Thermodynamics 1

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Mech Family

Notebooks

Notes

1. $v = \frac{1}{\rho}$ ⇒ Specific volume $= \frac{1}{\text{Density}}$
2. Thermal equilibrium ⇒ No change in temperature throughout the entire system.
3. Mechanical equilibrium ⇒ No change in pressure at any point of the system with time.
4. We need two independent and intensive properities to define the state of a system. (Simple compressible system)
5. Isothermal process ⇒ constant temperature.
6. Isobaric process ⇒ constant pressure.
7. Isochoric (Isometric) process ⇒ constant specific volume.
8. * Steady ⇒ No change with time.
   * Uniform ⇒ No change with location.
9. Staitionary system ⇒ $\Delta E = \Delta U$
10. The mass flow rate $(\dot{m}) = \rho \dot{V} = \rho A_c V_{avg}$
11. Adiabatic process ⇒ No heat transfer.
12. $W_{shaft} = 2\pi n T$
13. $W_{spring} = \frac{1}{2} K (x_2^2 - x_1^2)$ ⇒ $F = kx$
14. * Heat transfer to a system and work done by a system are positive (+).
    * Heat transfer from a system and work done on a system are negative (−).

[15] Enthalpy (H) = $U + PV$

[16] The properties of saturated liquid and saturated vapor for water are listed in tables:

* A-4 ⟶ under temperature
* A-5 ⟶ under pressure

[17] The subscript 'f' is used to denote properties of a saturated liquid, and the subscript 'g' to denote properties of a saturated vapor.

[18] Enthalpy of vaporization (h_{fg}) ⟹ amount of energy needed to vaporize a unit mass of saturated liquid at a given mass.

[19] Quality (x) ⟹ $x = \frac{m_{vapor}}{m_{total}}$

$x = 0$ ⟶ 100% sat. liquid

$x = 1$ ⟶ 100% sat. vapor

[20]
* $u_{avg} = u_f + x u_{fg}$
* $h_{avg} = h_f + x u_{fg}$
* $v = v_f + x v_{fg}$

$\lambda_{fg} = \lambda_g - \lambda_f$

λ : any property

[21] We treat compressed liquid as saturated liquid at the given temperature.

[22] Ideal-gas Relation ⟹
* $PV = mRT \Rightarrow P_v = RT$
* $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$

23 Interpolation Formula:

$$y = y_1 + (x - x_1) \left| \left(\frac{y_2 - y_1}{x_2 - x_1} \right) \right|$$

24 Sea level ⟶ $P = 101.325$ kpa $= 1$ atm

25 1 liter $= 0.001\ m^3$

26 $\dot{Q} = \dot{m}_{evaporation} \cdot \Delta h$

27 Pressure $(P) = \frac{F}{A}$

28 For "ideal gas" problems, apply the gas relation for all parts of the system separately once and then for the entire system.

29 W
- Rigid container ⟶ $= 0$
- Constant pressure ⟶ $= P(V_2 - V_1)$
- polytropic process ⟶ $n \neq 1$ ⟶ $W = \frac{mR(T_2 - T_1)}{1 - n}$
  - $n = 1$ ⟶ $W = PV \ln\left(\frac{V_2}{V_1}\right)$
- Area under curve

30 Conservation of energy principle

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

31 $Q = \dot{Q}\Delta t$, $W = \dot{W}\Delta t$, $\Delta E = \frac{dE}{dt}\Delta t$

32 For a stationary system ⟹ $Q - W = \Delta U$

33 * C_v ⟶ the change in the internal energy of a substance per unit change in temperature at constant volume.

* C_p ⟶ the change in the enthalpy of a substance per unit change in temperature at constant pressure.

34

* $h = u + P$
* $Pv = RT$

$\Rightarrow h = u + RT$ (For ideal gases)

35

* $u = c_v (T_2 - T_1)$
* $h = c_p (T_2 - T_1)$

$\Rightarrow$ (For ideal gases)

36 Solving Thermodynamics Problems.

1) Summarize given data in own words.
2) Clearly understand what is being asked for.
3) Identify all states and sketch a P-V or T-V diagram.

Thermodynamics '1'

* CHAPTER 1: Introduction and Basic Concepts

⇒ 1.1: Thermodynamics and Energy:

* Thermodynamics → the science of energy
  - Therme : heat
  - Dynamics: power
  - Energy and Energy Transformations:
    - Power Generation
    - Relationships among the properties of matter
    - Refrigeration

* Conservation of Energy Principle: [1st Law of Thermodynamics]

  ⇒ Energy cannot be created or destroyed, but changes from one form to another.

* Change in Energy:

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

* Energy is a thermodynamic property.

* Energy has **quality** as well as **quantity**, and actual processes occur in the direction of the decreasing quality of energy.

[2nd Law of Thermodynamics]

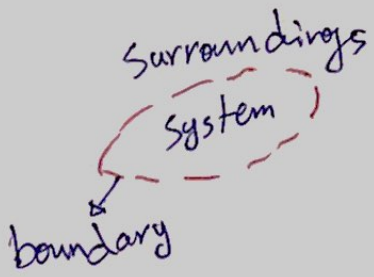
1.2: Importance of Dimensions and Units:

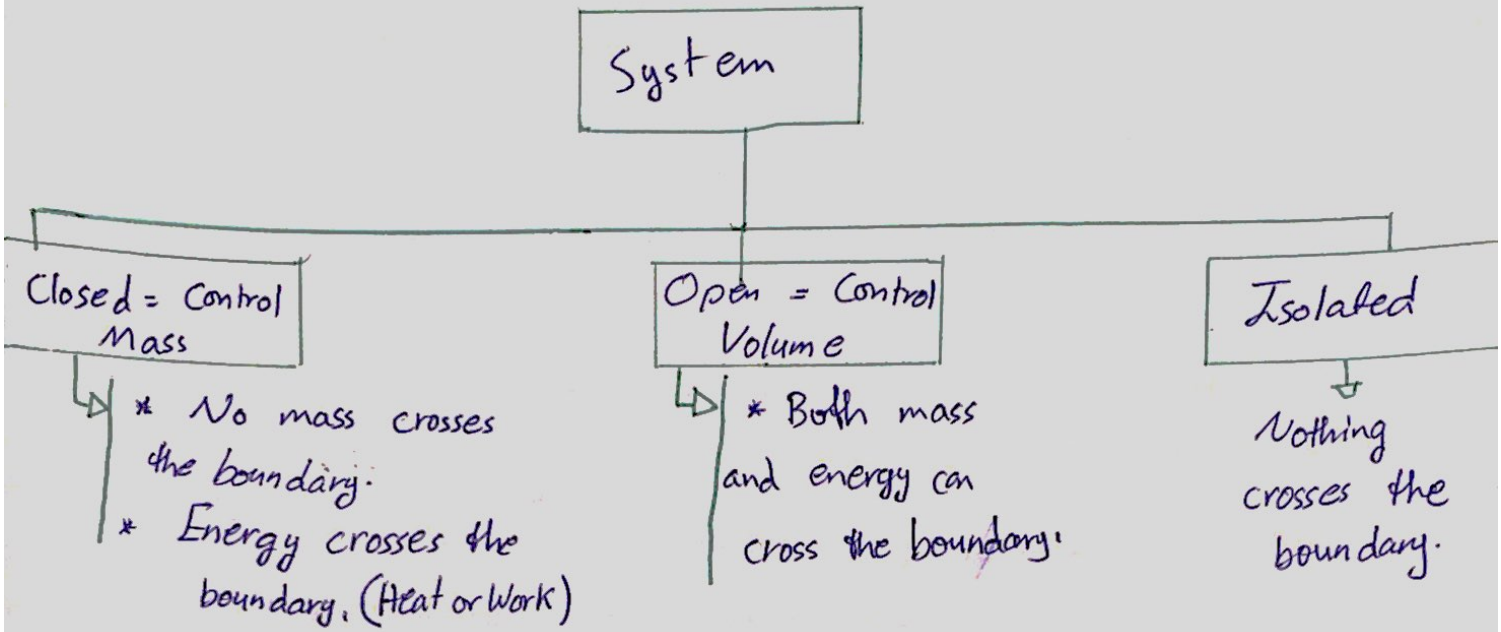
* Fundamental Units:-

Dimension	Unit
Length	m
Mass	kg
Time	s
Temperature	K
Electric Current	A
Amount of Light	cd
Amount of Matter	mol

1.3: Systems and Control Volumes:

* A **system** is defined as a quantity of matter or a region is space to study.
* The mass or region outside the system is called the **surroundings**.
* The **boundary** is the real or imaginary surface that separates the system from its surroundings.





* The boundaries of a control volume are called a **control surface**, and they can be real or imaginary.

⇒ 1.4: Properties of a System:

* Types of properties:
  1) **Extensive properties** → Vary directly with the mass.
     (Ex: Mass, Volume, Momentum, Energy, --- etc.)
  2) **Intensive properties** → Independent of the amount of mass.
     (Ex: Temperature, Pressure, Density, --- etc.)
* **Specific Properties** are extensive properties per unit mass. [Ex: Specific Volume → $v = \frac{V}{m}$]
* Generally, upper case letters are used to denote extensive properties (m is an exception), and lower case letters are used for intensive properties (P, T are the exceptions).

1.5: Density and Specific Gravity

* **Density** is defined as mass per unit volume.

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

* $$v = \frac{V}{m} = \frac{1}{\rho}$$ → The reciprocal of density is the specific volume (v).
* The density of a substance generally depends on temperature and pressure.
* $\rho_{gases} \propto P$, $\rho_{gases} \propto \frac{1}{T}$
* The variation of liquids and solids density with pressure is usually negligible.
* **Specific gravity (or relative density)** is defined as the ratio of the density of a substance to the density of some standard substance at a specified temperature.

$$\Rightarrow SG = \frac{\rho}{\rho_{substance}}$$

* **Specific weight** is defined as the weight of a unit volume of a substance.

$$\Rightarrow \gamma_s = \rho g \ (N/m^3)$$

* 'g' is the gravitational acceleration.

1.6: State and Equilibrium:

* Thermodynamics deals with equilibrium states.
* **Equilibrium** is a state of balance where there are no driving forces.
* A system isn't in thermodynamic equilibrium unless the conditions of all the relevant types of equilibrium are satisfied.
  * **Thermal equilibrium** → No change in temperature throughout the entire system.
  * **Mechanical equilibrium** → No change in pressure at any point of the system with time.
  * **Phase equilibrium** → When the mass of each phase of a two-phase system reaches an equilibrium level and stays there.
  * **Chemical equilibrium** → No chemical reactions occur.
* Specifying a certain number of properties is sufficient to fix a state.
* **The state postulate** gives the number of properties required to fix the state of a system.

⇒ The state of a simple compressible system is completely specified by two independent, intensive properties.

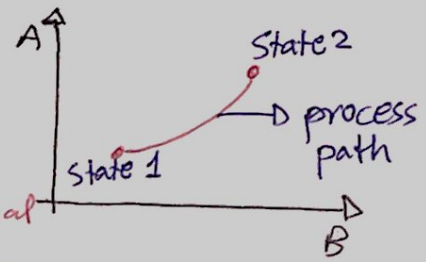
* Simple compressible system → No electrical, magnetic, gravitational, motion, and surface tension effects.

1.7: Processes and Cycles:

* A **process** is any change that a system undergoes from one equilibrium state to another.

* The series of states through which a system passes during a process is called the process **path.**

* A **quasi-static (quasi-equilibrium) process** is a process during which the system deviates from equilibrium by an infinitessimal amount. It is sufficiently slow which allows the system to adjust itself internally so that properties in one part of the system do not change any faster than those at other parts.



* A quasi-equilibrium process is an idealized process and is not a true representation of an actual process.

* The prefix "iso-" is used to designate a process for which a particular property remains constant.

Ex:
* **Iso thermal process** → constant temperature
* **Iso baric process** → constant pressure
* **Iso choric (Isometric) process** → constant specific volume

* A system is said to have undergone a cycle if it returns to its initial state at the end of the process.

* **Steady** → No change with time
* **Uniform** → No change with location
* The **steady-flow process** is a process during which a fluid flows through a control volume steadily.
* During a steady-flow process, fluid properties (V, m, etc.) within the control volume may change with position but not with time.

⇒ 1.8: Temperature and the Zeroth Law of Thermodynamics:

* **The zeroth law of thermodynamics** states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.

* CHAPTER 2: Energy, Energy Transfer, and General Analysis.

* 2.2: Forms of Energy:

=▷ Total Energy (E) is the sum of all the forms in which energy exists in a certain system. (Such as: thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear forms) → [$e = \frac{E}{m}$ (kJ/kg)]

* Total Energy
  - ▷ Macroscopic Forms are those a system possesses as a whole with respect to some outside reference frame. (Such as kinetic and potential energies.)
  - ▷ Microscopic Forms are those related to the molecular structure of a system and the degree of molecular activity, and they are independent of outside reference frames.

=▷ Internal Energy (U) is the sum of all the microscopic forms of energy.

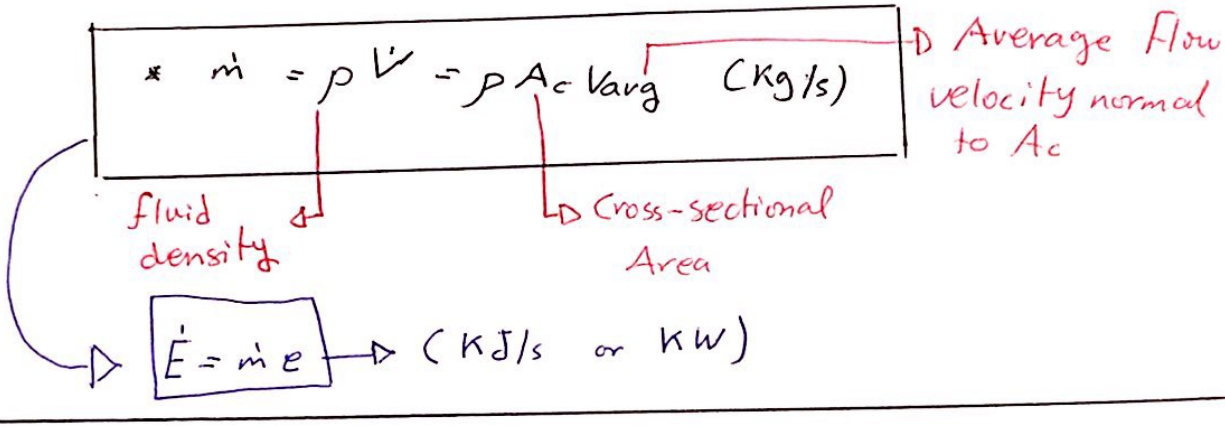
=▷ Kinetic Energy (KE) is the energy that a system possesses as a result of its motion relative to some reference frame. → [$KE = m\frac{V^2}{2}$ (kJ) → $ke = \frac{V^2}{2}$ (kJ/kg)]

=▷ Potential Energy (PE) is the energy that a system possesses as a result of its elevation in a gravitational field. → [$PE = mgh$ (kJ) → $pe = gh$ (kJ/kg)]

⇒ Staitonary Systems: are closed systems whose velocity and elevation of the center of gravity remain constant during a process. ($\Delta E = \Delta U$)

⇒ The Mass Flow Rate ($\dot{m}$) is the amount of mass flowing through a cross section per unit time.

⇒ The Volume Flow Rate ($\dot{V}$) is the volume of a fluid flowing through a cross section per unit time.



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* Internal Energy
  - Sensible Energy → associated with the kinetic energies of the molecules.
  - Latent Energy → associated with the phase of a system.
    * A system in the gas phase is at higher latent energy level than it is in the solid or liquid phase.
  - Chemical Energy → associated with the atomic bonds in a molecule.
  - Nuclear Energy → associated with the strong bonds within the nucleus of the atom itself.

⇒ Forms of Energy: ⇒ Static → stored in a system.
⇒ Dynamic → represent energy interactions.

⇒ The only two forms of energy interactions associated with a closed system are heat transfer and work.

⇒ Thermal energy = latent energy and sensible energy.

⇒ Mechanical energy ⇒ form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device.

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*2.3: Energy Transfer by Heat.

⇒ Heat(Q) is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.

⇒ An adiabatic process is one during which there is no heat transfer.

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*2.4: Energy Transfer by Work.

⇒ Work (W) is the energy transfer associated with a force acting through a distance.

⇒ Power ($\dot{W}$) is the work done per unit time.

⇒ Heat and work are directional quantities.

* Heat transfer to a system and work done by a system are positive.

* Heat transfer from a system and work done on a system are negative.

*2.5: Mechanical Forms of Work.

⇒ Work (W) = $F s = \int_1^2 F\,ds$ (KJ)

- $F s$: constant force.
- $\int_1^2 F\,ds$: Not constant.

⇒ Requirements for a work interaction between a system and its surroundings to exist:

1) There must be a force acting on the boundary.

2) The boundary must move.

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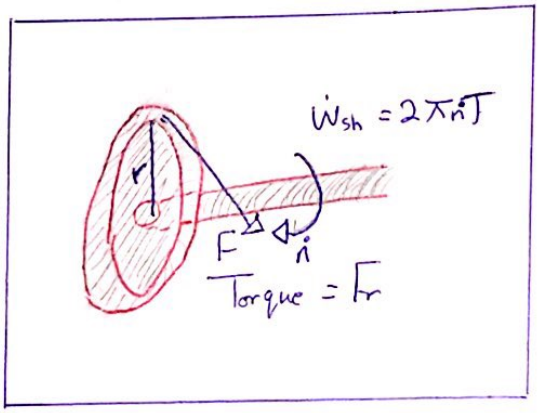
* Forms of Mechanical Work:

1 Shaft Work:

⇒ $T = Fr$, $s = 2\pi r n$

⇒ $W_{sh} = F s = \left(\frac{T}{r}\right) \cdot (2\pi r n)$

⇒ $\boxed{W_{sh} = 2\pi n T}$ (KJ)



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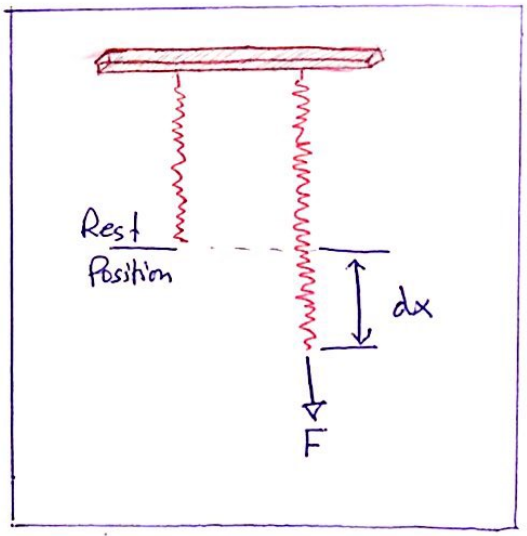
2 Spring Work:

⇒ $\delta W_{spring} = F\,dx$,

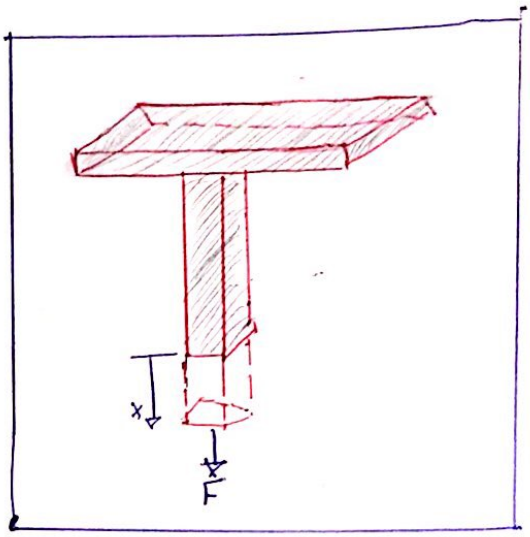
$F = Kx$ (KN)

⇒ $W_{spring} = \boxed{\frac{1}{2} K \left(x_2^2 - x_1^2\right) (KJ)}$

* 'K' is the spring constant



[3] Work Done on Elastic Solid Bars:



⇒ As long as F is in the elastic range,

$$W_{elastic} = \int_1^2 F\,dx = \int \sigma_n A\,dx \quad (kJ)$$

* $\sigma_n = \frac{F}{A}$ ⇒ normal stress

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[4] Work Associated with the Stretching of a Liquid Film.

⇒ $$W_{surface} = \int_1^2 \sigma_s\,dA \quad (kJ)$$

* σ_s = surface tension

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[5] Work Done to Raise or to Accelerate a Body.

⇒ * The work transfer needed to raise a body is equal to the change in the potential energy of the body.

* The work needed to accelerate a body is equal to the change in kinetic energy of the body.

*2.6: The First Law of Thermodynamics

⇒ The first law states that for all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.

* Mechanisms of Energy Transfer:

1 Heat Transfer "Q":

⇒
* Heat gain increases the energy of molecules and thus the internal energy of the system.
* Heat loss decreases the energy of molecules and thus the internal energy of the system.

2 Work Transfer "W":

⇒
* Work done on the system increases the energy of the system.
* Work done by the system decreases the energy of the system.

3 Mass Flow "m":

⇒ When mass enters a system, the energy of the system increases because mass carries energy with it.

* 2.7: Energy Conversion Efficiencies:

=▷ $$\text{Efficiency} = \frac{\text{Desired output}}{\text{Required output}}$$

=▷ The efficiency of equipment that involves the combustion of a fuel is based on the heating value of the fuel, which is the amount of heat released when a unit amount of fuel at room temperature is completely burned and the combustion products are cooled to the room temperature.

=▷ $$\text{Combustion Efficiency}(\eta) = \frac{Q}{HV} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

=▷ Most fuels contain hydrogen, which forms water when burned.

* LHV ⟶ lower heating value ⟶ water leaves as a vapor.
* HHV ⟶ higher heating value ⟶ water in the combustion gases completely condensed.

=▷ $$\eta_{overall} = \eta_{combustion}\,\eta_{thermal}\,\eta_{generator} = \frac{\dot{W}_{net,electric}}{HHV \times \dot{m}_{fuel}}$$

* Generator Effeciency ⟶ the ratio of the electrical power output to the mechanical power input.

* Thermal Effeciency ⟶ the ratio of the net shaft work output of the turbine to the heat input to the working fluid.

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* Efficiencies of Mechanical and Electrical Devices:

⇒ $$\eta_{mech} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{mech,out}}{E_{mech,in}} = 1 - \frac{E_{mech,loss}}{E_{mech,in}}$$

⇒ $$\eta_{pump} = \frac{\text{Mechanical energy increase of the fluid}}{\text{Mechanical energy output}} = \frac{\Delta \dot{E}_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{W}_{pump,}}{\dot{W}_{pump}}$$

⇒ $$\eta_{turbine} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decrease of the fluid}} = \frac{\dot{W}_{shaft,out}}{|\Delta \dot{E}_{mech,fluid}|} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine,e}}$$

CHAPTER 3: Properties of Pure Substances

* A pure substance is one that has a fixed chemical composition throughout.

* 3.2: Phases of a Pure Substance

* Solid ⟶
  * Molecules are arranged in a three-dimensional pattern that is repeated throughout.
  * Strongest intermolecular bonds.
  * Molecules oscillate about their equilibrium positions.
* Liquid ⟶
  * Molecules can rotate and translate freely.
  * Intermolecular forces are weaker relative to solids, but still relatively strong compared with gases.
* Gas ⟶
  * Molecules are far apart apart from each other.
  * No molecular order.
  * Very small intermolecular forces.
  * Higher energy level.

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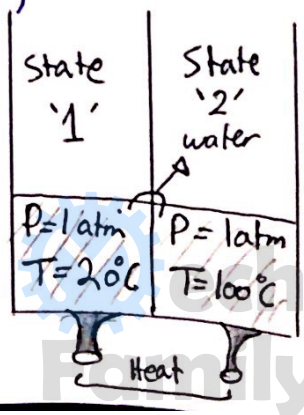
* 3.3: Phase-change Processes of Pure Substances

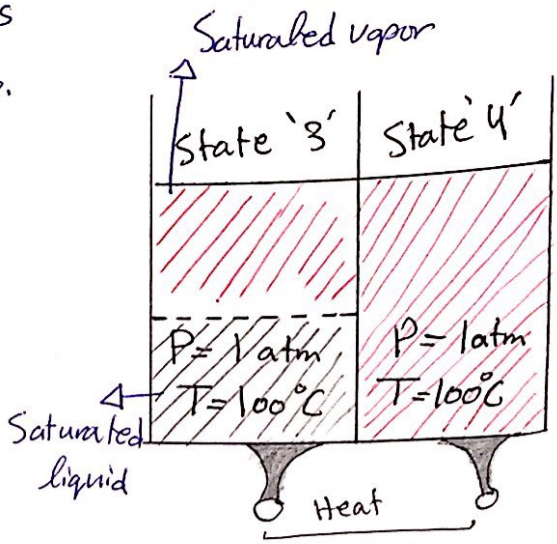
* Compressed Liquid = Subcooled Liquid ⟶ water exists in the liquid phase and isn't about to evaporate. (State '1')
* Saturated Liquid ⟶
  * Water is about to evaporate
  * Any heat addition will cause some water to evaporate. (State '2')



* Saturated vapor → A vapor that is about to condense. (State '4')

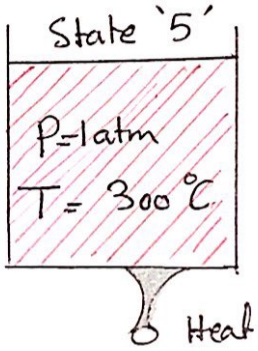
* Saturated liquid - vapor mixture

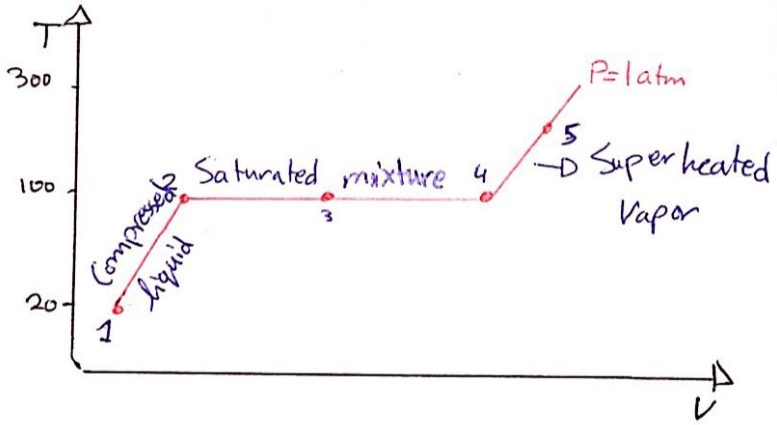
→ both liquid and vapor phases coexist. (State '3')



* Superheated vapor

→ A vapor that is not abc to condense. (State '5')





⇒ The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.

⇒ Saturation temperature (T_{sat}) → the temperature at which a pure substance changes phase (At a given pressure).

⇒ Saturation pressure (P_{sat}) → the pressure at which a pure substance changes phase (At a given temperature).

* Latent heat → the amount of energy absorbed or released during a phase-change process.
  - → latent heat of fusion → amount of energy absorbed during melting.
  - → latent heat of vaporization → amount of energy absorbed during vaporization

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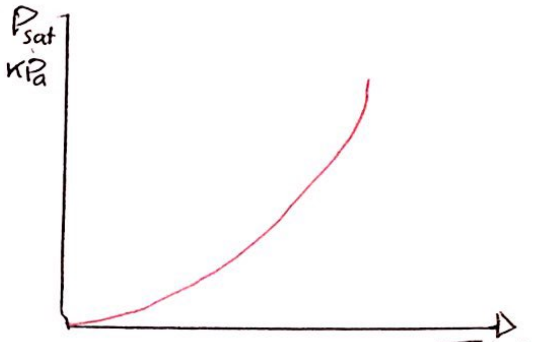
* $T_{sat} = f(P_{sat})$
* Liquid-vapor saturation curve
  → A T_{sat} vs P_{sat} plot.



⇓

liquid-vapor saturation curve of a pure substance

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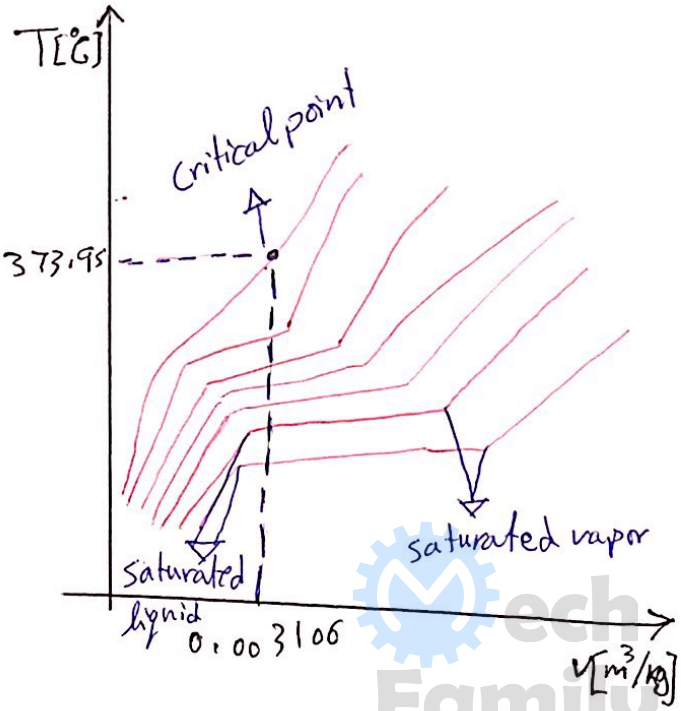
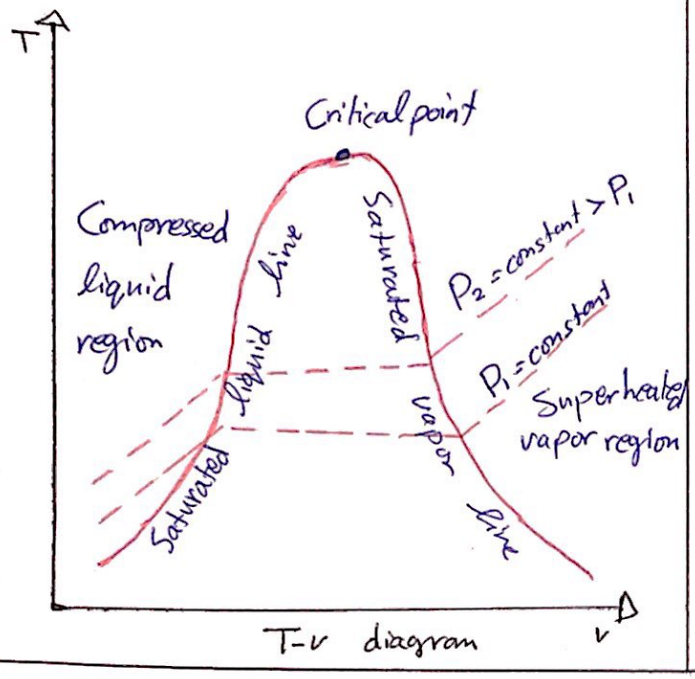
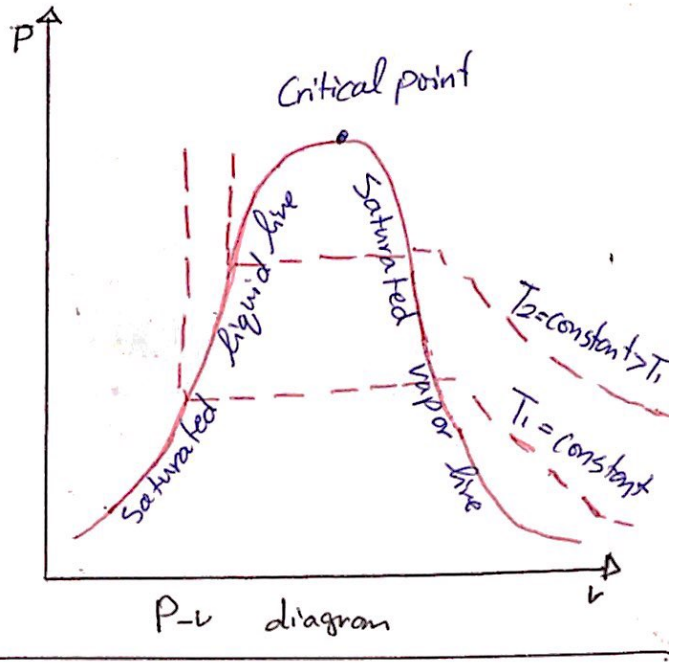
*3.4: Property Diagrams for Phase-change Processes

[1] The T-v Diagram:

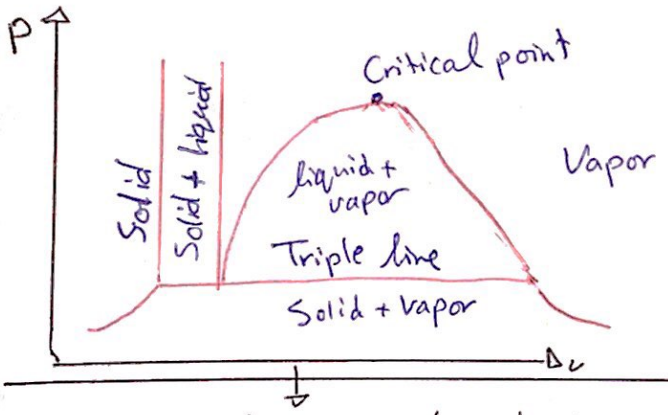
* Critical point → the point at which the saturated liquid and saturated vapor states coexist.



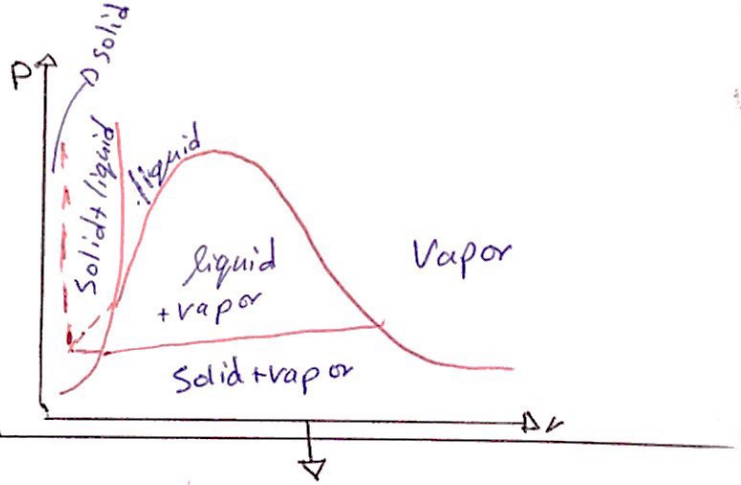




2 The P-v Diagram:



a substance that contracts on freezing

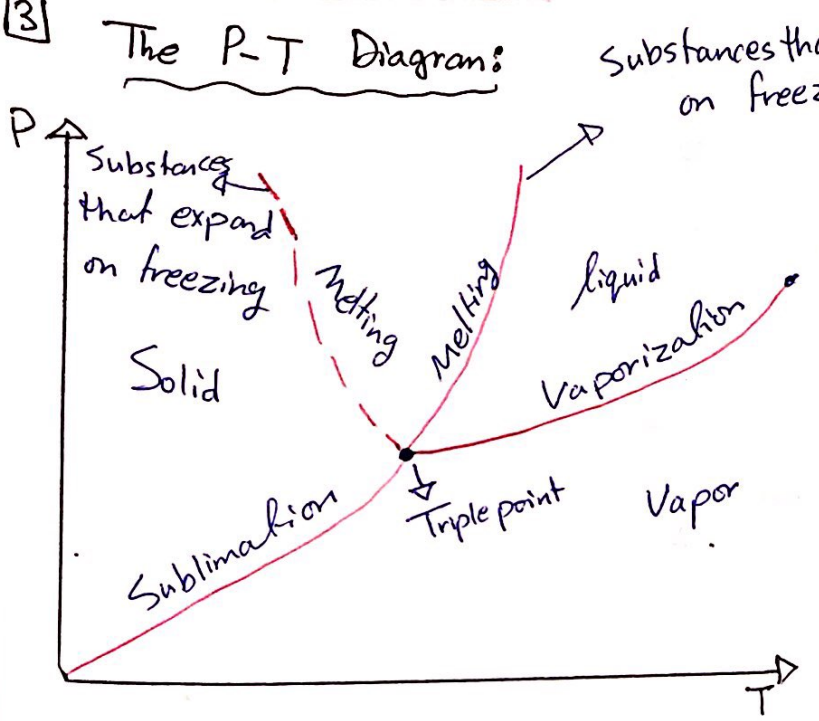


a substance that expands on freezing

* Triple line ⟶ 3 phases (vapor, liquid, solid)
  ↳ = Triple point
* There are two ways a substance can pass from the solid to vapor phase:
  1) solid ⟶ liquid ⟶ vapor
  2) Sublimation ⟹ solid ⟶ vapor
     ↓
     (Substances with triple point pressure above the atmospheric pressure).

3

The P-T Diagram:



⇒ T-t diagram = phase diagram.

⇒
* The sublimation line separates the solid and vapor regions.
* The vaporization line separates the liquid and vapor regions.
* The melting line separates the solid and liquid lines.

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* 3.5: Property Tables

* Enthalpy (H) ⟶ * a thermodynamic quantity equivalent to the total heat content of a system. It is equal to the internal energy of the system plus the product of pressure and volume.

* $H = U + PV \quad (kJ)$ ⇒ $h = u + Pv \quad (kJ/kg)$

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* The properties of saturated liquid and saturated vapor for water are listed in Tables
  - A-4 ⟶ under temperature
  - A-5 ⟶ under pressure

* The subscript 'f' is used to denote properties of a saturated liquid, and the subscript 'g' to denote the properties of a saturated vapor.

* Enthalpy of vaporization (h_{fg}) ⟶ represents the amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure.
  * $h_{fg} \propto \frac{1}{T} \propto \frac{1}{P}$
  * $h_{fg} = 0$ at the critical point

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* Quality (x) ⟶ * the ratio of the mass of vapor to the total mass of the mixture.
  * $x = \frac{m_{vapor}}{m_{total}}$ | $m_{total} = m_{vapor} + m_{liquid}$ | $= \frac{v_{avg} - v_f}{v_{fg}}$
  * Its value is between 0 and 1.
    * 0 ⟶ 100% saturated liquid.
    * 1 ⟶ 100% saturated vapor.

---

* Using 'x':
  * $u_{avg} = u_f + x u_{fg}$ (kJ/kg)
  * $h_{avg} = h_f + x h_{fg}$ (kJ/kg)
  * $v = v_f + x v_{fg}$ (m^3/kg)

* Note:
  ⇒ $\lambda_{fg} = \lambda_g - \lambda_f$ ⇒ λ: any property

* Compressed liquid properties are relatively independent from pressure, which causes shortage of compressed liquid data.

⇒ We treat compressed liquid as saturated liquid at the given temperature.

⇒ $y \cong y_{f\,at\,T}$ ⇒ $y = (v, u \text{ or } h)$

---

* 3.6: The Ideal Gas Equation of State.

* Equation of State ⇒ Any equation that relates the pressure, temperature, and specific volume of a substance.

* Ideal-gas Relation ⇒ $\boxed{PV = mRT \quad \text{or} \quad Pv = RT}$

  * R: gas constant $= \frac{R_u}{M} = \frac{\text{universal gas constant}}{\text{molar mass}}$
  * $R_u = 8.31447 \ kPa \cdot m^3/kmol \cdot K$
  * $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$

* Molar Mass (M) ⇒ The mass of one mole.

* The mas of a system is equal to the product of its molar mass and the mole number N.

  ⇒ $m = MN \ (kg)$

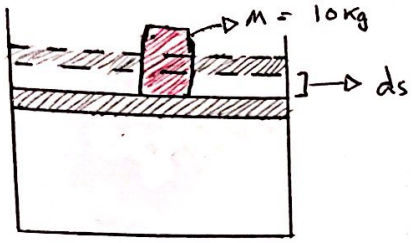
* $mR = (MN)R = NR_u \longrightarrow PV = NR_uT$

* $V = N\bar{v} \longrightarrow P\bar{v} = R_uT$

*CHAPTER 4: Energy Analysis of Closed Systems

* 4.1: Moving Boundary Work

* **Boundary work** ⟶ * expansion and compression work



Compression

* $W_b = \int_1^2 P\,dV$ (kJ) ---- ($P = f(V)$)

* (−) result ⟶ compression

* (+) result ⟶ expansion

* W = Area under the process P-V curve ⟶ $P = f(V)$

* **Polytropic process** ⟶ * $PV^n = C$ ⟶ n, C are constants

* $P = CV^{-n} \Rightarrow W_b = \int CV^{-n}\,dV$

$\Rightarrow W_b = \frac{mR(T_2 - T_1)}{1-n}$ $\quad n \neq 1$

* $n = 1 \Rightarrow W = PV \ln\left(\frac{V_2}{V_1}\right)$

---

*4.2: Energy Balance For Closed Systems

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

$E_{in} - E_{out}$: Net energy transfer by heat, work and mass.

ΔE_{system}: Change in internal, kinetic, potential energies.

* $Q = \dot{Q}\,\Delta t$, $W = \dot{W}\,\Delta t$, $\Delta E = \frac{dE}{dt}\,\Delta t$

* For a closed system undergoing a cycle $\Rightarrow E_{in} = E_{out}$

* First Law of Thermodynamics $\Rightarrow$ $\boxed{Q_{net,in} - W_{net,out} = \Delta E}$

* For a stationary system $\Rightarrow$ $\boxed{Q - W = \Delta U}$

* At constant pressure $\Rightarrow$ $\boxed{Q - W_{other} = \Delta H}$

*4.3: Specific Heats

* The specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree.

* C_v ⟶ the change in the internal energy of a substance per unit change in temperature at constant volume.

* C_p ⟶ the change in the enthalpy of a substance per unit change in temperature at constant pressure.

---

*4.4: Internal Energy, Enthalpy, And Specific Heats of Ideal Gases.

⇒ The internal Energy is a function of temperature. (For Ideal Gases)

$$\Rightarrow u = u(T)$$

⇒ * $h = u + Pv$
  * $Pv = RT$
  ⇒ $\boxed{h = u + RT}$ ⇒ R is constant and $u = u(T)$
  ⇒ $h = h(T)$

⇒ * $\Delta u = u_2 - u_1 = \int_1^2 C_v(T)\, dT$ (KJ/kg)

  * $\Delta h = h_2 - h_1 = \int_1^2 C_p(T)\, dT$ (KJ/KJ)

⇒ * When $C_v = C_{v,avg} = \text{constant}$

$$\Rightarrow u_2 - u_1 = C_{v,avg}(T_2 - T_1) \quad (KJ/Kg)$$

* When $C_p = C_{p,avg} = \text{constant}$

$$\Rightarrow h_2 - h_1 = C_{p,avg}(T_2 - T_1) \quad (KJ/kg)$$

CHAPTER 5: Mass and Energy Analysis of Control Volumes

* 5.1: Conservation of Mass

⇒ For closed systems, mass remains constant during a process. For control volumes, however, mass can cross the boundaries, and so we must keep track of the amount of mass entering and leaving the control volume.

* Mass Flow Rate ($\dot{m}$) ⟶ The amount of mass flowing through a cross section per unit time. $[\dot{m} = \rho V_{avg} A_c \ (kg/s)]$
* Volume Flow Rate ($\dot{V}$) ⟶ The volume of the fluid flowing through a cross section per unit time. $[\dot{V} = V A_c \ (m^3/s)]$

⇒ $\boxed{\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}}$ ⟶ Specific Volume

---

* Conservation of Mass Principle

⇒ The net mass transfer to or from a control volume during a time interval Δt is equal to the net change of the total mass within the control volume during Δt.

* $m_{in} - m_{out} = \Delta m_{CV} \quad (kg)$
* $\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{CV} \quad (kg/s)$

⇒ Mass Balance

⇒ In steady-flow processes, the total amount of mass contained within a control volume does not change with time.

⇒ $\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (kg/s)$

⇒ $\rho_1 V_1 A_1 = \rho_2 V_2 A_2$

* If the fluid is incompressible,

$\sum_{in} \dot{V} = \sum_{out} \dot{V}$ ⇒ $V_1 A_1 = V_2 A_2$

*5.2: Flow Work and the Energy of a Flowing Fluid

* **Flow work** ⟶ * Work needed to push the fluid into or out of the boundaries of a control volume.

* $W_{flow} = PV$ (KJ)
  - $P = \frac{F}{A}$
  - $V = A_c L$
* $w_{flow} = Pv$ (KJ/kg)

* **Energy of a flowing fluid (θ):**

θ = flow energy + internal energy + potential energy + kinetic energy (velocity)

$= \underbrace{Pv + u}_{h} + \frac{V^2}{2} + gz$ (KJ/kg)

* **Amount of energy transport:**

$= h + \frac{V^2}{2} + gz$ (KJ/kg)

$E_{mass} = m\theta = m\left(h + \frac{V^2}{2} + gz\right)$ (KJ)

* **Rate of energy transport:**

$\dot{E}_{mass} = \dot{m}\theta = \dot{m}\left(h + \frac{V^2}{2} + gz\right)$ (KW)

---

*5.3: Energy Analysis of Steady-Flow Systems

* **Steady-flow process** ⟶ * Fluid flows through the CV steadily.
  * Properties remain steady (No change with time).
  * E, V, m remain constant.
  * $W_b = 0$
  * $\dot{E}_{in} = \dot{E}_{out}$

  or $\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\theta = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}\theta$

* 5.4: Some Steady-Flow Engineering Devices

[1] Nozzles and Diffusers:

* A nozzle is a device that increases the velocity of a fluid at the expense of pressure.

[Increases velocity and decreases pressure.]

* A diffuser is a device that increases the pressure of a fluid by slowing it down.

[Increases pressure and decreases velocity]

* $\dot{Q} \simeq 0$, $\dot{W} = 0$, $\Delta P_e \simeq 0$, $\Delta K_e \neq 0$

---

[2] Turbines and Compressors:

* A turbine is a device that uses shaft work (mechanical energy) to drive an electric generator (electrical energy).

* A compressor is a device that requires work to increase the pressure of a fluid. (mechanical energy)

* Differences:

[1] A turbine delivers work, while a compressor requires work.

[2] Turbines extract energy by decreasing the pressure; however, compressors increase the pressure of fluids.

* $\dot{Q} \simeq 0$, $\Delta pe \simeq 0$, $\Delta K_e \simeq 0$

[3] Throttling Valves:

* Throttling Valves are any kind of flow-restricting devices that cause a significant pressure drop in the fluid.
* They cause a pressure drop, often accompanied by a large drop in temperature, without involving any work.
* $q \simeq 0$, $W = 0$, $\Delta pe \simeq 0$, $\Delta ke \simeq 0$

$$\Rightarrow h_2 \simeq h_1 \quad (KJ/kg)$$

$$\Rightarrow u_1 + P_1 v_1 = u_2 + P_2 v_2$$

* For ideal gases, during a throttling process the temperature remains constant.
* Examples: [1] Adjustable valves [2] Porous plugs [3] Capillary tubes.

[4a] Mixing Chambers:

* A mixing chamber is a section where two streams of fluids get mixed.
* $q \simeq 0$, $W = 0$, $\Delta ke \simeq 0$, $\Delta Pe \simeq 0$

[4b] Heat Exchangers:

* Heat exchangers are devices where two moving fluid streams exchange heat without mixing.
* Example: double-tube (tube-and-shell).
* Under steady operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant.
* $W = 0$, $\Delta ke \simeq 0$, $\Delta Pe \simeq 0$
* i) Entire heat exchanger is selected as the control volume $\rightarrow \dot{Q} = 0$
  ii) One of the fluids is selected as the CV $\rightarrow \dot{Q}$ = rate of heat transfer between the two fluids.

CHAPTER 6: The Second Law of Thermodynamics.

=> * Satisfying the first law doesn't ensure that a process can actually occur.

* The second law is about the quality of energy.

* 6.2: Thermal Energy Reservoirs

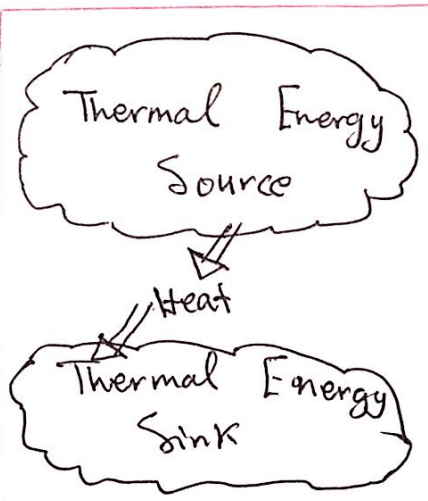
=> * A thermal energy reservoir is a hypothetical body that has a large thermal energy capacity and can supply or absorb finite amounts of heat without undergoing any change in temperature. (Ex: the atmosphere, oceans, furnaces)

* Any physical body whose thermal energy capacity is large relative to the amount of energy it supplies or absorbs can be modeled as a thermal energy reservoir.

* A source supplies energy in the form of heat, and a sink absorbs it.

* 6.3: Heat Engines

=> * A heat engine is a system that converts heat to mechanical energy, which can then be used to do mechanical work.

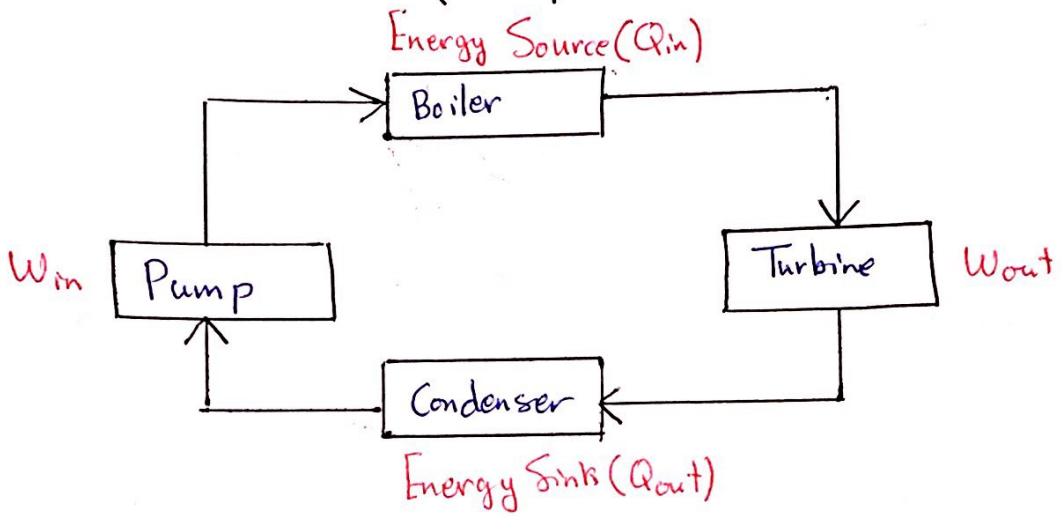


* Heat Engines

1) Receive heat from a high temperature source. (Solar energy, oil furnace, etc.)
2) Convert part of this heat to work.
3) Reject the remaining waste heat to a low temperature sink (the atmosphere, rivers, etc.).
4) Operate on a cycle.

* Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the working fluid.

* Steam Power Plant (Example of a heat engine)



* Q_{in} = amount of heat supplied to steam in boiler from a high temperature source (furnace).
* Q_{out} = amount of heat rejected from steam in condenser to a low temperature sink (the atmosphere, etc.).
* W_{out} = amount of work delivered by steam as it expands in turbine.
* W_{in} = amount of work required to compress water to boiler pressure.
* $W_{net,out} = W_{out} - W_{in} = Q_{in} - Q_{out}$ (kJ)

* Thermal Efficiency :-

⇒ Thermal Efficiency (η_{th}) is the ratio of the work done by the heat engine to the heat supplied to it.

$$\Rightarrow \eta_{th} = \frac{W_{net,out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

* Q_H ⟶ magnitude of heat transfer between the cyclic device and the high-temperature medium.
* Q_L ⟶ magnitude of heat transfer between the cyclic device and the low-temperature medium.
* Cyclic devices such as heat engines, refrigerators, and heat pumps operate between a high-temperature medium (or reservoir) at T_H and a low-temperature medium (or reservoir) at T_H.

⇒ * $W_{net,out} = Q_H - Q_L$

* $\eta_{th} = \frac{W_{net,out}}{Q_H} = 1 - \frac{Q_L}{Q_H}$

* The Second Law of Thermodynamics: Kelvin-Plank Statement

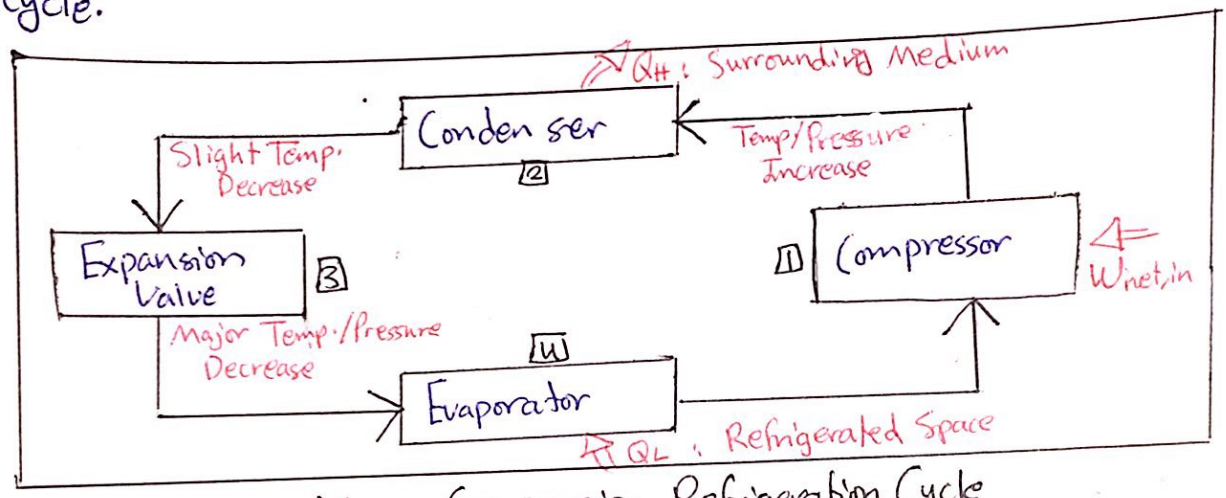
⇒ "It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work."

⇒ 1) A heat engine must exchange heat with a low-temperature sink as well as a high-temperature source to keep operating.
2) No heat engine can have a thermal efficiency of 100%.

* 6.4: Refrigerators and Heat Pumps

* Refrigerators are devices required to transfer heat from a low-temperature medium to a high-temperature one. (Ex: Heat engines)

* A refrigerant is the working fluid used in the refrigeration cycle.



Vapor-Compression Refrigeration Cycle

1) The refrigerant enters the compressor as vapor and is compressed to the condenser pressure.
2) It cools down and condenses as it flows through the condenser by rejecting heat to the surrounding medium.
3) Major pressure and temperature drop due to the throttling effect.
4) Evaporation due to absorbing heat from the refrigerated space.

* Coefficient of Performance (COP):-

* Coefficient of Performance ⟶ the ratio of useful heating or cooling provided to work required.

⇒ $\frac{\text{Desired output}}{\text{Required input}}$

* $COP_{Refrigerator} = \frac{Q_L}{W_{net,in}} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$

⇒ As the amount of heat removed from the refrigerated space can be greater than the amount of work input, the COP can be greater than 1.

* $COP_{Heat\ Pump} = \frac{Q_H}{W_{net,in}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}} = COP_R + 1$

* Refrigerators and heat pumps operate on the same cycle but differ in their objectives.

⇒ * The objective of a refrigerator is to maintain the refrigerated space at a low temperature by removing heat from it and discharging it to a higher temperature medium.

* The objective of a heat pump is to maintain a heated space at a high temperature by absorbing heat from a low temperature source.

* The Second Law of Thermodynamics: Clausius Statement

⇒ "It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body."

⇒ A refrigerator cannot operate unless its compressor is driven by an external power source.

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* 6.6: Reversible and Irreversible Processes

* A reversible process is defined as a process that can be reversed without leaving any trace on the surroundings.

* Reversible processes do not occur in nature and are idealizations of actual processes.

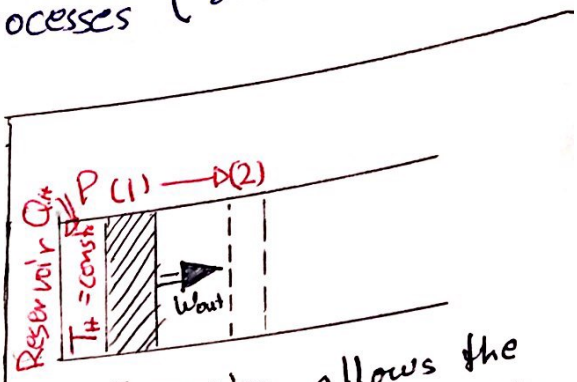
* Engineers are interested in reversible processes because work-producing devices deliver the most work, and work-consuming devices consume the least work when reversible processes are used instead of irreversible ones.

* Irreversibilities are the factors that cause a process to be irreversible (Such as: friction, heat transfer, and unrestrained expansion of gas).

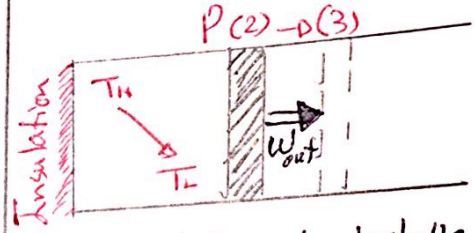
6.7: The Carnot Cycle

* The Carnot cycle is reversible.
* It is composed of four reversible processes (2 isothermal and 2 adiabatic).

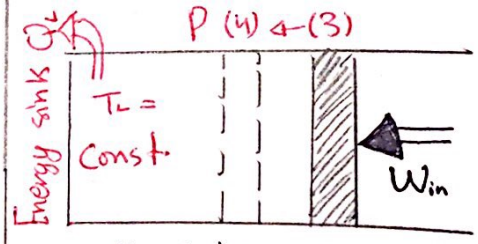
* 1→2: **Reversible Isothermal Expansion:-**
  * T_H remains constant.
  * Heat is transferred to the gas "Q_H".
  * Boundary work (+).
* 2→3: **Reversible Adiabatic Expansion:-**
  * Temperature drops from T_H to T_L.
  * No heat transfer.
  * Work output (+).
* 3→4: **Reversible Isothermal Compression:-**
  * T_L remains constant
  * Heat is transferred from the gas "Q_L".
  * Boundary work (-).
* 4→1: **Reversible Adiabatic Compression:-**
  * Temperature rises from T_L to T_H.
  * Work input (-).
  * No heat transfer.



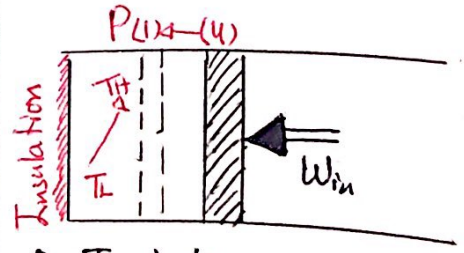
⇒ Expansion allows the gas to cool. However, the reservoir heats it. So, T_H remains constant.



⇒ Insulation is installed instead of the reservoir. So, the process becomes adiabatic.



⇒ Insulation is replaced by a sink. So, T_L remains constant.



⇒ Insulation is installed instead of the sink. So, the process becomes adiabatic.

* 6.8: The Carnot Principles

⇒ [1] The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

[2] The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

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* We must express T_H and T_L in Kelvins.

* 6.10: The Carnot Heat Engine

* Carnot Heat Engine ⟶ a hypothetical heat engine that operates on the reversible Carnot cycle.

* Carnot Efficiency ⟶ * the highest efficiency a heat engine operating between the two thermal energy reservoirs at temperatures "T_L" and "T_H" can have.

* $\eta_{th,rev} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H}$

---

* 6.11: The Carnot Refrigerator and Heat Pump

* COP_R $\begin{cases} < COP_{R,rev} \longrightarrow \text{Irreversible Refrigerator} \\ = COP_{R,rev} \longrightarrow \text{Reversible Refrigerator} \\ > COP_{R,rev} \longrightarrow \text{Impossible Refrigerator} \end{cases}$

* The above relation applies to heat pumps by replacing all COP_R's by COP_{HP}.