Basics of Mechanical Engineering-3

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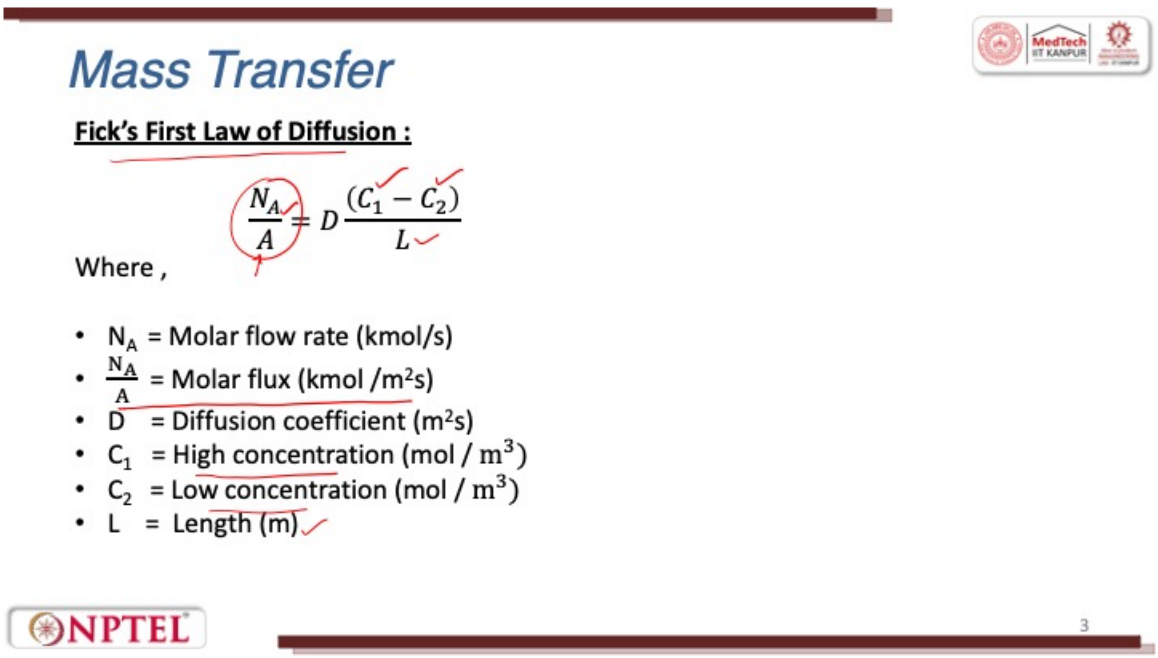
Week 07

Lecture 31: Tutorial 8 (Mass Transfer and Applications)

Welcome back to the course Basics of Mechanical Engineering 3. I am Dr. Amandeep Singh Oberoi from IIT Kanpur. I am going to conduct a tutorial session on Mass Transfer and Applications in this lecture. I discussed heat transfer and more tutorials in the previous weeks. This is Mass Transfer and Applications; applications such as boilers, heat exchangers, or condensers, etc., for which we will try to calculate the efficiency.

First, let me talk about Mass Transfer. Mass Transfer: to recall the concept, it is the movement of molecules or chemical species from one location to another, mainly due to concentration gradients. It occurs in processes like diffusion, absorption, distillation, drying, and membrane separation. The main mechanisms are diffusion or convection. Diffusion is the random movement from high to low concentration.

Convection is the transfer by bulk movement of fluids. The importance of mass transfer in engineering is: it is used in chemical, mechanical, and environmental engineering fields, key to designing chemical reactors, separation units, and many industrial operations. You can see here distillation, where mass transfer occurs, absorption, where mass transfer happens. Then there is extraction from a solvent to solute. And here you can also see through drying itself, through convection as well, mass transfer is happening.



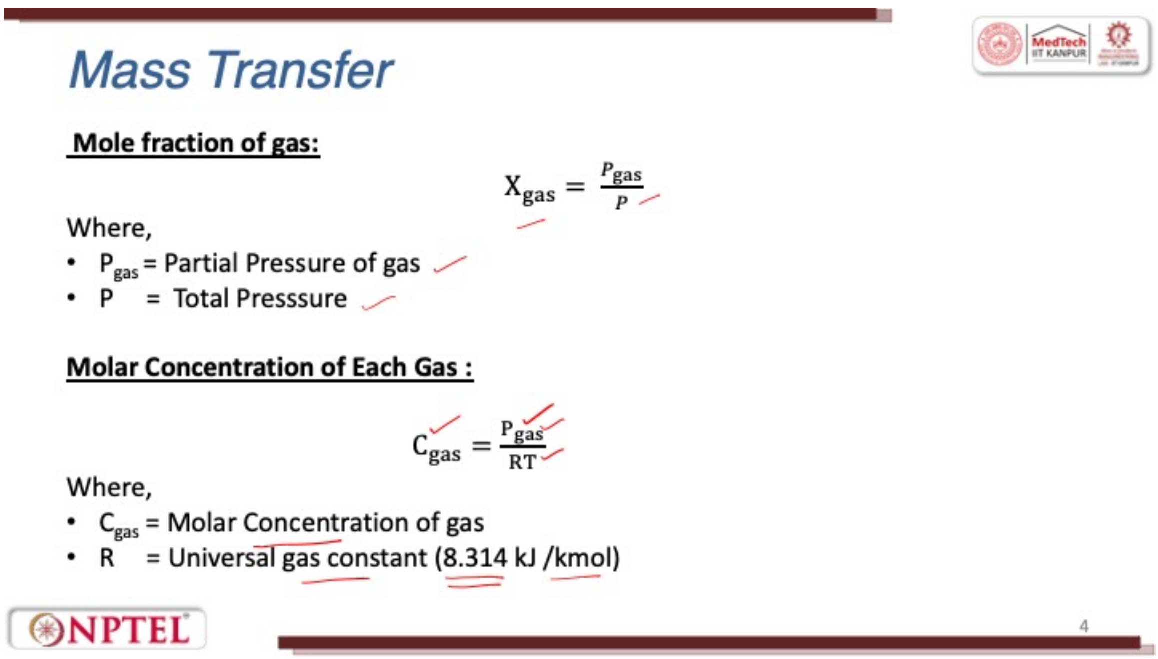
To talk about the parameters or key determinants of mass transfer, we need to understand Fick's first law of diffusion, which states N_A/A—this is molar flux, as written here.

$$\frac{N_A}{A} = D\frac{(C_1 - C_2)}{L}$$

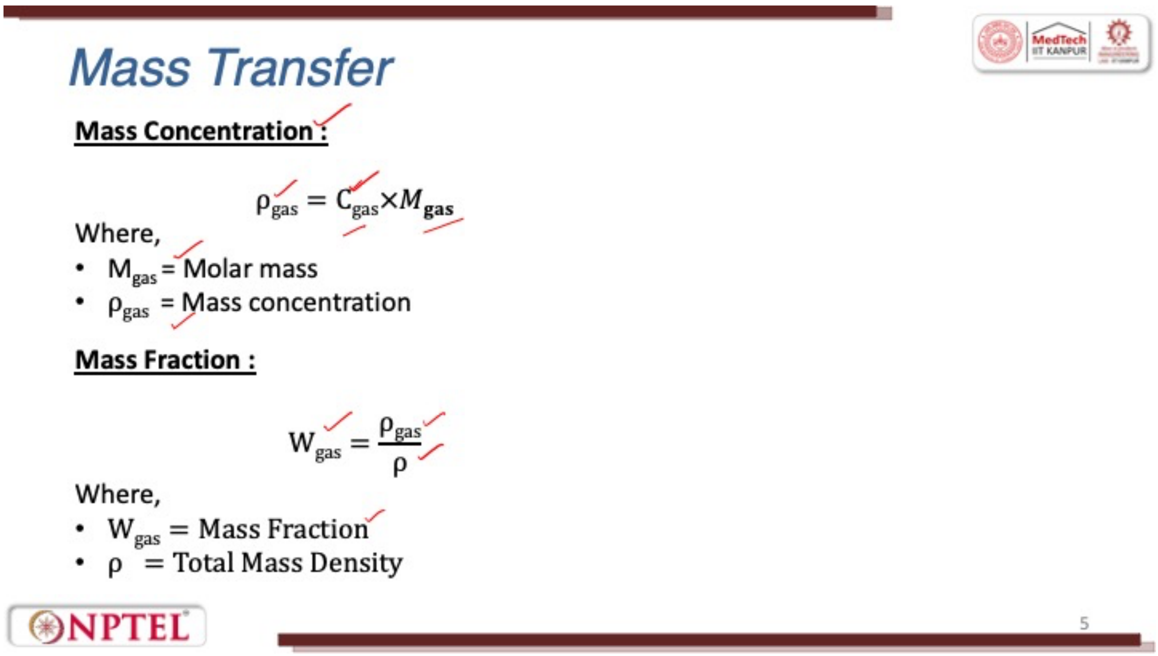
Where ,

- N_A = Molar flow rate (kmol/s)
- $\frac{N_A}{A}$ = Molar flux (kmol /m^2s)
- D = Diffusion coefficient (m^2s)
- C_1 = High concentration (mol / m^3)

- C_2 = Low concentration (mol / m^3)
- L = Length (m)



Now, the mole fraction of gas is given by X gas is equal to P gas by P, where P gas is the partial pressure of the gas. P is the total pressure of the gas. The molar concentration of each gas, if we need to see, is the concentration of the gas. Molar concentration: C gas is the molar concentration of gas, which is equal to P gas by RT. This is derived from the gas law, where R is the universal gas constant with a value of 8.314 kilojoules per kilomole.



When discussing molar concentration, we should also consider mass concentration and mass fraction. Mass concentration, $\rho_{gas} = C_{gas} \times \boldsymbol{M_{gas}}$

Where,

- M_{gas} = Molar mass
- ρgas = Mass concentration

Mass fraction is $Wgas = \frac{\rho gas}{\rho}$

Where,

- W_{gas} = Mass Fraction
- ρ = Total Mass Density

This mass fraction is rho gas by rho. That is the mass concentration of gas by total mass density.

Mass Transfer

Problem statement : *A vessel contains a binary mixture of oxygen and nitrogen with partial pressures in the ratio 0.21 and 0.79 at 15 °C. The total pressure of the following mixtures is 1.1 bar. Calculate the following*

i. Molar concentration
ii. Mass concentration
iii. Mass Fractions

$O_2 + N_2$
(0.21) (0.79)
15°C

Solution :

$$\frac{P_{O_2}}{P} = 0.21$$

$$\frac{P_{N_2}}{P} = 0.79$$

$$P = 1.1 \text{ bar} = 1.1 \times 10^5 \text{ Pa}$$

$$T = 15°C = 15 + 273 = 288 K$$

NPTEL

Mass Transfer

Solution : i) Molar concentration

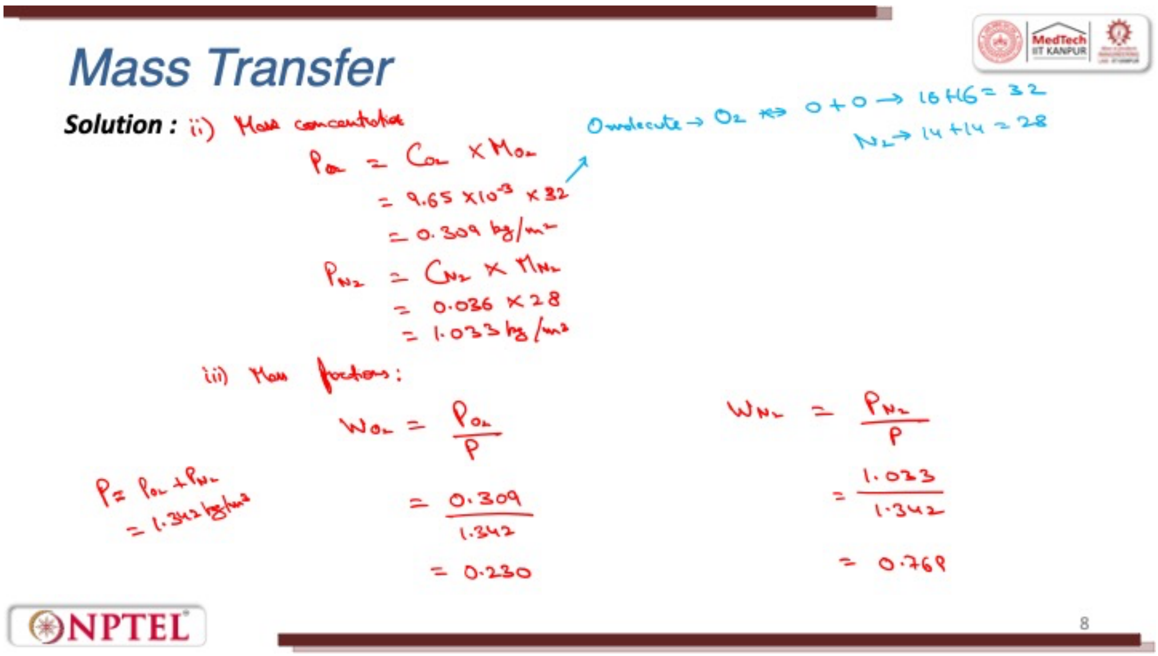
$$P_{O_2} = 0.21 \times P = 0.21 \times 1.1 \times 10^5 = 0.231 \times 10^5 \text{ Pa}$$

$$P_{N_2} = 0.79 \times P = 0.79 \times 1.1 \times 10^5 = 0.869 \times 10^5 \text{ Pa}$$

$$C_{O_2} = \frac{P_{O_2}}{RT} = \frac{0.231 \times 10^5}{8314 \times 288} = 9.65 \times 10^{-3} \text{ kmol/m}^3$$

$$C_{N_2} = \frac{P_{N_2}}{RT} = \frac{0.869 \times 10^5}{8314 \times 288} = 0.036 \text{ kmol/m}^3 \text{ (approx.)}$$

NPTEL



Let me try to see a problem, and we'll use these relations. A vessel contains a binary mixture of oxygen and nitrogen with partial pressures in the ratio 0.21 and 0.79 at 15 ^oC. The total pressure of the following mixtures is 1.1 bar. Calculate the following

i. Molar concentration

ii. Mass concentration

iii. Mass Fractions

Given:

$P_{O2}/P = 0.21$

$P_{N2}/P = 0.79$

$P = 1.1 \text{ bar} = 1.1 \times 10^5 \text{ Pa}$

$T = 15\,^oC = 15 + 273 = 288 \text{ K}$

Solution:

i. Molar concentration:

$P_{O2} = 0.21 \times P$

$= 0.21 \times 1.1 \times 10^5$

$= 0.231 \times 10^5$ Pa

$P_{N2} = 0.79 \times P$

$= 0.79 \times 1.1 \times 10^5$

$= 0.869 \times 10^5$ Pa

$C_{O2} = \frac{P_{O2}}{RT}$

$= \frac{0.231 \times 10^5}{8.314 \times 288} = 9.65 \times 10^{-3}\ k\ mol/m^3$

$C_{O2} = \frac{P_{N2}}{RT}$

$= \frac{0.869 \times 10^5}{8.314 \times 288} = 0.036\ k\ mol/m^3$ (approx.)

ii. Mass concentration:

$P_{O2} = C_{O2} \times M_{O2}$

$= 9.65 \times 10^{-3} \times 32$

$= 0.309$ kg/m^2

$P_{N2} = C_{N2} \times M_{N2}$

$= 0.036 \times 28$

$= 1.033$ kg/m^3

iii. Mass fractions:

$W_{O2} = \frac{P_{O2}}{P}$ ($P = P_{O2} + P_{N2} = 1.342$ kg/m^3)

$= \frac{0.309}{1.342} = 0.230$

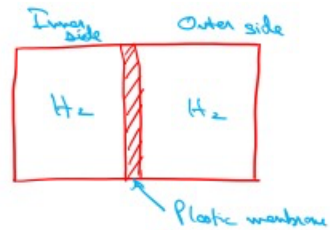
$W_{N2} = \frac{P_{N2}}{P}$

$= \frac{1.033}{1.342} = 0.769$

Mass Transfer

Problem statement : *A thin plastic membrane separates hydrogen from air. The mole concentration of hydrogen in membrane of inner and outer surface 0.45 and 0.002 kmol/m³ . The binary diffusion coefficient of hydrogen of operation temperature 53 x 10⁻¹⁰ m²/s. Find the mass flow rate of H_2 by diffusion through the membrane and at standard temperature if the thickness is:*

i. 2 mm
ii. 0.5 mm



Solution:

$D = 53 \times 10^{-10}\ m^2/s$

$C_1 = 0.045\ kmol/m^3$

$C_2 = 0.002\ kmol/m^3$

9

Mass Transfer

Solution: i) $t = 2\ mm = 0.002\ m$

ii) $t = 0.5 = 0.0005\ m$

Molar flux

$$\frac{N_A}{A} = D\,\frac{C_1 - C_2}{L}$$

$$= \frac{5.3 \times 10^{-10}\,(0.045 - 0.002)}{0.002}$$

$$= 1.139 \times 10^{-8}\ kmol/m^2$$

Mass flow

$$\frac{\dot{m}_A}{A} = \frac{N_A}{A} \times M_{H_2}$$

$$= 1.139 \times 10^{-8} \times 2$$

$$= 2.278 \times 10^{-8}\ kg/m^2$$

$$= 9.116 \times 10^{-8}\ kg/m^2$$

10

So, there is another problem statement. A thin plastic membrane separates hydrogen from air. The mole concentration of hydrogen in membrane of inner and outer surface 0.45 and 0.002 kmol/m^3 . The binary diffusion coefficient of hydrogen of operation temperature 53 x 10^{-10} m^2/s. Find the mass flow rate of H_2 by diffusion through the membrane and at standard temperature if the thickness is:

i. 2 mm

ii. 0.5 mm

Given:

D = 53 x 10^{-10} m^2/s

C1 = 0.045 k mol/^{3}

C2 = 0.002 k mol/m^3

Solution:

i. t = 2 mm = 0.002 m

Molar flux:

$$\frac{N_A}{A} = D\ \frac{C1 - C2}{L}$$

$$= \frac{5.3 \times 10^{-10}\ (0.045 - 0.002)}{0.002}$$

= 1.139 x 10^{-8} k mol/m^3

Mass flux:

$$\frac{m°_A}{A} = \frac{N_A}{A} \times M_{H2}$$

= 1.139 x 10^{-8} x 2

= 2.278 x 10^{-8} kg/m^3

ii. t = 0.5 = 0.0005 m

You can calculate this by yourself. I will just give you the answer.

The answer is 9.116 × 10^{-8} kg/m^3.

Heat Exchangers

- A heat exchanger is a device that transfers thermal energy between two or more fluids at different temperatures.
- It's a crucial component in numerous applications, from heating and cooling systems to power generation and industrial processes.

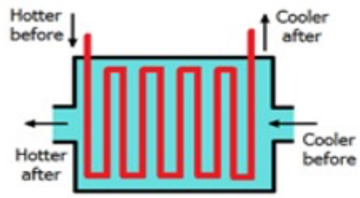
Heat exchanger effectiveness (ε) measures how well a heat exchanger transfers heat compared to the maximum possible heat transfer.

$$\varepsilon = \frac{Q}{Q_{max}}$$

Where,

Q - Actual heat transfer (W).

Q_{max} - Maximum possible heat transfer (W).



Heat Exchanger

https://energyeducation.ca/wiki/images/thumb/f/f7/Heatexchngar.png/350px-Heatexchngar.png

Now, I will talk about applications of thermodynamics, such as heat exchangers, boilers, condensers, etc. What are heat exchangers? Let us recall the concept. A heat exchanger is a device that transfers thermal energy between two or more fluids at different temperatures. It is a crucial component in numerous applications, from heating and cooling systems to power generation and industrial processes.

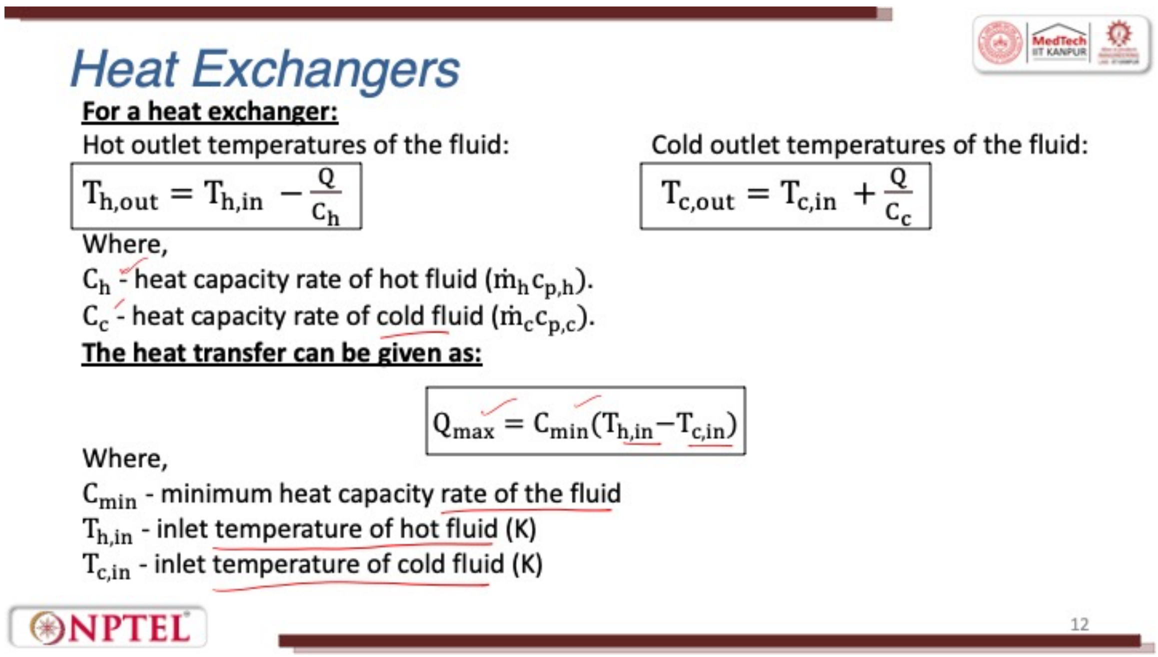
Heat exchanger effectiveness, also denoted as ε, measures how well a heat exchanger transfers heat compared to the maximum possible heat transfer. That is, $\varepsilon = \frac{Q}{Q_{max}}$

Where,

Q - Actual heat transfer (W).

Q_{max} - Maximum possible heat transfer (W)

Here, you see a heat exchanger; it was hotter before and cooler after, or it could be cooler before and hotter after. Heat exchange can happen in any direction.



For a heat exchanger, certain parameters are taken into account for the design, such as the hot outlet temperature of the fluid. That is,

$$T_{h,\,out} = T_{h,\,in} - \frac{Q}{C_h}$$

The cold outlet temperature,

$$T_{c,\,out} = T_{c,\,in} + \frac{Q}{C_c}$$

Where,

C_h - heat capacity rate of hot fluid ($\dot{m}_h c_{p,\,h}$).

C_c - heat capacity rate of cold fluid ($\dot{m}_c c_{p,\,c}$)

Heat transfer can be given as

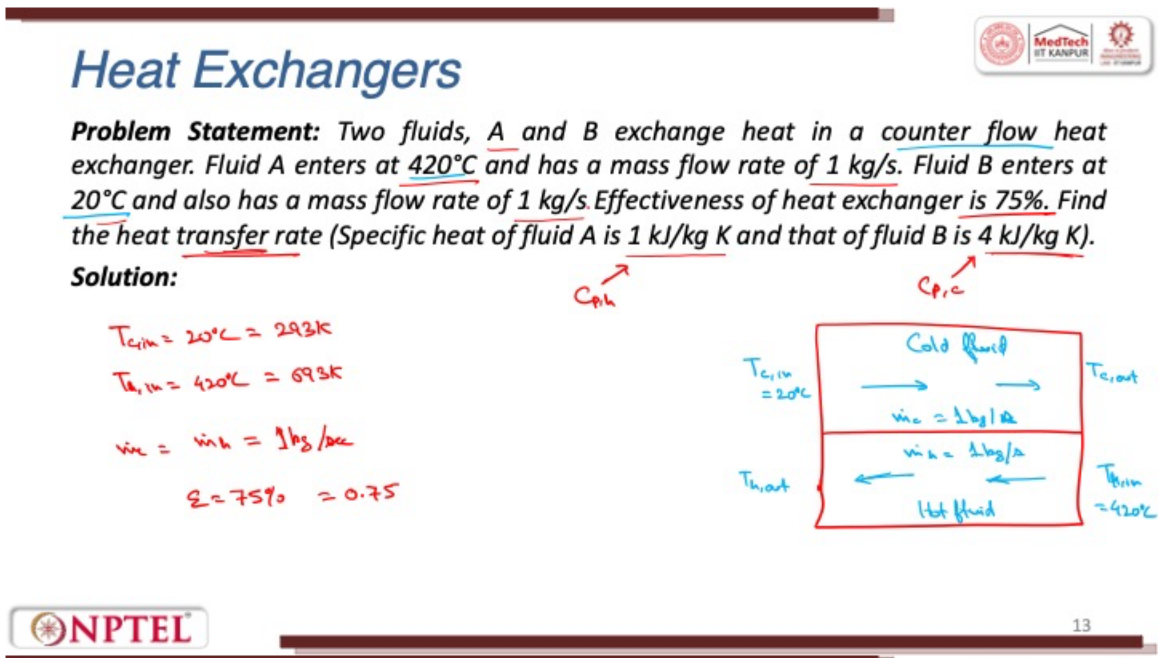
$$Q_{max} = C_{min}(T_{h,\,in} - T_{c,\,in})$$

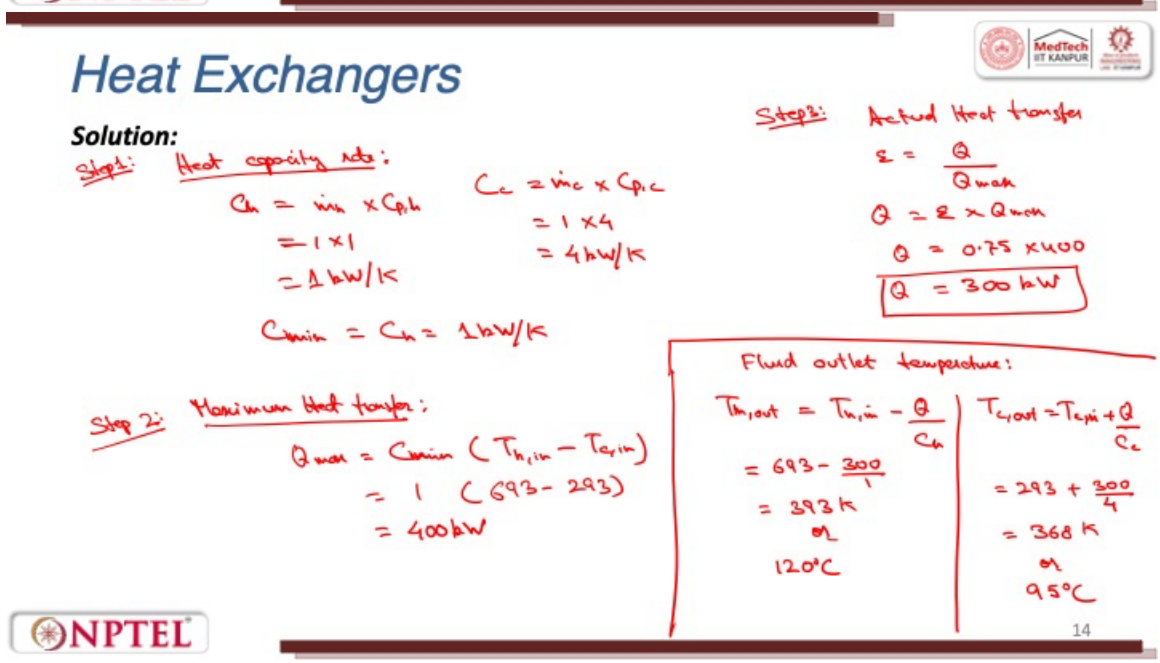
Where,

C_{min} - minimum heat capacity rate of the fluid

$T_{h,\,in}$ - inlet temperature of hot fluid (K)

$T_{c,\,in}$ - inlet temperature of cold fluid (K)





Let me take one problem statement here. Two fluids, A and B exchange heat in a counter flow heat exchanger. Fluid A enters at 420°C and has a mass flow rate of 1 kg/s. Fluid B enters at 20°C and also has a mass flow rate of 1 kg/s Effectiveness of heat exchanger is 75%. Find the heat transfer rate (Specific heat of fluid A is 1 kJ/kg K and that of fluid B is 4 kJ/kg K).

Given:

$T_{c,\ in}$ = 20°C = 293 K

$T_{h,\ in}$ = 420°C = 693 K

$C_{p,\ h}$ = 1kJ/kg K

$C_{p,\ c}$ = 4kJ/kg K

$m°_c = m°_h = 1kg/sec$

$\varepsilon = 75\% = 0.75$

Solution:

Step 1: Heat capacity rate:

$C_h = m°_h$ x $C_{p,\ h}$

= 1 x 1 = 1 kW/K

$C_{min} = C_h$ = 1 kW/K

Step 2: Maximum heat transfer:

$Q_{max} = C_{min} (T_{h,\ in} - T_{c,\ in})$

= 1 (693 – 293) = 400 kW

Step 3: Actual heat transfer:

$\varepsilon = \frac{Q}{Q_{max}}$

$Q = \varepsilon$ x Q_{max}

Q = 0.75 x 400

Q = 300 kW

One more thing you can calculate. I am just leaving it for you. You can also calculate the fluid outlet temperature.

Fluid Outlet Temperature:

$T_{h,\ out} = T_{h,\ in} - \frac{Q}{Ch}$

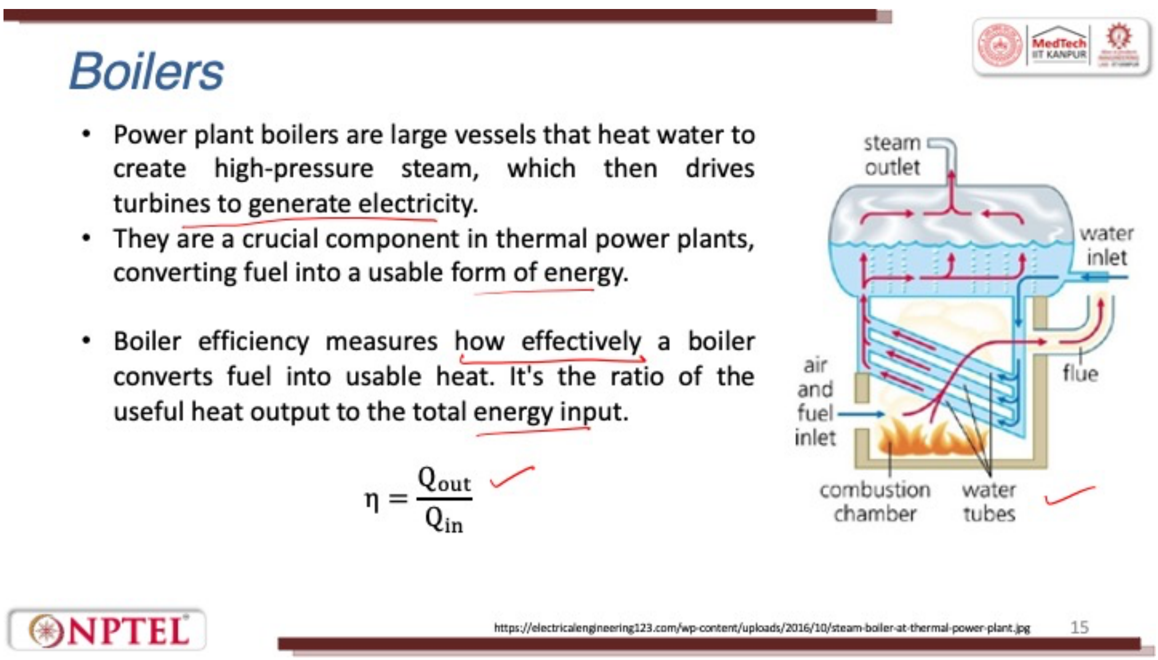
= 693 – 300/1 = 393 K or 120 °C

$T_{c,\,out} = T_{c,\,in} + \frac{Q}{Cc}$

= 293 + 300/4

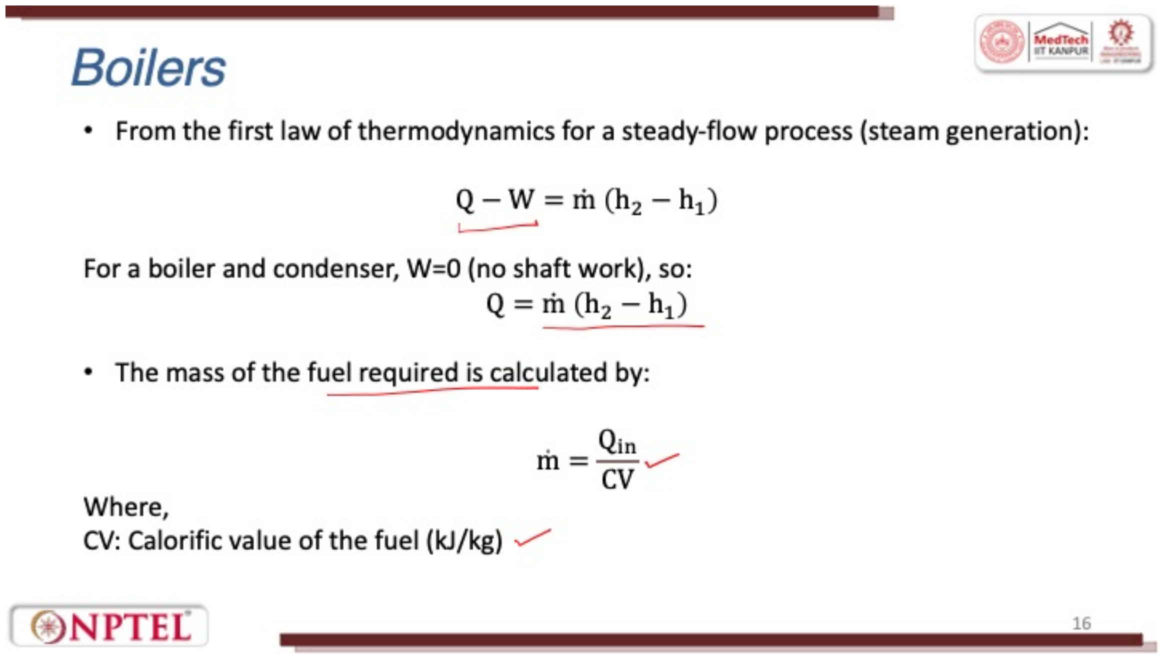
= 368 K or 95°C

This you can calculate further.



I will come to the next application, that is Boilers. Power plant boilers are large vessels that heat water to create high-pressure steam, which then drives turbines to generate electricity. They are crucial components in thermal power plants, converting fuel into a usable form of energy. Boiler efficiency measures how effectively a boiler converts fuel into usable heat.

The ratio of the useful heat output to the total energy input is the boiler efficiency. So, this is a boiler setup. This was discussed in the previous lecture. Professor Ramkumar has already discussed it.



Now, the first law of thermodynamics for a steady flow process, such as steam generation, states:

$$Q - W = \dot{m}\,(h_2 - h_1)$$

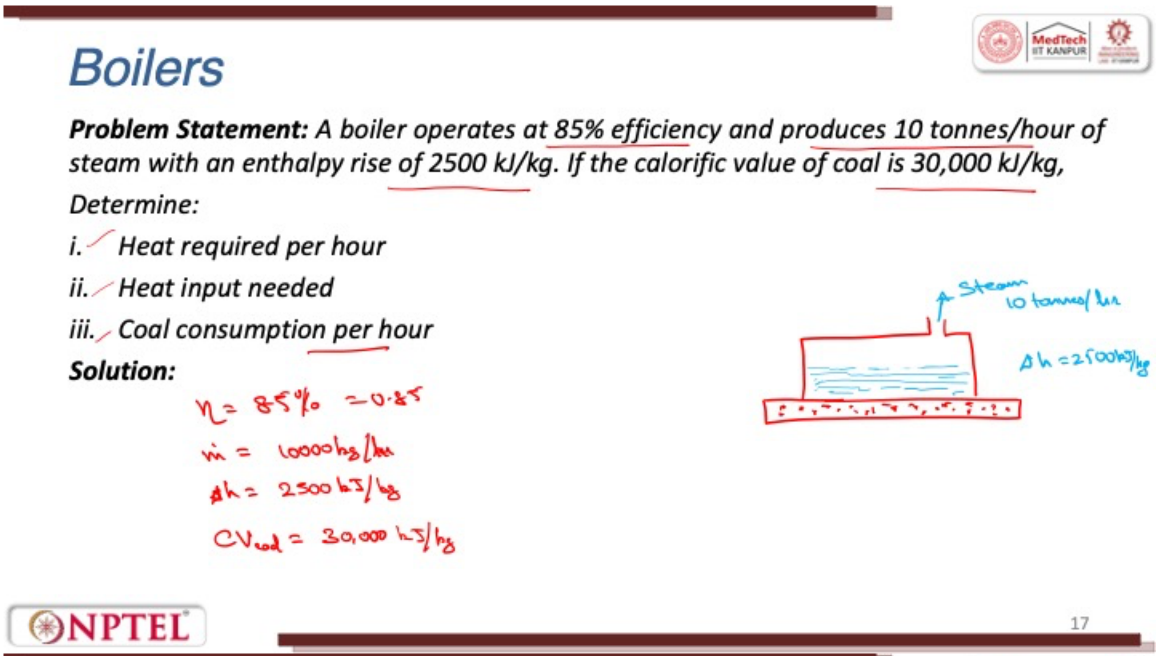
This we have discussed. We will talk about enthalpy and entropy. For a boiler and condenser, when W=0 (no shaft work), so:

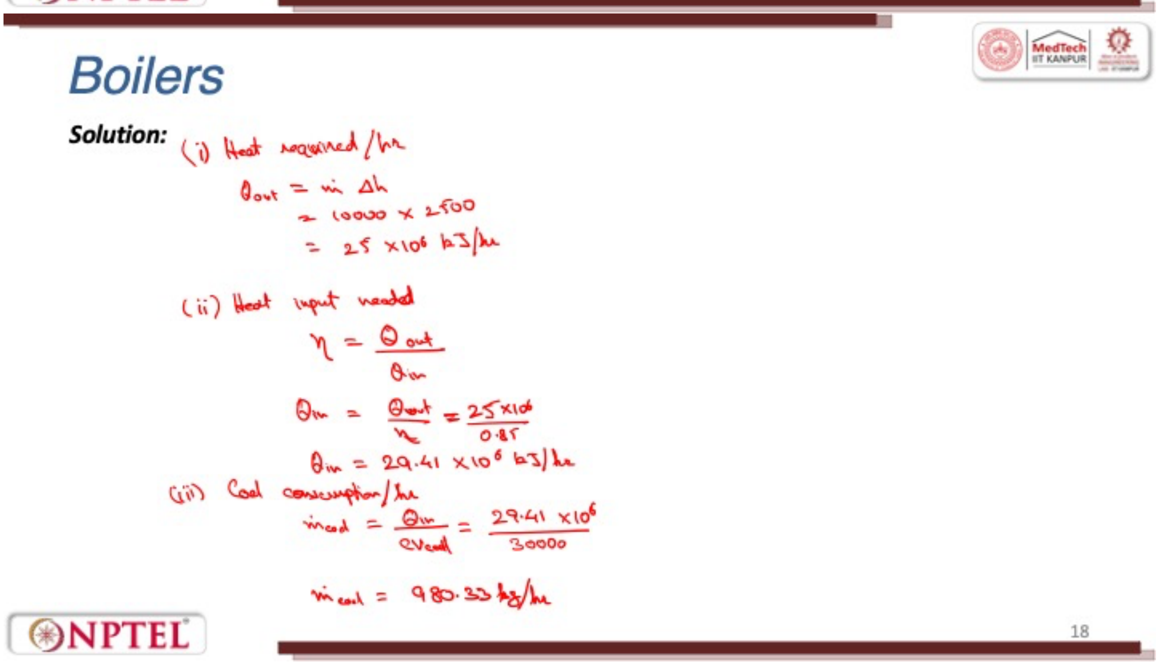
$$Q = \dot{m}\,(h_2 - h_1)$$

The mass of the fuel required is calculated by

$$\dot{m} = \frac{Q_{in}}{CV}$$

Where CV is a calorific value of the fuel in kilojoules per kg depending upon the fuel that we are using. Are we using coal? Primarily, coal is used depending on the type of coal available. Hard coal or soft coal—depending on the calorific value—the mass of the fuel is calculated.





Now, let me present a problem statement for a boiler. A boiler operates at 85% efficiency and produces 10 tonnes/hour of steam with an enthalpy rise of 2500 kJ/kg. If the calorific value of coal is 30,000 kJ/kg,

Determine:

i. Heat required per hour

ii. Heat input needed

iii. Coal consumption per hour

Given:

n = 85% = 0.85

$\dot{m}$ = 10000 kg/hr

h = 2500 kJ/kg

CV_{coal} = 30000 kJ/kg

Solution:

i. Heat required/hr

$Q_{out} = \dot{m}\Delta h$

= 10000 x 2500

= 25 x 10^6 kJ/hr

ii. Heat input needed

$n = \frac{Q_{out}}{Q_{in}}$

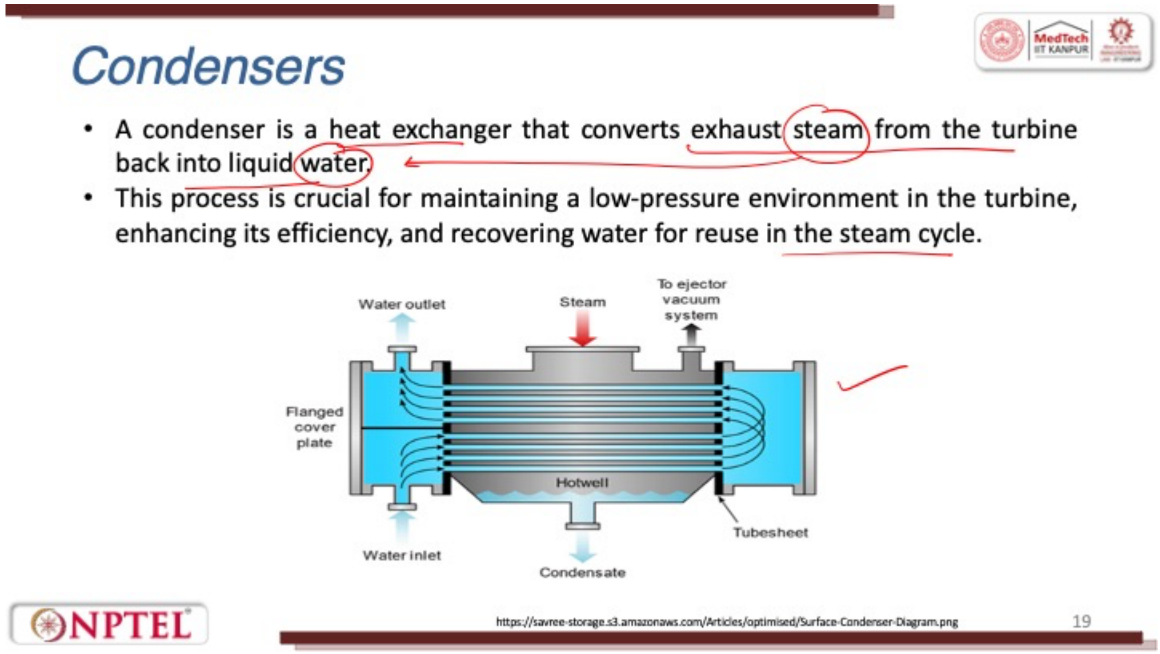
$Q_{in} = \frac{Q_{out}}{n} = \frac{25\times106}{0.85}$

Q_{in} = 29.41 x 10^6 kJ/hr

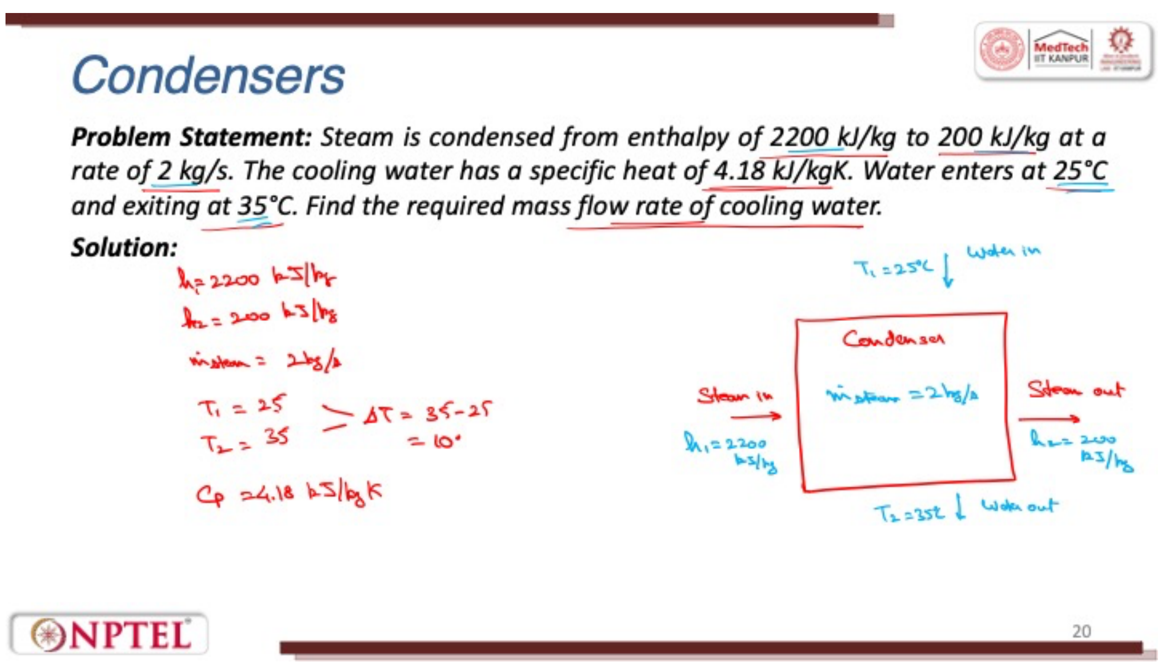
iii. Coal consumption/hr

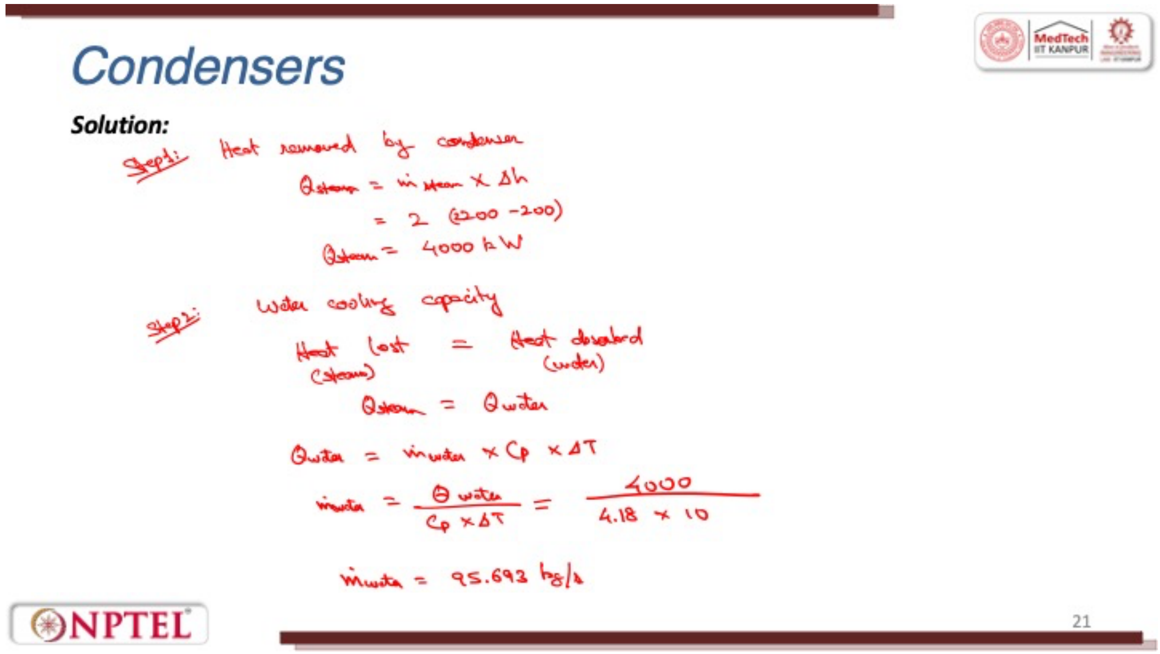
$\dot{m}_{coal} = \frac{Q_{in}}{CV_{coal}} = \frac{25\times10^6}{30000}$

$\dot{m}_{coal}$ = 980.33 kg/hr



Next I will talk about Condensers. A condenser is a heat exchanger that converts exhaust steam from the turbine back into liquid water. That is from the hot to the colder part. This process is crucial for maintaining a low-pressure environment in a turbine, enhancing its efficiency and recovering water for reuse in the steam cycle. The condenser mechanism has already been discussed. I will now address the problem statement directly. The calculations are very similar to those we have done for the heat exchanger and the boilers.





Here, the problem states that Steam is condensed from enthalpy of 2200 kJ/kg to 200 kJ/kg at a rate of 2 kg/s. The cooling water has a specific heat of 4.18 kJ/kgK. Water enters at 25°C and exiting at 35°C. Find the required mass flow rate of cooling water.

Given:

h1 = 2200 kJ/kg

h2 = 200 kJ/kg

$\dot{m}_{steam}$ = 2kg/s

T1 = 25

T2 = 35

= $\Delta T = 35 - 25 = 10°$

Cp = 4.18 kJ/kg K

Step 1: Heat removed by condenser

$Q_{steam} = \dot{m}_{steam} \times \Delta h$

= 2 (2200 – 200)

Q_{steam} = 4000 kW

Step2: Water cooling capacity

Heat cooling capacity

Heat lost = Heat absorbed

$Q_{steam} = Q_{water}$

$Q_{water} = \dot{m}_{water} \times Cp \times \Delta T$

$\dot{m}_{water} = \frac{Q_{water}}{Cp \times \Delta T} = \frac{4000}{4.18 \times 10}$

$\dot{m}_{water}$ = 95.693 kg/s

With this, my lecture is closed, and I have covered heat transfer, mass transfer, and applications of thermodynamics in these two tutorials. I will talk about the virtual laboratory setup in the next lecture, where I will discuss heat transfer systems and try to see some experiments in the virtual environment.

Thank you.