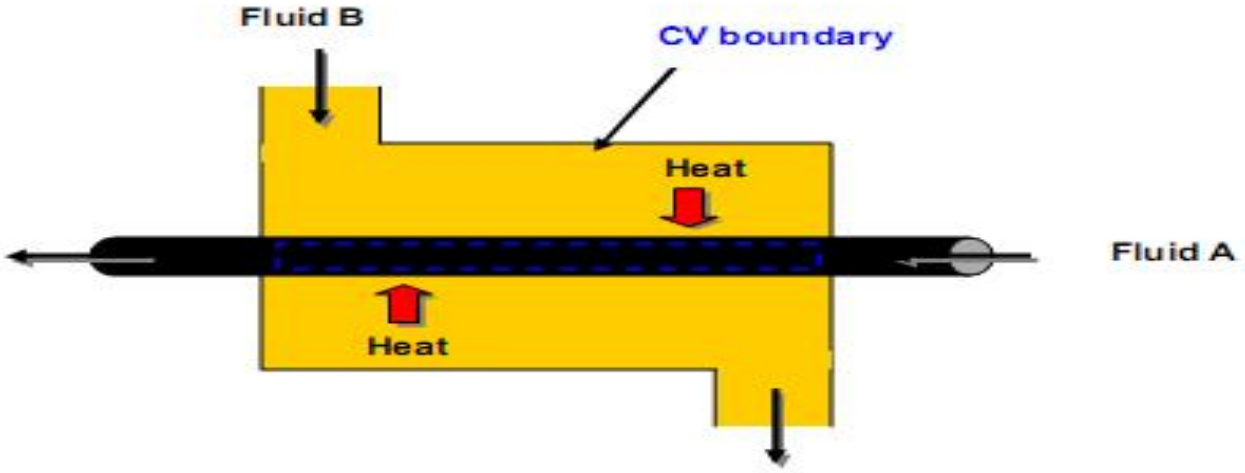
For each exit — For each inlet

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

The first law of thermodynamics for control volumes



(a) System: Entire heat exchanger ($Q_{CV}=0$)

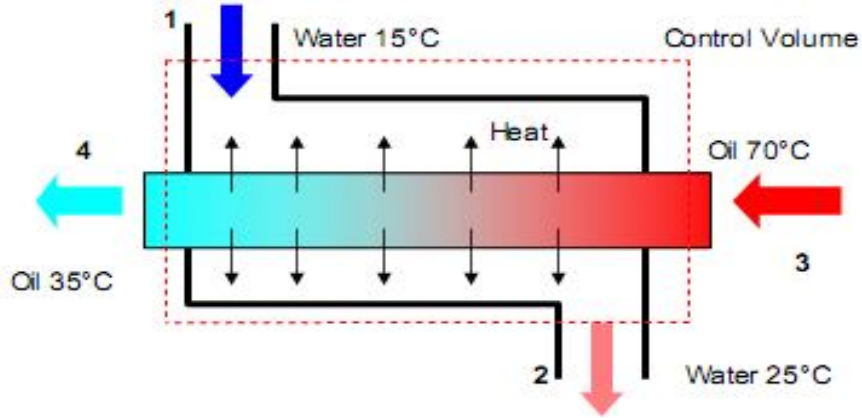


(b) System: Fluid A ($Q_{CV} \neq 0$)

The first law of thermodynamics for control volumes

Example

- Engine oil is to be cooled by water in a condenser. The engine oil enters the condenser with a mass flow rate of 6 kg/min at 1 MPa and 70°C and leaves at 35°C. The cooling water enters at 300 kPa and 15°C and leaves at 25°C. Neglecting any pressure drops; determine a) the mass flow rate of the cooling water required, and b) the heat transfer rate from the engine oil to water.



The first law of thermodynamics for control volumes

5. Pipe and duct flow

- The transport of liquids or gases in pipes and ducts is great importance in many engineering applications.
- Flow through a pipe or a duct usually satisfies the steady-flow conditions and thus can be analyzed as steady-flow process.

$$\dot{Q} \neq 0,\ \dot{W} \neq 0,\ \Delta h \neq 0,\ \Delta ke = 0,\ \Delta pe \neq 0$$



$$\dot{Q} - \dot{W} = \dot{m}[\Delta h + \cancel{\Delta ke}^{0} + \Delta pe] \qquad (kW)$$

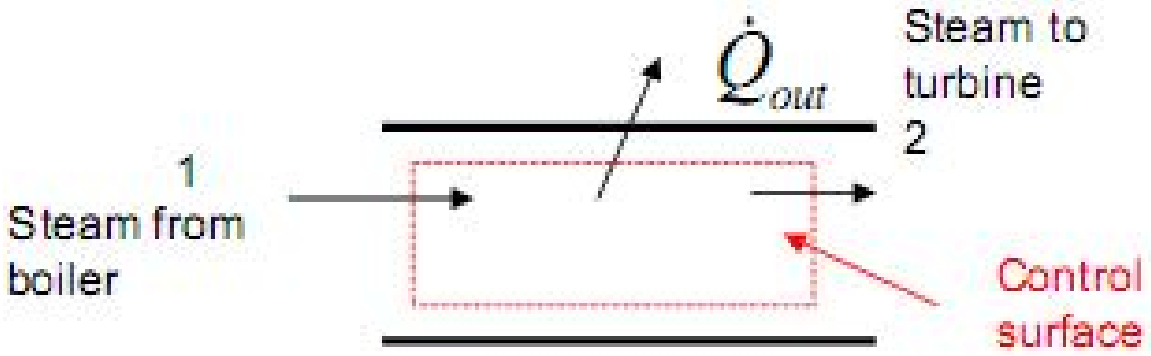
$$\dot{Q} - \dot{W} = \dot{m}[\Delta h + \Delta pe] \qquad (kW)$$

$$q - \dot{w} = \Delta h + \Delta pe \qquad (kJ/kg)$$

The first law of thermodynamics for control volumes

Example

- In a simple steam power plant, steam leaves a boiler at 3 MPa, 600^0C, and enters a turbine at 2 MPa, 500^0C. Determine the in-line heat transfer from the steam per kilogram mass flowing in the pipe between the boiler and the turbine.



The first law of thermodynamics for control volumes

Example

- Air at 100^0C, 0.15 MPa, 40 m/s, flows through a converging duct with a mass flow rate of 0.2 kg/s. The air leaves the duct at 0.1 MPa, 113.6 m/s. The exit-to-inlet duct area ratio is 0.5. Find the required rate of heat transfer to the air when no work is done by the air.

