EN671: Solar Energy Conversion Technology

Fundamentals of Flat Plate Collectors

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Basics of Heat Transfer

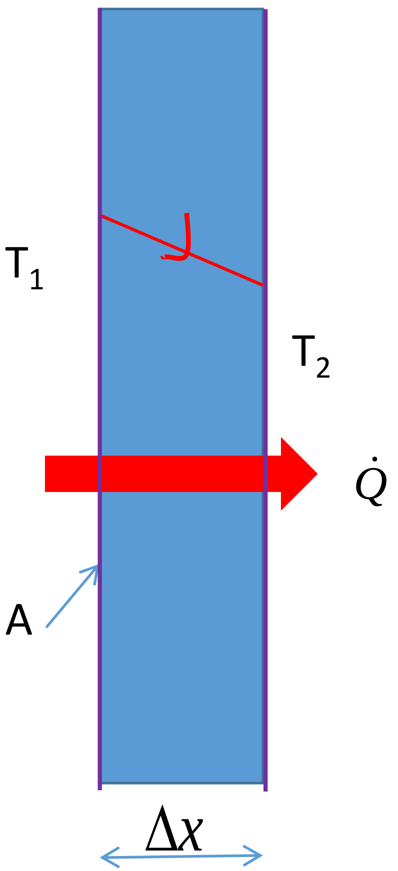
- Heat is a form of energy that can be transferred from one system to another as a result of temperature difference.
- Thermodynamic analysis is concerned with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another.
- The science that deals with the determination of the *rates* of such energy transfers is known as *heat transfer*.
- The transfer of energy as heat is always from the higher temperature medium to the lower temperature medium, and heat transfer stops when the two mediums reach the same temperature.

Modes of heat transfer

- Conduction (Fourier law of heat conduction)
- Convection – Newton’s law of cooling
  - Natural Convection
  - Forced convection
- Radiation - Stefan Boltzmann’s Law
- All modes of heat transfer require the existence of a temperature difference.

Conduction

- Conduction is the transfer of heat between two bodies or two parts of the same body through molecules which are more or less stationary.
- The rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer.



Heat conduction through a large plane wall of thickness Δx and area A.

$$\text{Rate of heat conduction} \propto \frac{(\text{Area})\times(\text{Temperature difference})}{\text{Thickness}}$$

$$\dot{Q}_{\text{cond}} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x} \qquad (\text{W})$$

When $x \to 0$ $\dot{Q}_{\text{cond}} = -kA\dfrac{dT}{dx}$

Conduction

- Thermal conductivity: The rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference.
- The thermal conductivity of a material is a measure of the ability of the material to conduct heat.
- A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or *insulator.*

$$\frac{dT}{dx} = \frac{q}{K}$$

For same q, $if \;\; K \;\; is \;\; low,$ $\frac{dT}{dx}$ will be large (for insulator)

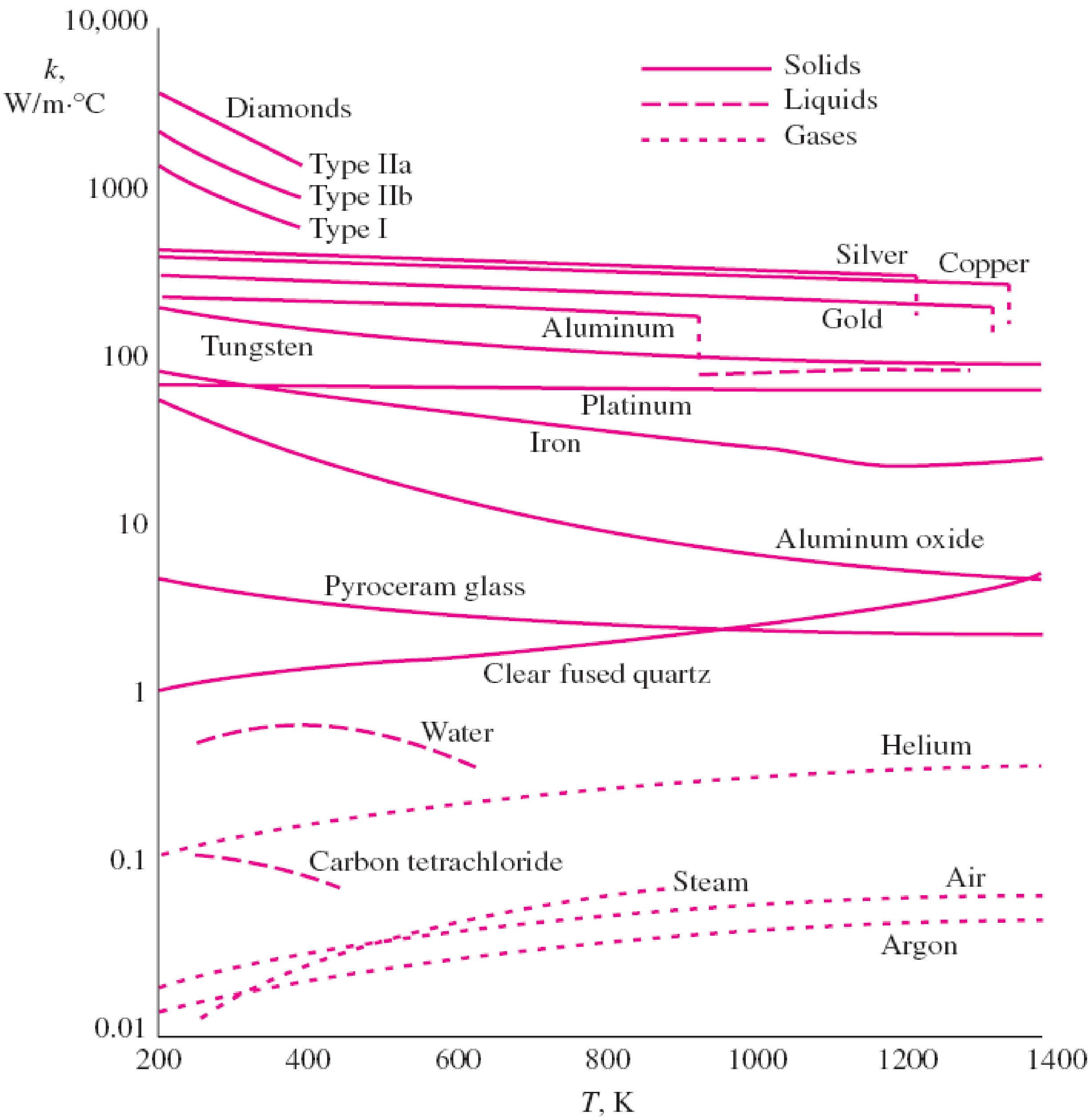
$\Rightarrow$ Large temperature difference accross the wall

For same q, $if \;\; K \;\; is$ high, $\frac{dT}{dx}$ will be small (for conductor)

$\Rightarrow$ Small temperature difference accross the wall

The thermal conductivities of some materials at room temperature

Material	k, W/m · °C*
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminum	237
Iron	80.2
Mercury (l)	8.54
Glass	0.78
Brick	0.72
Water (l)	0.607
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026



The variation of the thermal conductivity of various solids, liquids, and gases with temperature.

Thermal conductivities of materials vary with temperature

	k, W/m·K	
T, K	Copper	Aluminum
100	482	302
200	413	237
300	401	237
400	393	240
600	379	231
800	366	218

Thermal Diffusivity

$$\alpha = \frac{\text{Heat conduction}}{\text{Heat storage}} = \frac{k}{\rho c_p} \qquad (\text{m}^2/\text{s})$$

c_p Specific heat, J/kg · °C: Heat capacity per unit mass
ρc_p Heat capacity, J/m^3·°C: Heat capacity per unit volume
α Thermal diffusivity, m^2/s: Represents how fast heat diffuses through a material

- ✓ A material that has a high thermal conductivity or a low heat capacity will obviously have a large thermal diffusivity.
- ✓ The larger the thermal diffusivity, the faster the propagation of heat into the medium.
- ✓ A small value of thermal diffusivity means that heat is mostly absorbed by the material and a small amount of heat is conducted further.

The thermal diffusivities of some materials at room temperature

Material	α, m^2/s*
Silver	149×10^{-6}
Gold	127×10^{-6}
Copper	113×10^{-6}
Aluminum	97.5×10^{-6}
Iron	22.8×10^{-6}
Mercury (l)	4.7×10^{-6}
Marble	1.2×10^{-6}
Ice	1.2×10^{-6}
Concrete	0.75×10^{-6}
Brick	0.52×10^{-6}
Heavy soil (dry)	0.52×10^{-6}
Glass	0.34×10^{-6}
Glass wool	0.23×10^{-6}
Water (l)	0.14×10^{-6}
Beef	0.14×10^{-6}
Wood (oak)	0.13×10^{-6}

Convection

Convection: The mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of *conduction* and *fluid motion*.

- ✓ The faster the fluid motion, the greater the convection heat transfer.
- ✓ In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction.

- When the temperature difference produces a density difference which results in mass movement, the process is called free or natural convection.
- When the mass motion of the fluid is caused by an external device like an pump, compressor, blower, or fan the process is called forces convection.
- Heat transfer processes that involve *change of phase* of a fluid are also considered to be convection because of the fluid motion induced during the process, such as the rise of the vapor bubbles during boiling or the fall of the liquid droplets during condensation.

Convection

- Whether the convection process is natural or forced, there is always a liquid film immediately adjacent to the wall where the temperature varies from t_w to t_f (heat is first conducted through this fluid film and then it is transported by fluid motion)
- The rate of heat transfer through the film,

$$\boxed{Q = -K_f \times A \times \frac{t_f - t_w}{\delta}}$$

Film coefficient of heat transfer or heat transfer coefficient, $\boxed{h = K_f / \delta}$

Newton's law of Cooling: $\boxed{Q = hA\left(t_w - t_f\right)}$

- ✓ The convection heat transfer coefficient *h* is not a property of the fluid.
- ✓ It is an experimentally determined parameter whose value depends on all the variables influencing convection such as
  - ➢ the surface geometry
  - ➢ the nature of fluid motion
  - ➢ the properties of the fluid
  - ➢ the bulk fluid velocity

Correlations for convection heat transfer

Forced convection

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n};\, n = 0.4 \text{ when the fluid is heated}$$

$$n = 0.3 \text{ when the fluid is cooled}$$

Free/Natural convection

$$Nu = B.\left(Gr.\mathrm{Pr}\right)^{a};\text{value of B and a are flow specific}$$

Ex.1: Water flows inside a tube of 5 cm in diameter and 3 m long at a velocity of 0.8 m/s. Determine the heat transfer coefficient and the rate of heat transfer if the mean water temperature is 50^{o}C and wall is isothermal at 70 ^{o}C. For water at 60^{o}C, take K = 0.66 W/mK, $\upsilon = 0.478 \times 10^{-6} m^2 / s$

Pr = 2.98

Radiation

- Unlike conduction and convection, the transfer of heat by radiation does not require the presence of an *intervening medium*.
- Heat transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.
- In heat transfer studies we are interested in *thermal radiation*, which is the form of radiation emitted by bodies because of their temperature.
- All bodies at a temperature above absolute zero emit thermal radiation.
- Radiation is a *volumetric phenomenon*, and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees.

Radiation

If Q is the total radiant energy incident upon the surface of a body, some part of it will be absorbed (Q_a), some will be reflected (Q_r) and some will be transmitted (Q_t)through the body

$$\therefore Q = Q_a + Q_r + Q_t$$

$$\Rightarrow \frac{Q_a}{Q} + \frac{Q_r}{Q} + \frac{Q_t}{Q} = 1$$

$$\Rightarrow \underbrace{\alpha}_{\text{Absorptivity}} + \underbrace{\rho}_{\text{Reflectivity}} + \underbrace{\tau}_{\text{Transmissivity}} = 1$$

- ✓ For opaque body,

$$\boxed{\tau = 0 \text{ and } \alpha + \rho = 1, \text{ most solids are opaque}}$$

- ✓ A body which absorbs all the incident radiation is called a black body.
- ✓ A black body is also the best radiator.
- ✓ Most radiating surfaces are gray and have an emissivity factor less than unity

$$\boxed{\varepsilon = \frac{\text{Actual radiation of gray body at T (K)}}{\text{Radiation of a black body at T (K)}}}$$

The rate at which energy is radiated by a black body at temperature T (K) is given by the Stefan Boltzmann law:

$$\boxed{Q = \overbrace{\sigma}^{\text{Stefan-Boltzmann Constant} = 5.67\times10^{-8}\ \mathrm{W/m^2K^4}} \underbrace{A}_{\text{Surface area, } m^2} T^4}$$

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \qquad \text{(W)}$$

Radiation emitted by real surfaces

Emissivity ε: A measure of how closely a surface approximates a blackbody for which $\varepsilon = 1$ of the surface. $0 \le \varepsilon \le 1$.

Blackbody
(Ts = 450 K)

$$\boxed{\begin{aligned} \dot{Q}_{\text{emit, max}} &= \sigma T_s^4 \times (\varepsilon = 1) \\ &= 2327\ \text{W/m}^2 \end{aligned}}$$

Blackbody radiation represents the maximum amount of radiation that can be emitted from a surface at a specified temperature.

Emissivities of some materials at 300 K

Material	Emissivity
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

The radiant heat exchange between two gray bodies at temperature T_1 and T_2 depends on how the two bodies view each other and their emissivities

$$Q_{1-2} = \sigma A_1 \xi_{1-2} \left(T_1^4 - T_2^4\right)$$

ξ_{1-2} View factor for gray bodies (fraction of total radiant energy leaving gray surface 1 and reaching gray surface 2)

$$\xi_{1-2} = \frac{1}{\left(\frac{1}{\varepsilon_1} - 1\right) + \frac{1}{F_{1-2}} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2} - 1\right)}$$

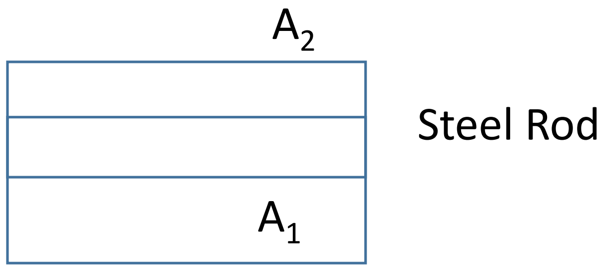
ε_1 and ε_2 are the emissivities of the two bodies of surface areas A_1 and A_2

F_{12} = *Configuration factor of two similar black bodies or the fraction of energy that leaves the black surface 1 and is incident on the black surface 2.*

Reciprocity Theorem $\Rightarrow$ $A_1 F_{12} = A_2 F_{21}$

- **For two infinite parallel gray planes, (all the energy leaving surface 1 strikes surface 2)** $A_1 = A_2$, $F_{12} = F_{21}$, $\xi_{1-2} = \dfrac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$
- **For two concentric cylinders or spheres, A_1 = surface area of the inner cylinder,** $F_{12} = 1$, $\xi_{1-2} = \dfrac{1}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2} - 1\right)}$
- **When the enclosed body (area A_1) is very small compared to the enclosure surface, $A_2 >> A_1$,** $\xi_{1-2} = \varepsilon_1$

Ex. 2: A long steel rod of 2 cm diameter is to be heated from 450°C to 550°C. It is placed concentrically in along cylindrical furnace which has an inside diameter of 16 cm. Inner surface of the furnace is at a temperature of 1100°C and has an emissivity of 0.85. If the surface of the rod has an emissivity of 0.6, calculate the average rate of heat absorption during the heating process.

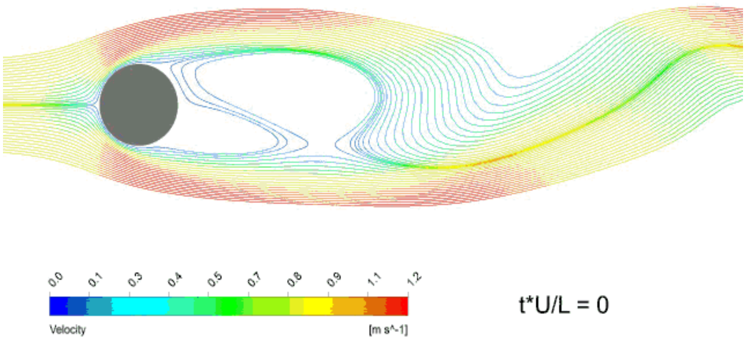


Reynolds Number

- ✓ The transition from laminar to turbulent flow depends on the *geometry, surface roughness, flow velocity, surface temperature,* and *type of fluid*.
- ✓ The flow regime depends mainly on the ratio of *inertia forces* to *viscous forces* (Reynolds number).

$$\mathrm{Re} = \frac{\text{Inertia forces}}{\text{Viscous forces}} = \frac{V_{avg} D}{\nu} = \frac{\rho V_{avg} D}{\nu}$$

- ✓ Critical Reynolds number, Re_{cr}: The Reynolds number at which the flow becomes turbulent.
- ✓ The value of the critical Reynolds number is different for different geometries and flow conditions.



The Reynolds number can be viewed as the ratio of inertial forces to viscous forces acting on a fluid element.

Nusselt Number

In convection studies, it is common practice to make non-dimensionalize the governing equations and combine the variables, which group together into *dimensionless numbers* in order to reduce the number of total variables.

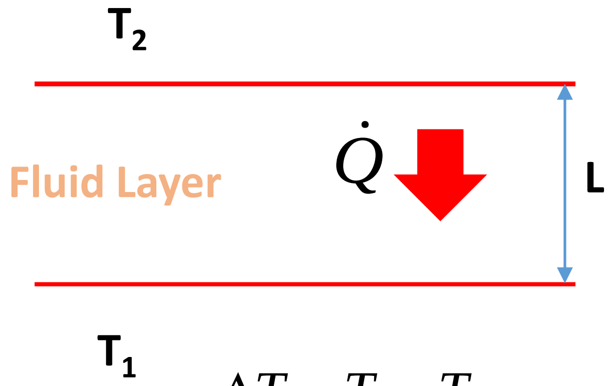
Nusselt number: Dimensionless convection heat transfer coefficient

$$Nu = \frac{h \times L_c}{k}$$

L_c characteristic length

$$\dot{q}_{conv} = h\Delta T$$

$$\dot{q}_{cond} = k\frac{\Delta T}{L} \qquad \frac{\dot{q}_{conv}}{\dot{q}_{cond}} = \frac{h\Delta T}{k\Delta T / L} = \frac{hL}{k} = \mathrm{Nu}$$



$$\Delta T = T_2 - T_1$$

Heat transfer through a fluid layer of thickness *L* and temperature difference ΔT.

- ✓ The Nusselt number represents the enhancement of heat transfer through a fluid layer as a result of convection relative to conduction across the same fluid layer.
- ✓ The larger the Nusselt number, the more effective the convection.
- ✓ A Nusselt number of Nu = 1 for a fluid layer represents heat transfer across the layer by pure conduction.

Prandtl Number

The relative thickness of the velocity and the thermal boundary layers is best described by the *dimensionless* parameter Prandtl number

$$\Pr = \frac{\text{Molecular diffucivity of momentum}}{\text{Molecular diffucivity of heat}} = \frac{\nu}{\alpha} = \frac{\mu C_p}{k}$$

Typical ranges of Prandtl numbers for common fluids

Fluid	Pr
Liquid metals	0.004–0.030
Gases	0.7–1.0
Water	1.7–13.7
Light organic fluids	5–50
Oils	50–100,000
Glycerin	2000–100,000

Courtesy: Heat and Mass Transfer: Fundamentals & Applications Fourth Edition Yunus A. Cengel, Afshin J. Ghajar McGraw-Hill, 2011

- ✓ The Prandtl numbers of gases are about 1, which indicates that both momentum and heat dissipate through the fluid at about the same rate.
- ✓ Heat diffuses very quickly in liquid metals (Pr << 1) and very slowly in oils (Pr >> 1) relative to momentum.
- ✓ Consequently the thermal boundary layer is much thicker for liquid metals and much thinner for oils relative to the velocity boundary layer.

Grashof Number and Rayleigh Number

Grashof number, Gr, is defined as the ratio between the buoyancy force and the viscous force.

$$\boxed{Gr = \frac{g\beta'\Delta T L^3}{\nu^2} = \frac{g\beta'(T_S - T_\infty)L^3}{\nu^2}}$$

- ✓ **Grashof number replaces the Reynolds number in the convection correlation equation.**
- ✓ In free convection, buoyancy driven flow sometimes dominates the flow inertia, therefore, the Nusselt number is a function of the Grashof number and the Prandtl number [Nu=f(Gr, Pr)].
- ✓ The Rayleigh number, Ra = Gr x Pr.
- ✓ **The most important use of the Rayleigh number is to characterize the laminar to turbulence transition of a free convection boundary layer flow.**
- ✓ For example, when $Ra>10^9$, the vertical free convection boundary layer flow over a flat plate becomes turbulent.

Heat Transfer coefficient between inclined parallel surfaces

- Buchberg *et al.* developed the following correlations based on the experimental investigation of natural convection heat transfer coefficient for the enclosed space *(between the absorber plate to the first cover and the first cover to the second cover).*

$$Nu = 1 + 1.446\left[1 - \frac{1708}{Ra\cos\beta}\right] \quad \text{for } 1708 < Ra\cos\beta < 5900$$

$$Nu = 0.229(Ra\cos\beta)^{0.252} \quad \text{for } 5900 < Ra\cos\beta < 9.23\times10^{4}$$

$$Nu = 0.157(Ra\cos\beta)^{0.285} \quad \text{for } 9.23\times10^{4} < Ra\cos\beta < 10^{6}$$

Properties are to be evaluated at the arithmetic mean of the surface temperatures

Heat Transfer coefficient between inclined parallel surfaces

- Holland *et al.*

$$Nu = 1 + 1.44\left[1 - \frac{1708}{Ra \cos\beta}\right]^{+}\left(1 - \frac{\sin(1.8\beta)^{1.6} \times 1708}{Ra \cos\beta}\right) + \left[\left\{\frac{Ra \cos\beta}{5830}\right\}^{1/3} - 1\right]^{+}$$

The '+' exponent means that only the positive value of the term in square brackets is to be considered. The zero is to be used for negative value. The angle of inclination, β, of the FPC can vary between 0° and 75°, and Ra is the Rayleigh number, which is given by:

$$Ra = Gr \cdot Pr = \frac{g\beta' \Delta T d^3}{\nu\alpha}$$

If, $75° < \beta < 90°$, then

$$Nu = \left[1,\ 0.288\left(\frac{\mathrm{Ra} \times \sin\beta}{A}\right)^{1/4},\ 0.039(\mathrm{Ra} \times \sin\beta)^{1/3}\right]_{\max}$$

Ex.3: Calculate the convective heat transfer coefficient between two parallel plates. The plates are separated 20 mm with an inclination of 40^{o}. The lower and upper plates are 50 and 30^{o}C, respectively.

At mean air temperature of 40 ^{o}C, the air properties are given as;

$T = 313\,\mathrm{K}$ $\quad k = 0.0272\ \mathrm{W/m\ ^{\circ}C}$ $\quad \nu = 1.70\times 10^{-5}\ \mathrm{m^2/s}$

$\alpha = 2.40\times 10^{-5}\ \mathrm{m^2/s}$

$$\boxed{Ra = Gr \times \mathrm{Pr} = \frac{g\beta^{/}\Delta T L^{3}}{\alpha\nu}}$$

Summary

- Modes of heat transfer
  - Conduction
  - Convection
  - Radiation
- Non-dimensional numbers related the heat transfer
- Correlations to estimate heat transfer coefficients
- Solved basic heat transfer problems

Thank you