



MA3010 Weekly Concepts

Thermodynamics & Heat Transfer (Nanyang Technological University)



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Week 1 : 2nd Law

Possible Assumptions Tutorial 1 :

1. Steady-state heat transfer

[Topic : Thermodynamics of HE & Reverse HEs]

1. Thermal Energy Reservoirs

$$Q = mc(\Delta T)$$

2. Heat Engines

$$W_{\text{net out}} = Q_{\text{in}} - Q_{\text{out}} = Q_H - Q_L$$

$$\text{HE efficiency} = W_{\text{net out}} / Q_H = 1 - (Q_L / Q_H)$$

3. Refrigerators & Heat Pumps

$$W_{\text{net in}} = Q_H - Q_L$$

$$\text{COPR} = (Q_L) / (Q_H - Q_L) = (1) / (Q_H / Q_L - 1)$$

[Topic : Carnot Cycle]

4. The Carnot Cycle

$$\text{For Carnot Cycle : } Q_H / Q_L = T_H / T_L$$

5. Carnot HE, Refrigerators & Heat Pumps

$$\text{Carnot HE efficiency} = 1 - (T_L / T_H)$$

$$\text{Carnot Refrigerator COP} = 1 / [(T_H / T_L) - 1]$$

$$\text{Carnot HP COP} = 1 / [1 - (T_H / T_L)]$$

Weeks 2-4a : Entropy

Possible Assumptions :

1. Tutorial 2 : Entropy change :
 - a. Assume steady-state
 - b. Assume constant specific heats
 - c. Assume isolated system for isolated system problems
2. Tutorial 3 : Entropy & Increase of Entropy Principle
 - a. Assume air is an ideal gas if there is air
 - b. Assume internally reversible for systems with no irreversibilities
3. Tutorial 4 : Entropy in Thermo Devices
 - a. Steady-state, steady flow
 - b. Ideal gas with specific constant heats
 - c. Negligible KE & PE
 - d. Reversible steady flow for reversible devices
 - e. Adiabatic for adiabatic devices

[Topic : Entropy Change & Tds]

1. Entropy of Pure Substances

$$\Delta S = S_2 - S_1 = m(s_2 - s_1)$$

2. Entropy Change of Liquids & Solids

$$Tds \text{ equation : } s_2 - s_1 = C_{\text{avg}} (\ln T_2 - \ln T_1) = C_{\text{avg}} (\ln T_2 / \ln T_1)$$

3. Entropy Change of Ideal Gases

Know the 2 Tds equations for ideal gas, one for cv and the other for cp

4. Entropy Change for Reversible Processes

$$\Delta S = Q / T_0 ; T_0 \text{ is the constant temp}$$

5. Entropy Change for Irreversible Processes

Addition of the S_{gen} term to account for irreversibilities, S_{gen} is only either a positive number (irreversible) or zero (reversible)

6. Entropy Change for Systems

$$\Delta S_{system} = S_{in} - S_{out} + S_{gen}$$

6.1 Special cases

Adiabatic : $\Delta S = S_{gen}$

Isentropic : $\Delta S = 0$; $S_2 = S_1$

Isolated system : $\Delta S_{system} + \Delta S_{surr} = \Delta S_{isolated} = S_{gen}$

7. Entropy Change for Flow Control Volumes

[Topic : Steady State Control Volume Devices]

8. Steady State Control Volume Devices

Know the equation for steady state steady flow devices

9. Reversible Steady Flow Work

Know the reversible steady flow work equation

10. Polytropic Work in Steady Flow Devices

Polytropic work in closed system using n

Isentropic special case of polytropic work ($n=k$) for ideal gas

Multistage compression + intercooling : know min. work pressure ratio formula

[Topic : Isentropic Efficiency]

11. Memorise all the $h-s$ diagrams for turbines, compressors and nozzles

Weeks 4b : Gas Mixtures

Possible Assumptions Tutorial 5 :

1. *Steady-state, steady-flow*
2. *Ideal gas mixture with constant specific heats*

[Topic : Composition, PVT behaviour & Properties]

1. Composition of Gas Mixtures

$$\text{Molar Mass} = \text{Substance Mass} / \text{No. of Moles}$$

2. PVT Behaviour

$$\text{Dalton + Amagat's Law : } P_i / P_m = V_i / V_m = N_i / N_m$$

Weeks 5-6 : Gas-Vapour Mixtures & Air-conditioning

Possible Assumptions Tutorial 6 :

1. *Steady-state, steady-flow*
2. *Air & water vapour are ideal gases*

[Topic : Air Properties, Temperature Properties & Adiabatic Saturation]

1. Dry & Atmospheric Air

$$\text{Enthalpy dry-air : } h = C_p T ; T \text{ is in degrees}$$

$$\text{Total Pressure : } P = \text{Air Pressure } P_a + \text{Vapour Pressure } P_v$$

2. Specific & Relative Humidity of Air

$$\text{Specific humidity : } \omega = \text{mass vapour} / \text{mass dry air}$$

$$\text{Maximum saturation : } P_v = P_g$$

$$\text{Relative humidity : } \phi = P_v / P_g, \text{ ratio of moisture to max.}$$

3. Dew Point Temperature

Dry-bulb temp : normal temp at atmospheric air

Dew point temp : temp which condensation begins

4. Air-Conditioning Processes

4.1 Simple Heating & Cooling :

Process appears as horizontal line on psycho chart

4.2 Heating with Humidification

Water spray : temp decreases after humidification due to evaporation

Steam spray : temp increases

4.3 Cooling with Dehumidification

Cooling air past dew point to form condensate with water vapour

Air is dehumidified when condensate is removed

4.4 Evaporative Cooling

Used in desert

Cool air and increase humidity

4.5 Adiabatic Airstream Mixing

Week 7 : Heat Transfer Mechanisms, 1-D Heat Conduction, Internal Heat Generation

Possible Assumptions Tutorial 7 :

1. *Thermal conductivity k is constant*
2. *Steady-state heat transfer in 1-direction only*

[Topic : Heat Transfer Mechanisms]

1. Conduction Heat Transfer : Fourier's Law of Conduction
2. Convection Heat Transfer : Newton's Law of Cooling
 - a. Newton's law of cooling : $Q = hA(\Delta T)$
3. Radiation Heat Transfer : Net Radiation Exchange
 - a. $Q_{\text{rad}} = \text{emissivity} \times \text{Boltzman constant} \times \text{surface area} \times (T_s^4 - T_{\text{surr}}^4)$

[Topic : 1-D Heat Conduction]

4. Cartesian Coordinates
5. Cylindrical Coordinates

[Topic : Internal Heat Generation]

6. Plane wall
7. Cylinder

Week 8 : Steady-State Heat Conduction & Transient Heat Conduction

Possible Assumptions Tutorial 8 :

1. *Steady-state 1-D heat transfer*
2. *Negligible heat loss through insulation*
3. *Constant thermal conductivity*
4. *No radiation heat transfer*
5. *For thin strip heater : thermal resistance of thin heating element is negligible*

Possible Assumptions Tutorial 9 (Lumped Body) :

1. *Negligible radiation*
2. *Constant heat transfer coefficient over entire surface so lumped analysis can be used*
3. *Constant thermal properties*

[Topic : Thermal Resistance Networks]

1. Heat conduction in cylinders & spheres
2. Thermal resistance networks
 - a. Know the thermal resistance formulas for conduction, convection, cylindrical wall and spherical wall

[Topic : Lumped System Analysis]

3. Know all 4 formulas required for transient lump system analysis problem :
 - a. Characteristic length formula
 - b. Biot number formula
 - c. Time constant τ formula
 - d. Time formula

Week 9 : Fundamentals of Convection

- Reynold's numbers :
 - a. Flat plate laminar flow : $Re < 5 \times 10^5$
- Know Newton's law of cooling for convection heat transfer
- Friction coefficient : directly related to heat transfer coefficient
 - a. Average friction / heat transfer coefficient - know the formula
- Fluid flow classification :
 - a. Viscous flow region : flow where frictional effects are significant
 - b. Inviscid flow region : regions where viscous forces are negligible compared to inertial or pressure forces
- Fluid viscosity :
 - a. Dynamic viscosity (μ)
 - b. Kinematic viscosity (ν)
- Friction coefficient (C_f) : directly related to heat transfer coefficient & power req.
- Reynold's Number :
 - a. $Re = [V_{avg} \times D] / \nu$
 - b. $Re = [\rho \times V_{avg} \times D] / \mu$
- Nusselt Number : $[Nu \times L_c] / k$; L_c = characteristic length, k = thermal conductivity

Week 10 : External Forced Convection

Possible Assumptions :

1. Steady-state operating conditions
2. Smooth cylinder for cross-flow problems
3. Might have to assume fully turbulent flow for turbulent problems

[Topic : Parallel Flow Over Flat Plate]

- Drag force F_d = friction drag + pressure drag
- Reynold's number for flat plate :
 - a. Flat plate laminar flow : $Re < 5 \times 10^5$
 - b. Reynold's no. at distance x : $Re = (V \cdot x) / \nu$
- Nusselt No. for flat plate :
 - a. $Nu = (h \cdot x) / k$
 - b. Know how to identify the provided formula for Nusselt no. laminar flow

- i. $(0.664 * Re^{0.5} * Pr^{1/3})$
- Avg friction coefficient (Cf) : know how to use the provided Cf formula for laminar flow over flat plates
- Turbulent flow over flat plates :
 - a. Know how to use the provided formulas for avg Nu & avg Cf for turbulent flat plate flow
- Mixed flow over flat plates
 - a. Know how to calculate Nu & Cf for mixed flow which is different from pure laminar and turbulent
 - b. Mixed flow problem has to be solved in segments, taking flow from start to particular point(s), and mathematically calculating the differences between them to find the properties needed (Refer to lecture note Ex.3 Mixed Flow)
- Special cases of flow over flat plate :
 - a. Uniform heat flux
 - b. Unheated starting length

[Topic : Cross Flow Over Cylinder & Spheres]

- Critical reynold number : $Re = 2 \times 10^5$
- Cross-flow over cylinders :
 - a. Average Nusselt number - use diameter to evaluate the Nusselt number
 - i. $Nu = (h*D) / k$, fluid properties are evaluated at mean temperature
- Cross-flow over spheres :
 - a. Average Nusselt number $Nu = (h*D) / k$
 - i. Fluid properties are evaluated at free-stream temperature $T(\infty)$, except for dynamic viscosity of a sphere, which is evaluated at the surface temperature

Week 11 : Internal Forced Convection

Possible Assumptions :

1. Steady-state operating conditions
2. Constant surface temperature for constant surface temp problems
3. Constant heat flux for constant heat flux problems
4. Negligible heat conduction along pipe
5. Negligible work done by viscous forces
6. Negligible thermal resistance from pipe outer to inner surface

[Topic : Reynold's Number in Pipe Flow for Circular & Non-Circular Pipes]

- Topic assumptions :
 - a. Negligible frictional heating during flow, pressure drop is dominant
 - b. Significant fluid temperature change is a result of heat transfer
- Reynold's numbers in tubes :
 - a. Laminar : $Re < 2300$
 - b. Turbulent : $Re > 10,000$
- Reynold's number formulas :
 - a. Circular tube :
 - i. $Re = 4(\text{mass flow}) / \mu \pi D$
 - b. Non-circular tube (rectangle) :

- i. Diameter calculation uses the Hydraulic Diameter (D_h) value, which the friction factor is based upon, $D_h = [4 \times \text{Flow Area}] / \text{Wetted Perimeter}$
- ii. $Re = [V_{avg} \times D_h] / \text{kinematic viscosity}$
- iii. Recall that kinematic viscosity = dynamic viscosity / density

[Topic : Velocity & Flow Profile Properties]

- Velocity profile :
 - a. Hydrodynamic entry length (L_h) : region where velocity profile develops, aka entrance region
- Thermal profile :
 - a. Thermal entrance length : thermally developing flow
 - b. Thermally fully developed flow : temperature profile of a pipe will always be the same, although mean temp. (T_m) across profiles might be able to change
 - c. Bulk mean fluid temperature : used to evaluate fluid properties
 - i. Bulk mean fluid temp $T_b = 0.5 (T_{inlet} + T_{exit})$
- Fully developed flow : the flow is both hydrodynamically and thermally developed
 - a. Both local friction factor & local convection coefficients remain constant
- Entry lengths in tube flow (memorise the formulas in case not given) :
 - a. Laminar flow ($Re < 2300$) :
 - i. Hydrodynamic entry length $L_h = 0.05 \times Re \times \text{Diameter}$ (NOT GIVEN)
 - ii. Thermal entry length $L_t = 0.05 \times Re \times Pr \times \text{Diameter}$ (NOT GIVEN)
 - b. Turbulent flow ($Re > 2300$) :
 - i. Hydrodynamic entry length = thermal entry length = $10 \times \text{Diameter}$ (NOT GIVEN)

[Topic : Techniques To Solve Internal Flow Problems]

- General thermal analysis techniques : (Stopped at slide 23)
 - a. Conservation of energy :
 - b. Boundary conditions :
 - i. Constant surface heat flux
 - ii. Constant surface temperature : use log mean temperature difference to evaluate constant surface temperature problems
- Techniques to find the heat transfer coefficients for internal flow :
 - a. For fully developed laminar flow :
 - i. Perform energy balance on the volume element
 - b. For laminar flow with constant surface heat flux :
 - i. apply boundary conditions $dT/dx = 0$ at point $r = 0$, and $T = T_s$ at point $r = R$
 - c. For internal laminar flow :
 - i. For laminar flow with uniform surface temp : $Nu = 3.66$
 - ii. For laminar flow with uniform heat flux : $Nu = 4.36$

Week 12 : Radiation Heat Transfer

- Stefan-Boltzmann Law (σ) : 5.67×10^{-8} , do all radiation problems in Kelvin
- Connection between black-body radiation rate & total emissive power :
 - a. Total Emissive Power : $E_b(T) = \sigma \times T^4$