Basics of Mechanical Engineering-3

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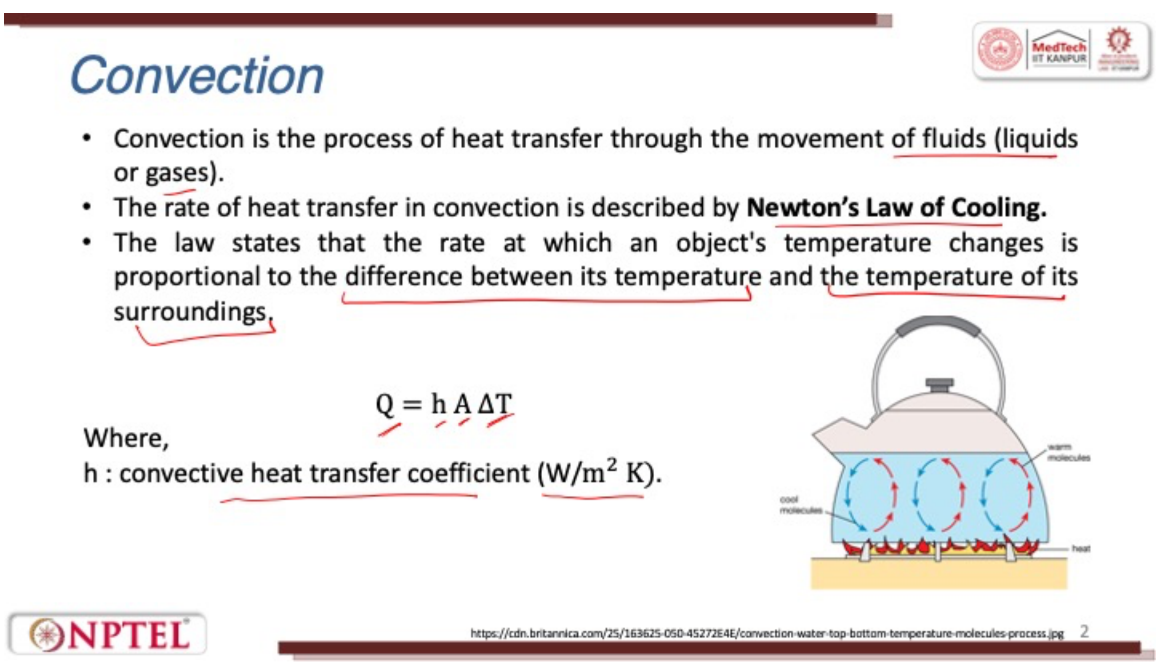
Week 07

Lecture 30: Tutorial 6 Heat Transfer, Part 2 of 2

Welcome back to the next part of the tutorial on Heat Transfer in the course Basics of Mechanical Engineering 3. I am Dr. Amandeep Singh Oberoi from IIT Kanpur. We have talked about conduction and discussed certain problem statements where conduction is the transfer of heat through a medium, that is, through the movement of molecules.

Now, convection is also a transfer of heat. This transfer of heat is through fluids, that is, through some medium, through gases or through liquids. For example, heat transfer through air is convection, as we have discussed. Let me try to recall the concept and take certain problem statements.

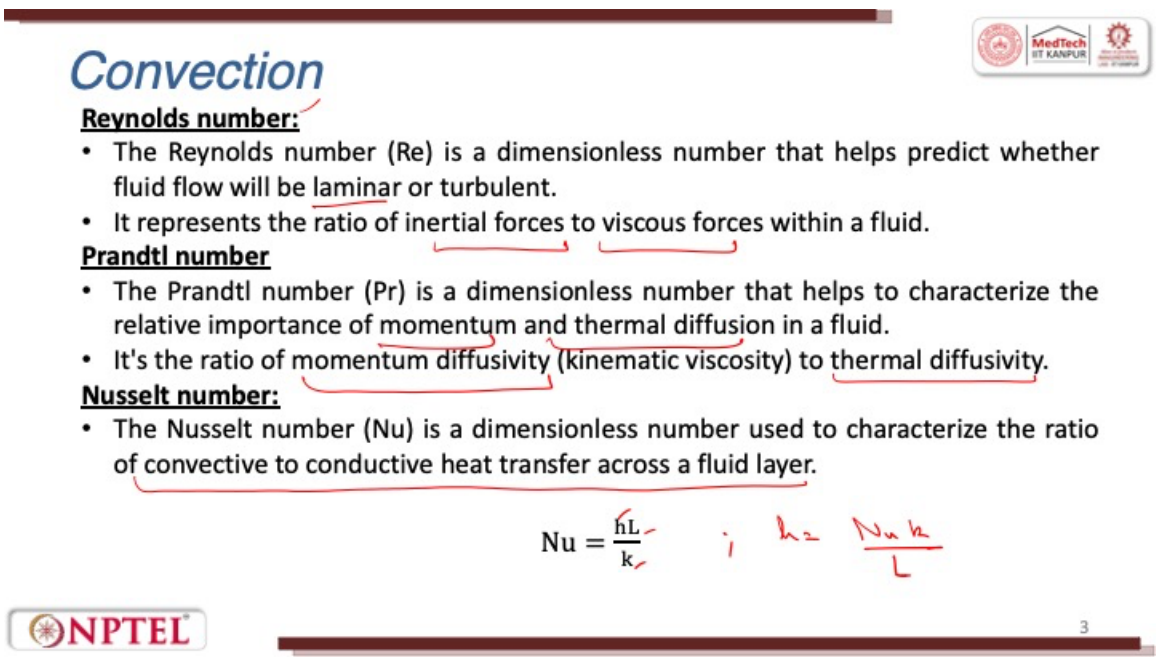


Convection: Convection is the process of heat transfer through the movement of fluids, that is, liquids or gases. The rate of heat transfer in convection is described by Newton's law of cooling. The law states that the rate at which an object's temperature changes is proportional to the difference between its temperature and the temperature of its surroundings.

That is, it simply says the rate of heat transfer $Q = h\,A\,\Delta T$

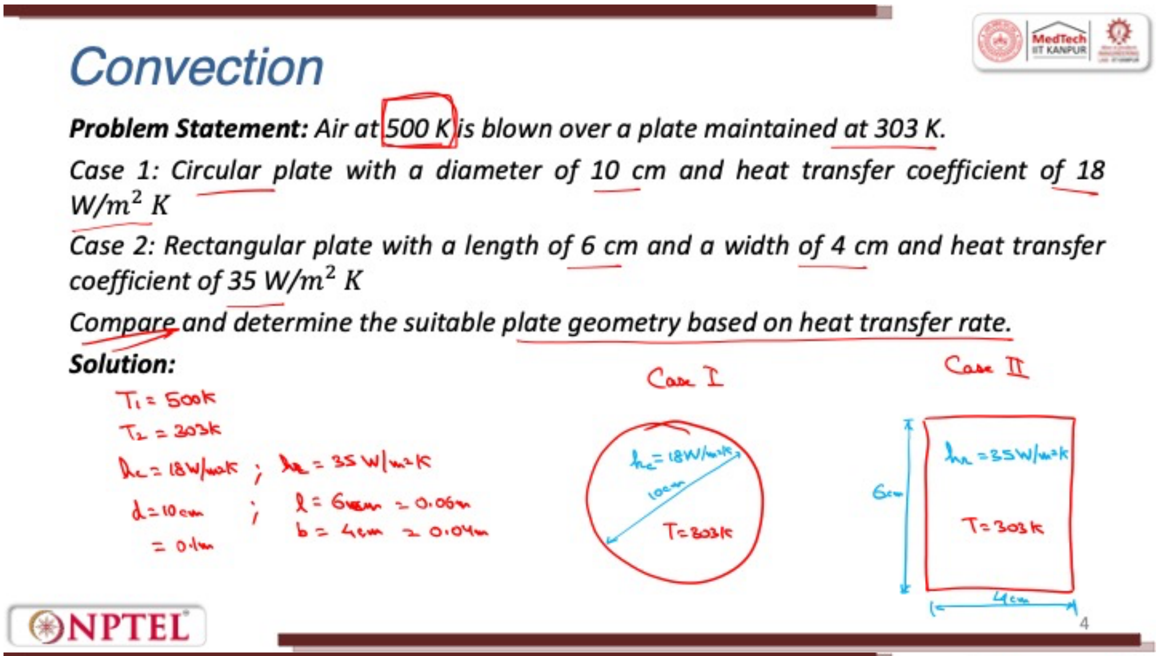
Where, h : convective heat transfer coefficient ($W/m^2\,K$)

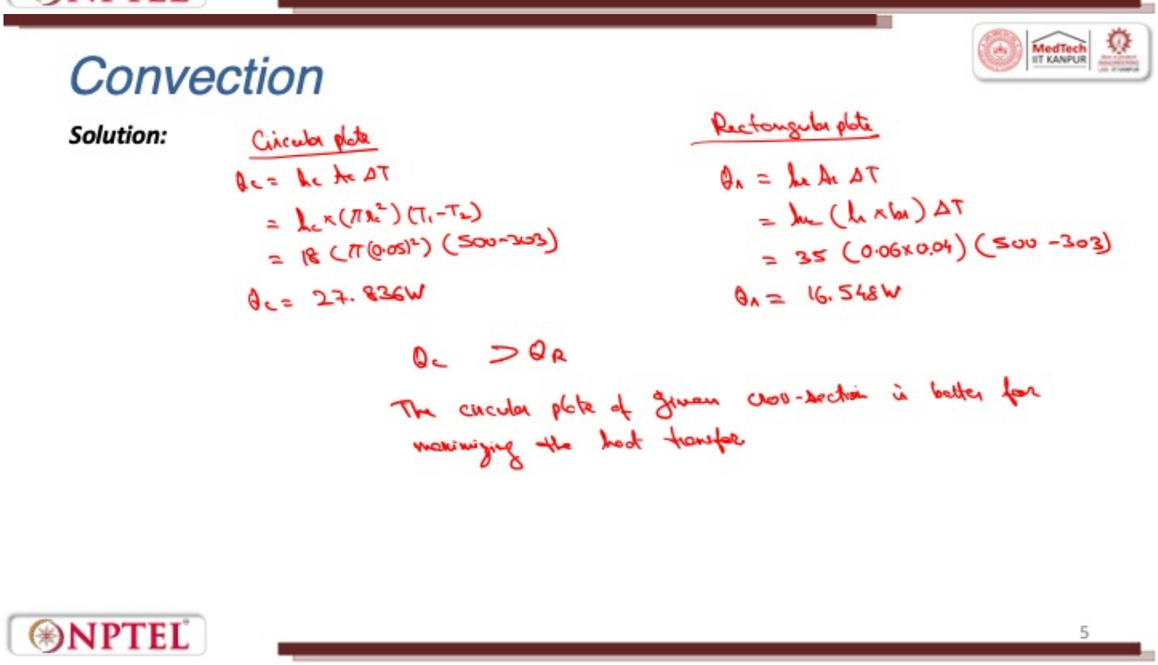
ΔT is the difference between the temperature and the temperature of the surroundings.



Now certain important numbers are there, like Reynolds number. The Reynolds number (Re) is a dimensionless number that helps predict flow patterns. It determines whether fluid flow will be laminar or turbulent, representing the ratio of inertial forces to viscous forces within a fluid. If the number is higher than a specific threshold limit, the flow is turbulent. Within that range, lower than that, it is a streamlined flow, or we call it a laminar flow.

Then comes the Prandtl number. The Prandtl number is another dimensionless number that helps characterize the relative importance of momentum and thermal diffusion in a fluid. It is the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity. Then comes the Nusselt number. Nusselt number is again a dimensionless number used to characterize the ratio of Convective to conductive heat transfer across fluid that is $\mathrm{Nu} = \frac{\mathrm{hL}}{\mathrm{k}}$. Where h as I mentioned is convective heat transfer coefficient, k is the conductive heat transfer coefficient, L is the length that is under consideration.





Let me take a problem statement here. Air at 500 K is blown over a plate maintained at 303 K.

Case 1: Circular plate with a diameter of 10 cm and heat transfer coefficient of 18 W/m^2 K

Case 2: Rectangular plate with a length of 6 cm and a width of 4 cm and heat transfer coefficient of 35 W/m^2 K

Compare and determine the suitable plate geometry based on heat transfer rate.

Given:

$T1 = 500$ K

$T2 = 303$ K

$hc = 18\ W/m^2K$; $hr = 35\ W/m^2K$

d = 10 cm = 0.1; l = 6 cm = 0.06 m

b = 4 cm = 0.04 m

Solution:

Circular plate:

$Qc = h\,A\,\Delta T$

$= hc \times (\pi\,(0.05)^2)\,(500 - 303)$

$Qc = 27.836$ W

Rectangular plate:

$Qr = h\,A\,\Delta T$

$= hr\,(lr \times br)\,\Delta T$

$= 35\,(0.06 \times 0.04)\,(500 - 303)$

$Qr = 16.548$ W

So, $Qc > Qr$

The circular plate of given cross section is better for maximizing the heat transfer.

Convection

Problem Statement: *A flat plate of length 1 meter and width 0.3 meters is exposed to forced convection. The Reynolds number of the flow is $Re=2.65\times10^5$, the Prandtl number is $Pr=0.682$, and the thermal conductivity of air is $k=0.0364$ W/m K. The surface temperature of the plate is 250 ^0C and the ambient air temperature is 78 ^0C. Assuming turbulent flow, the Nusselt number for the plate can be determined using the relation:*

$$Nu = 0.332\ Re^{0.5}\ Pr^{0.33}$$

Determine the total heat transfer rate from the plate.

Solution:

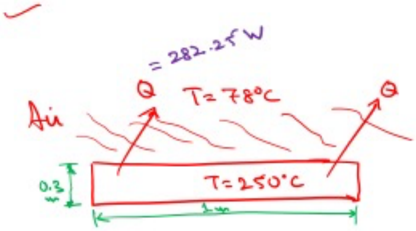
Re = Pr =

w = 0.3m

k = 0.0364 W/mK

T_1 = 250°C

T_2 = 78°C



Convection

Solution:

$$Q = hA\Delta T$$

$$h = \frac{Nu\, k}{L}$$

$$Nu = 0.332 (Re)^{0.5}\ Pr^{0.33}$$

$$= 0.332 (2.65\times10^5)^{0.5} (0.682)^{0.33}$$

$$= 150.45$$

$$h = \frac{150.45 \times 0.0364}{1}$$

$$h = 5.47\ W/m^2K$$

$$Q = 5.47 \times (1 \times 0.3) \times (250-78)$$

$$Q = 282.25 W$$

Let me see another problem statement where there is a flat plate once again. A flat plate of length 1 meter and width 0.3 meters is exposed to forced convection. The Reynolds number of the flow is $Re=2.65\times10^5$, the Prandtl number is $Pr=0.682$, and the thermal conductivity of air is $k=0.0364$ W/m K. The surface temperature of the plate is 250 ^0C and the ambient air temperature is 78 ^0C. Assuming turbulent flow, the Nusselt number for the plate can be determined using the relation:

$$Nu = 0.332\ Re^{0.5}\ Pr^{0.33}$$

Determine the total heat transfer rate from the plate.

Given:

$Re = 2.65 \times 10^5$

$Pr = 0.682$

$w = 0.3$ m

$k = 0.0364$ W/mK

$T1 = 250\ ^0C$

$T1 = 78\ ^0C$

Solution:

$Q = h\,A\,\Delta T$

$h = \frac{Nu\,k}{L}$

$Nu = 0.332\ Re^{0.5}\ Pr^{0.33}$

$= 0.332\ (2.65 \times 10^5)^{0.5}\ (0.682)^{0.33}$

$= 150.45$

$h = \frac{150.45 \times 0.0364}{1}$

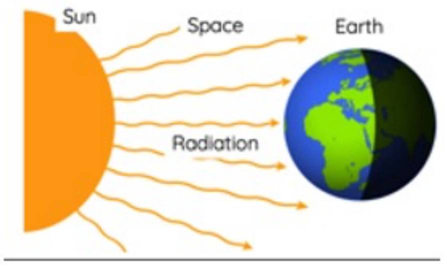
$h = 5.47$ W/m^{2}K

$Q = 5.47 \times (1 \times 0.3) \times (250 - 78)$

$Q = 282.25$

Radiation

- Radiation is the transfer of thermal energy through electromagnetic waves, most commonly infrared, but it can also be visible and ultraviolet. Unlike conduction (which requires direct contact between materials) and convection (which requires a fluid medium), radiation does not need any medium and can occur in a vacuum.
- For example, heat from the Sun travels millions of kilometers through space before warming the Earth.



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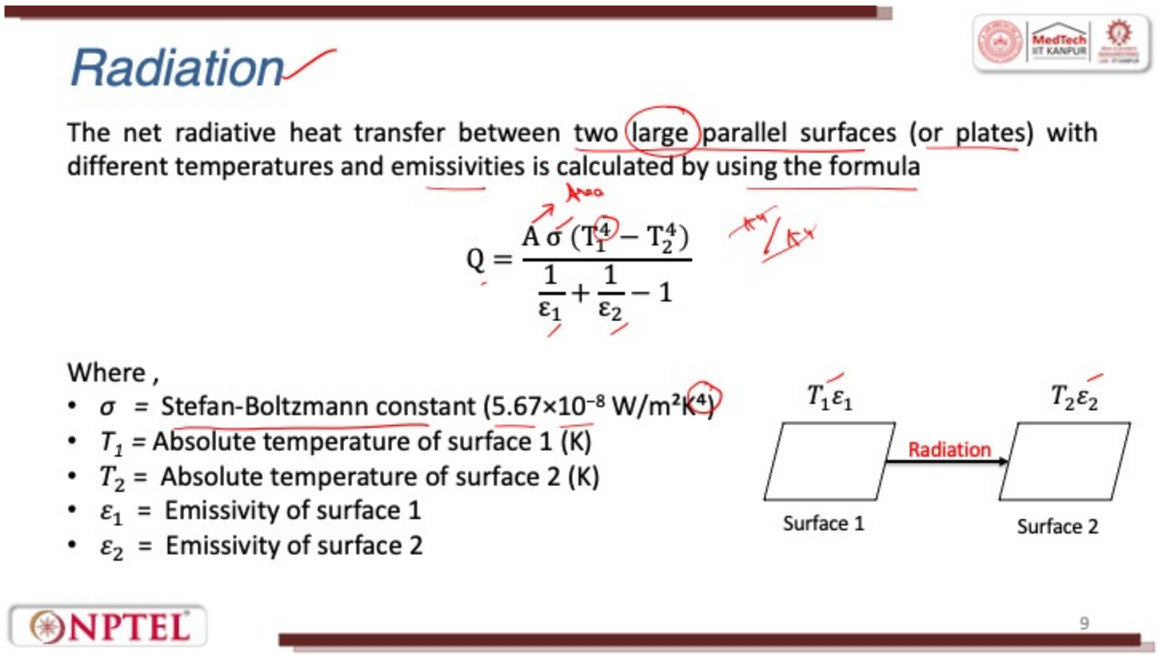
Next, we will take some problem statements on radiation. That is another mode of heat transfer. We discussed about conduction. We discussed about convection, where heat transfer happens due to movement either of molecules or of fluid. In radiation, it is only transfer of thermal energy through electromagnetic waves most commonly infrared, but it can also be visible and ultraviolet. Unlike conduction which requires direct contact between materials, a convection which requires a fluid medium, radiation does not need any medium and can occur in a vacuum. travels millions of kilometers through space before warming the earth.

The factor that determines the radiation capacity of a body is known as emissivity. Emissivity is the amount of heat that a specific body could transfer in comparison to a black body which has emissivity value of 1.

When we talk about emissivity and its comparison to a black body, it is taken at the same environmental conditions, specifically at same temperature. For example, if at suppose 100 degrees, black body transfers a specific amount of heat. What is the amount of heat this body transfers at 100 degree, which is under test. This we will do a small test under virtual laboratory in the next lectures, when we will discuss about the virtual laboratory demonstration on thermodynamics.



Regarding radiation; the net radiative heat transfer between two large surfaces or plates with different temperatures and emissivities is calculated by this formula. When we say large plates, they are large because we need the heat transfer to happen through radiation. It is

$$Q = \frac{A\,\sigma\,(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

So, there is radiation that goes from surface 1 to surface 2 depending upon the emissivity of both the surfaces that is there. Where ,

- σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m²K⁴)
- T_1 = Absolute temperature of surface 1 (K)
- T_2 = Absolute temperature of surface 2 (K)
- ε_1 = Emissivity of surface 1
- ε_2 = Emissivity of surface 2

Radiation

Problem statement : *Two large plates are maintained at a temperature of 900 K and 500 K respectively each plate has area of 6 metres square . Compare the heat exchange between the plates for the following cases .*

i. both plates are black

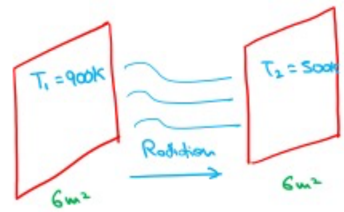
ii. plates have a emissivity of 0.5

Solution:

$T_1 = 900K$

$T_2 = 500K$

$A = 6m^2$



Radiation

Solution: 1. Heat exchange (transfer) when both plates are black

$\varepsilon_1 = \varepsilon_2 = 1$

$$Q_{\varepsilon=1} = \frac{A\,\sigma\,(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

$$= \frac{6 \times 5.67 \times 10^{-8}\,(900^4 - 500^4)}{\frac{1}{1} + \frac{1}{1} - 1}$$

$$\left(\frac{1}{100}\right)^4 = 10^{-8}$$

$$= \frac{6 \times 5.67\,\left(\left(\frac{900}{100}\right)^4 - \left(\frac{500}{100}\right)^4\right)}{1}$$

$$= 202\ \text{kW (approx.)}$$

Radiation

Solution: 2. Heat exchange (transfer) for given emissivity where

$\varepsilon_1 = \varepsilon_2 = 0.5$

$$Q_{\varepsilon=0.5} = \frac{A\,\sigma\,(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

$$= \frac{6 \times 5.67\,\left(\left(\frac{900}{100}\right)^4 - \left(\frac{500}{100}\right)^4\right)}{\frac{1}{0.5} + \frac{1}{0.5} - 1}$$

$$= 67.3\ \text{kW (approx.)}$$

Now, let me take a problem statement, and we'll try to understand how to calculate the emissivity for a specific problem. Two large plates are maintained at a temperature of 900 K and 500 K respectively each plate has area of 6 metres square . Compare the heat exchange between the plates for the following cases .

i. both plates are black

ii. plates have a emissivity of 0.5

Given:

T1 = 900 K

T2 = 500 K

A = 6 m^2

1. Heat exchange (transfer) when both plates are blocked

ε1 = ε2 = 1

$$Q_{\varepsilon=1} = \frac{A\,\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1}$$

$$= \frac{6\times 5.67\times10^{-8}\left(900^4 - 500^4\right)}{\frac{1}{1}+\frac{1}{1}-1}$$

$$= \frac{6\times 5.67\left(\frac{900^4}{100} - \frac{500^4}{100}\right)}{1} \qquad \left(\frac{1}{100}\right)^4 = 10^{-8}$$

= 2.02 kW (approx.)

2. Heat exchange (transfer) for given emissivity volume

ε1 = ε2 = 0.5

$$Q_{\varepsilon=0.5} = \frac{A\,\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1}$$

$$= \frac{6\times 5.67\times10^{-8}\left(900^4 - 500^4\right)}{\frac{1}{0.5}+\frac{1}{0.5}-1}$$

= 67.3 kW (approx.)

This was regarding radiation. With this, my tutorial session on heat transfer is finished. I will try to talk about mass transfer and some applications of thermodynamics in the coming tutorial.

Thank you.