Revision – Prerequisites for MA3010

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1^{st} Law of Thermodynamics

- Conservation of energy principle
  - Energy cannot be created nor destroyed; it can be converted/transferred from one form/body to another.

- Energy transfer mechanisms
  1. Heat
  2. Work

- Heat is energy transferred via temperature differences

- Work is energy transferred via physical means
  - E.g., moving boundary work

Recap: Nomenclature

Upper Case: Extensive Properties (total amount; dependent on mass)		$\div m$ / $\times m$	Lower Case: Intensive Properties (property per unit mass; independent of mass)
Q	Heat	q	Heat per unit mass
W	Work	w	Work per unit mass
U	Internal energy	u	Internal energy per unit mass; specific internal energy
H	Enthalpy: $H = U + PV$	h	Enthalpy per unit mass; specific enthalpy
V	Volume	v	Volume per unit mass; specific volume
E	Total energy	m	Mass
P	Pressure (intensive property)	c	Specific heat (for solids, liquids)
T	Temperature (intensive property)	c_p	Specific heat at constant pressure (for gases)
		c_v	Specific heat at constant volume (for gases)

For solids/liquids, $c_v = c_p = c$

For ideal gases, $u = c_v T$

$h = c_p T$

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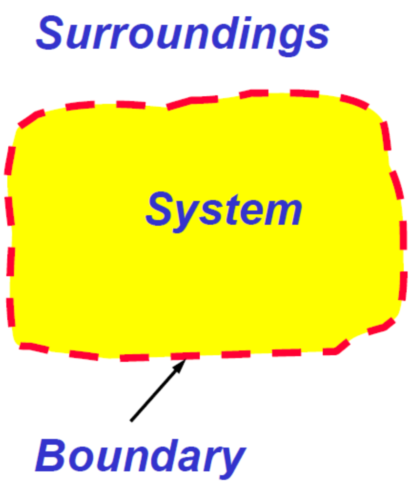
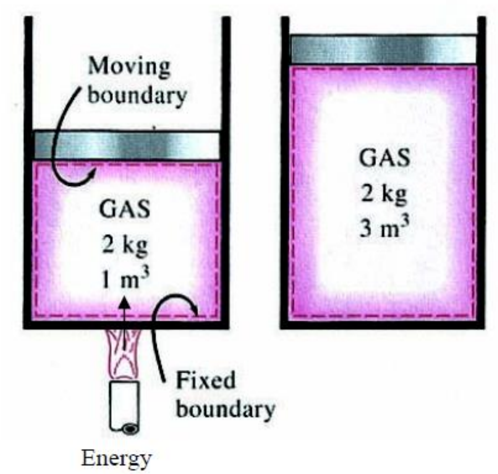
Recap: Systems



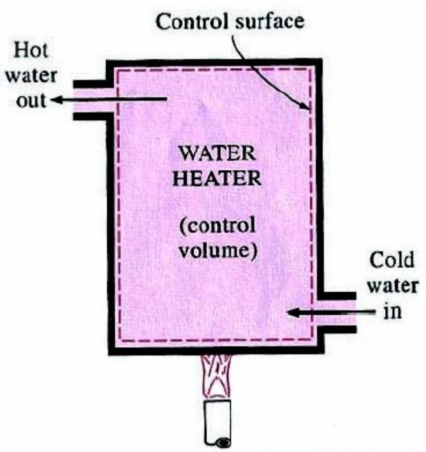
1. Closed Systems

- Fixed mass
- Energy can be transferred through boundary by heat or work
- Boundary can be movable



2. Flow Systems

- Conservation of mass



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Principles of Conservation

- Principle of conservation:
  change in property = amount entering – amount leaving

- Principle of conservation of mass: $\Delta m = m_{in} - m_{out}$

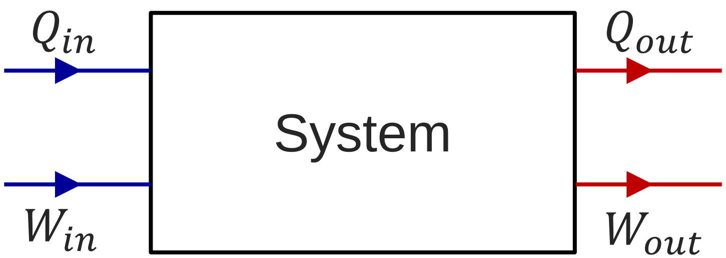
- Principle of conservation of energy: $\Delta E = E_{in} - E_{out}$

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

Closed Systems

- Since there are 2 mechanisms for energy transfer,

$$\Delta E_{sys} = \underbrace{Q_{in} - Q_{out}}_{\substack{\text{Energy transfer}\\ \text{by heat}}} + \underbrace{W_{in} - W_{out}}_{\substack{\text{Energy transfer}\\ \text{by work}}}$$



Sign convention:
heat/work into system = +ve

i.e., work done **on** system = **+ve**
work done ***by*** system = ***-ve***

- Conservation of energy for closed systems: $\Delta E_{sys} = Q - W$

Net heat transfer into system   Net work done by system

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

Moving Boundary Work

- Moving boundary work done ***by*** system: $W = \int_1^2 P\, dV$

If volume is constant, there is no moving boundary work done!

- Work done by system = system pushing against the boundary (volume increases, $V_2 > V_1$, W after integrating is +ve)

$$\Delta E_{sys} = Q - (+W)$$

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

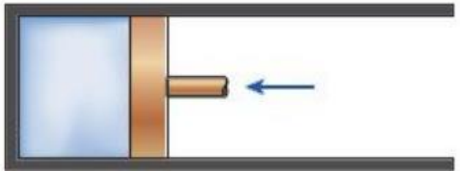
Negative since energy is lost by system

- Work done on system = boundary pushing against the system (volume decreases, $V_2 < V_1$, W after integrating is -ve)

$$\Delta E_{sys} = Q - (-W)$$

$$\Delta E_{sys} = Q + W$$

Positive since energy is gained by system



Closed Systems: U or H?

$$\Delta E = Q_{in} - Q_{out} + W_{in} - W_{out}$$

- E: total energy

$$E = U + K.E. + P.E.$$

It is always 'U' (internal energy)!

- If kinetic and potential energies are negligible,

$E = U$ -or- $\Delta E = \Delta U = m\Delta u$

- For solids & liquids: $\Delta U = mc\Delta T$

- For ideal gases: $\Delta U = mc_v\Delta T$

Closed Systems: Special Case

- A **constant pressure process** is a special case when 'H' appears.

$$\Delta E = \Delta U + \Delta K.E. + \Delta P.E. = Q_{in} - Q_{out} + W_{in} - W_{out}$$

A constant pressure process will have moving boundary work because its volume must change to keep the pressure, P, constant:

$$\rightarrow U_2 - U_1 + \Delta K.E. + \Delta P.E. = Q_{in} - Q_{out} - P(V_2 - V_1) + \underbrace{W_{in} - W_{out}}_{\text{Energy transfer by other types of work}}$$

Energy change due to moving boundary work

$$U_2 - U_1 + P(V_2 - V_1) + \Delta K.E. + \Delta P.E. = Q_{in} - Q_{out} + W_{in} - W_{out}$$

$$(U_2 + PV_2) - (U_1 + PV_1) + \Delta K.E. + \Delta P.E. = Q_{in} - Q_{out} + W_{in} - W_{out}$$

$$\because H = U + PV \quad \rightarrow H_2 - H_1 + \Delta K.E. + \Delta P.E. = Q_{in} - Q_{out} + W_{in} - W_{out}$$

Note: Moving boundary work terms have been removed from R.H.S. when U is converted to H

Flow Systems

- Additional mechanism of energy transfer via mass flow:

$$\Delta E_{CV} = \underbrace{Q_{in} - Q_{out}}_{\text{Energy transfer by heat}} + \underbrace{W_{in} - W_{out}}_{\text{Energy transfer by work}} + \underbrace{E_{in,m} - E_{out,m}}_{\text{Energy transfer by mass flow}}$$

Sign convention:
energy entering the CV = +ve

Note: $\Delta E_{CV} = \Delta U_{CV} + \Delta K.E. + \Delta P.E.$ *It is always 'U' (internal energy)!*

- Conservation of mass: $\Delta m_{CV} = m_i - m_o$

Flow Control Volume – Flow Work

- Flow work is required to maintain continuous flow through the CV; i.e. energy needed to push the fluid

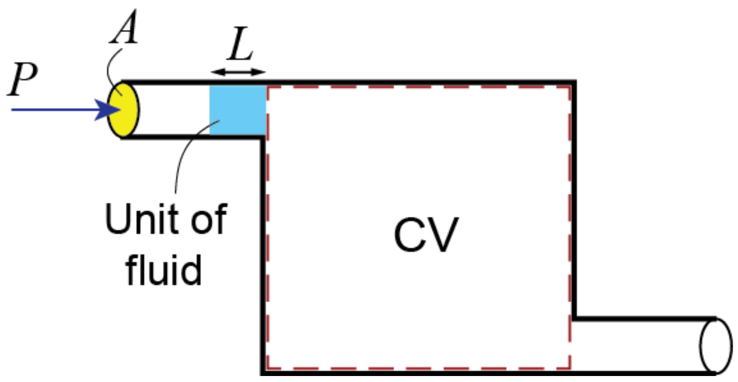
- Flow work is a property of the fluid flow: $W_{flow} = PV$

- Proof:

Force on fluid: $F = PA$

Flow work: $W_{flow} = FL$

$$= PAL = PV$$



- Flow work per unit mass: $w_{flow} = Pv$

Energy Transfer by Mass Flow

- Examining the energy transfer by mass flow:

$$E_{in,m} - E_{out,m} = \begin{array}{c}\text{Energy of fluid}\\ \text{entering CV}\end{array} - \begin{array}{c}\text{Energy of fluid}\\ \text{leaving CV}\end{array}$$

$$+ \begin{array}{c}\text{Flow work of}\\ \text{fluid entering CV}\end{array} - \begin{array}{c}\text{Flow work of}\\ \text{fluid leaving CV}\end{array}$$

$$E_{in,m} - E_{out,m} = m_{in}\left(u + \frac{v^2}{2} + gz\right)_{in} - m_{out}\left(u + \frac{v^2}{2} + gz\right)_{out}$$

$$+ m_{in}(Pv)_{in} - m_{out}(Pv)_{out}$$

$$E_{in,m} - E_{out,m} = m_{in}\left[(u + Pv) + \frac{v^2}{2} + gz\right]_{in} - m_{out}\left[(u + Pv) + \frac{v^2}{2} + gz\right]_{out}$$

$$= m_{in}\left(h + \frac{v^2}{2} + gz\right)_{in} - m_{out}\left(h + \frac{v^2}{2} + gz\right)_{out}$$

Energy Transfer by Mass Flow – Enthalpy

$$\dot{E}_{in,m} - \dot{E}_{out,m} = \dot{m}_{in}\left(h + \frac{v^2}{2} + gz\right)_{in} - \dot{m}_{out}\left(h + \frac{v^2}{2} + gz\right)_{out}$$

Due to the addition of flow work, the energy term of fluid leaving or entering the CV is transformed to enthalpy.

- If K.E. and P.E. are negligible:

$$\dot{E}_{in,m} - \dot{E}_{out,m} = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out}$$

Flow Control Volume – Energy Equations

- If there are multiple inlets and outlets, and assuming negligible K.E. and P.E. terms,

$$\dot{E}_{CV} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} + \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out}$$

- Steady state, steady flow*:

$$0 = \dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} + \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out}$$

- Steady state, steady flow with single inlet and outlet:

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} + \dot{m} h_{in} - \dot{m} h_{out} = 0$$

Rearranging:

$$\dot{m}_{out} h_{out} - \dot{m}_{in} h_{in} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out}$$

Property Tables

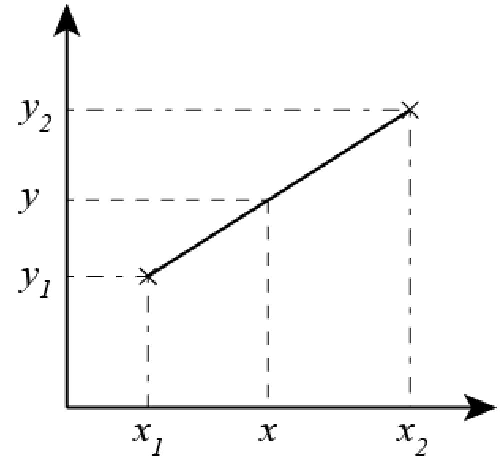
- Very useful for obtaining values for desired intensive properties such as specific volume, specific internal energy and specific enthalpy

- Applicable to both liquids and gases
- Provides the most accurate property values for gases
  - Always use property tables if available

- Commonly used tables:
  - Superheated tables – for vapour state
  - Saturation tables – for boiling/condensation

Linear Interpolation

- Desired values are usually not listed explicitly in the tables
  - Need to use linear interpolation:



Constant gradient:

$$\frac{y_2 - y_1}{x_2 - x_1} = \frac{y - y_1}{x - x_1}$$

-or-

Proportionality:

$$\frac{x - x_1}{x_2 - x_1} = \frac{y - y_1}{y_2 - y_1}$$

E.g. Specific volume of superheated water at 1 MPa and 270 °C:

$$\frac{300 - 250}{0.25799 - 0.23275} = \frac{270 - 250}{v - 0.2375}$$

$$\frac{v - 0.2375}{0.02524} = \frac{20}{50}$$

$$v = 0.24285\, m^3/kg$$

Check: the value should be between 0.23275 and 0.25799.

Superheated water (*Continued*)

T °C	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg · K
	P = 1.00 MPa (179.88°C)			
Sat.	0.19437	2582.8	2777.1	6.5850
200	0.20602	2622.3	2828.3	6.6956
250	0.23275	2710.4	2943.1	6.9265
300	0.25799	2793.7	3051.6	7.1246
350	0.28250	2875.7	3158.2	7.3029

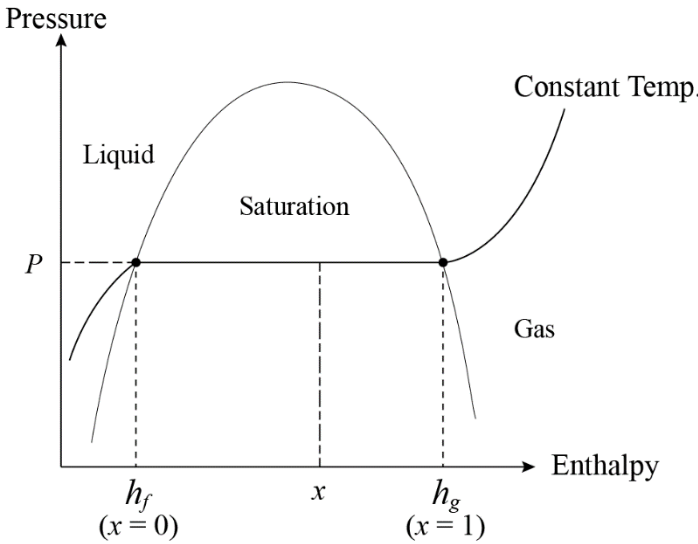
Saturation Tables

- Vapour fraction 'x' required to determine mixture properties during a phase-change process

$$v_{mix} = v_f + x(v_g - v_f)$$

$$u_{mix} = u_f + x(u_g - u_f) = u_f + xu_{fg}$$

$$h_{mix} = h_f + x(h_g - h_f) = h_f + xh_{fg}$$



Use the appropriate saturation tables (pressure or temperature), may require interpolation.

Saturated water—Pressure table

		Specific volume, m^3/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg			*Entropy,* kJ/kg · K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071

Ideal Gas Equations

- Ideal gas assumption:
  - Gas particles do not occupy any volume (an ideal gas can be compressed to zero volume)
  - No intermolecular forces of attraction & elastic collisions

Specific gas constant: $R_{sp} = \dfrac{R_u}{M}$

Universal gas constant: $R_u = 8.3145 \text{ J mol}^{-1} \text{ K}^{-1}$

Ideal gas equations:

$$Pv = R_{sp}T$$

$$PV = mR_{sp}T$$

$$PV = nR_uT$$

$$u = c_vT$$

$$h = c_pT$$

$$k = c_p/c_v$$

$$R_{sp} = c_p - c_v$$

Note: Units for temperature 'T' in Kelvin only!