Ideal Fluid and Real Fluids

Ideal fluid is one which has **no Viscosity** and **surface tension** and is **incompressible.**

In true sense no such fluid exists in nature.

However, fluids which have low viscosities as water and air can be treated as ideal fluids under certain conditions.

The assumption of ideal fluids helps in simplifying the mathematical analysis.

A real practical fluid is one which has **viscosity, surface tension** and **compressibility** in addition to **density**. The real fluids are actually available in nature.

Viscosity: may be defined as the property of a fluid which determines its resistance to shearing stresses.

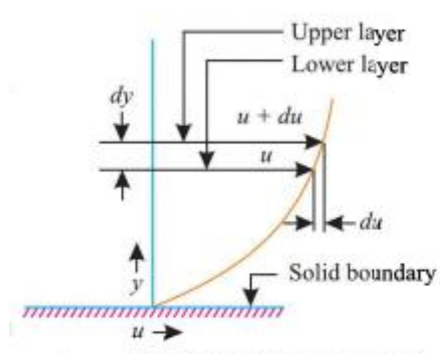
Viscosity is a measure of the internal fluid friction which causes resistance to flow.

Viscosity is primarily due to cohesion and molecular momentum exchange between fluid layers, and as flow occurs, theses effects appear as shearing stresses between the moving layers of fluid.

An ideal fluid has no viscosity. There is no fluid which can be classified as a perfectly ideal fluid.

Viscosity of fluids is due to cohesion and interaction between particles.

Refer to figure. When two of fluid, at a distance 'dy' apart, move one over the other at different velocities u and u+du, the viscosity together with relative velocity causes a shear stress acting between the fluid layers



Velocity variation near a solid boundary.

This shear stress is proportional to the rate of change of velocity with respect to y. It is denoted as τ

Mathematically $\tau \propto \frac{du}{dy}$ or $\tau = \mu \frac{du}{dy}$

Where μ= constant of proportionality and is known as coefficient or dynamic viscosity or only viscosity,

$\frac{du}{dy}$ =Rate of shear stress or rat of shear deformation or velocity gradient

Then, we have $\mu = \frac{\tau}{\frac{du}{dy}}$

Thus, viscosity may also define as the shear stress required to produce unit of shear strain.

Unit of viscosity: In S.I. units $N.s/m^2$

In M.K.S units $kgf.sec/m^2$

$$\left[\mu = \frac{force/area}{(length/time)\times\frac{1}{length}} = \frac{force/length^2}{\frac{1}{time}} = \frac{force \times time}{(length)^2}\right]$$

The unit of viscosity in C.G.S. is also called Poise=$\frac{dyne.sec}{cm^2}, one\ poise = \frac{1}{10}N.s/m^2$

Note: The viscosity of water at 20^oC is 0.01poise or one centipoise.

Unit of the viscosity $N.\frac{s}{m^2} = \frac{kg.m}{s^2}\frac{s}{m^2} = \frac{kg}{m.s}$

Kinematic viscosity:

Kinematic viscosity is defined as the ratio between the dynamic viscosity and density of fluid: it is denoted by ν. And mathematically

$$\nu = \frac{Viscosity}{density} = \frac{\mu}{\rho}$$

Unit of kinematic viscosity is m/s^2

LAMINAR AND TUBULENT FLOWS

The type of flow is defined by Reynolds number as laminar and turbulent flow

For flow on flat plate

What is Reynolds Number

Reynolds number of flows in tube

$Re_t = \frac{\rho D u}{\mu} = \frac{D u}{\nu}$ with out unit

For $Re_t < 2000$ the flow is laminar

For $Re_t > 2300$ the flow is turbulent

For 2000 < Re < 2300 the flow is transient

For flow over flat plate

$Re_t = \frac{\rho L u}{\mu} = \frac{L u}{\nu}$

For laminar flow over a flat plate $Re < 5x10^5$

For turbulent flow over a flat plate $Re > 5x10^5$

Prandtl number (Pr):

It is the ratio of kinematic viscosity (ν) to thermal diffusivity (α)

$$Pr = \frac{\mu Cp}{k} = \frac{\rho \nu Cp}{k} = \frac{\nu}{(k/\rho Cp)} = \frac{\nu}{\alpha}$$

Kinematic viscosity indicates the impulse transport through molecular friction whereas thermal diffusivity indicates the heat energy transport by conduction process.

Prandtl number is a property

Nusselt Number (Nu):

It is ratio of heat flow rate by convection process a unit temperature gradient to the flow rate by conduction process under a unit temperature gradient through a stationary thickness of L meters.

Nu=$\frac{Q_{conv.}}{Q_{cond.}} = \frac{h}{k/L} = \frac{hL}{k}$ For a flat plat

Put for tube

Nu= $\frac{h}{k/d} = \frac{hd}{k}$ For a pipe

Flow over a flat plate

1. Laminar flow when Re<$5x10^5$

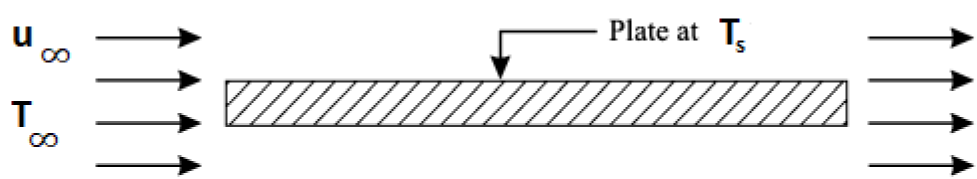
$$Nu_x = 0.332(Re_x)^{1/2}Pr^{1/3}$$

From this relation the local heat transfer can found

$$\overline{Nu} = 0.664(Re_L)^{1/2}(Pr)^{1/3}$$

This relation is to find the average Nu over the plate of length L

And the properties is taken at the Film Temperature which is defined as the arithmetic mean temperature of the fluid and plate temperature $T_f=\frac{T_S+T_\infty}{2}$



Ex.1 **Air at 20°C and pressure of 100kPa is flowing over a flat plate at a velocity of 3m/s. If the plate is 280mm wide and 56°C, calculate the following quantities at x=280mm.**

1. **Local convective heat transfer coefficient**
2. **Average convective heat transfer coefficient**
3. **Rate of heat transfer by convection**

Solution: A flat plate of width w=280mm=0.28mm and it is to calculate at length x=0.28m. The velocity u=3m/s, Plate temperature T_s=56°C, and air temperature T_∞=20°C

Analysis: The film temperature $T_f = \frac{T_s+T_\infty}{2} = \frac{56+20}{2} = 38^{o}C$

The properties is taken at the T_f=38°C

ρ=1.1374kg/m^3, k=0.02732W/m.°C, Cp=1.005kJ/kg.K, ν=16.768x10^{-6}m^2/s, Pr=0.7

At first we will calculate Re to set the type of flow

$$Re_x = \frac{\rho uL}{\mu} = \frac{uL}{\nu} = \frac{3\times0.28}{16.768\times10^{-6}} = 0.5\times10^5 < 5\times10^5$$

The flow is laminar

To find the heat transfer coefficient we will find the Nu at first

$$Nu_x = 0.332(Re_x)^{1/2}Pr^{1/3} = 0.332(0.5\times10^5)^{1/5}(0.7)^{1/3}\text{=65.916}$$

$$Nu_x = \frac{h_x\times l}{k} \rightarrow h_x = \frac{Nu_x\times k}{L} = 6.43\text{W/m}^2\text{.K}$$

And to find the average heat transfer coefficient

$$\bar{h} = 2h_x = 2\times65.916 = 12.86W/m^2\text{.K}$$

Or $\overline{Nu} = 0.664(Re_x)^{1/2}Pr^{1/3} = 0.664(0.5\times10^5)^{1/5}(0.7)^{1/3}$=131.832

And $\bar{h} = \frac{\overline{Nu}\times k}{L} = \frac{131.832\times0.02732}{0.28} = 12.86W/m^2$.K

The heat transfer is

$$\dot{Q} = A\bar{h}(T_s - T_\infty) = (0.28\times0.28)\times12.86(56-20) = 36.3W$$

Ex.2 Air at atmospheric pressure and 200°C flows over a plate with velocity of 5m/s. The plate is 15mm wide and is maintained at a temperature of 120°C. Calculate the Reynold's Number at distance of 0.5 meter and the local and average heat transfer coefficient and the rate of heat transfer by convection.

Solution: W=15mm=0.015m and L=0.5m T_∞=200°C, T_s=120°C, u=5m/s

Properties are at $T_f = \frac{T_s+T_\infty}{2} = \frac{120+200}{2} = 160^{o}C$

ρ=0.815kg/m^3, μ=24.5x10^{-6}N.s/m^2, Pr=0.7, k=0.0364W/m.K

$Re_x = \frac{u\rho L}{\mu} = \frac{5\times0.815\times0.5}{24.5\times10^{-6}} = 0.831\times10^5$ it is < 5x10^5

$Nu_x = 0.332(Re_x)^{0.5}(Pr)^{1/3} = 0.332(0.831\times0.832^5)^{0.5}(0.7)^{1/3} = 85$

$h_x = \frac{Nu_x k}{x} = \frac{85\times0.0364}{0.5} = 6.188W/m^2.K$

$\overline{Nu} = 0.664(Re_x)^{0.5}(Pr)^{1/3} = 0.664(0.831\times0.832^5)^{0.5}(0.7)^{1/3} = 170$

$\bar{h} = \frac{\overline{Nu}k}{L} = \frac{170\times0.0364}{0.5} = 12.376W/m^2.K$

$\dot{Q} = (W.L)\bar{h}(T_\infty - T_s) = (0.15\times0.5)12.376(200-120) = 74.256W$

Ex.3 **Air at atmospheric pressure and 40^{o}C flow with velocity 5m/s over a 2m long flat pate whose surface is kept at a uniform temperature of 120^{o}C. Determine heat transfer coefficient over the 2m length of the plate. Also find out the rate of heat transfer between the plate and the air per 1m width of the plate. [For air at 1atm and 80^{o}C, ν=2.107x10^{-5}m^2/s, k=0.03025W/m.K, Pr=.6965]**

Solution: air at atmospheric pressure T_∞=40^{o}C, u=5m/s over flat plate L=2m T_s=120^{o}C

It is to find the heat transfer coefficient and rate of heat transfer per unit 1m width

$Re_L = \frac{L.u}{\nu} = \frac{2\times5}{2.017\times10^{-5}} = 4.958\times10^5$ the flow is laminar

$\overline{Nu} = 0.664(Re)^{0.5}(Pr)^{1/3} = 0.664(4.958\times10^5)^{0.5}(0.6965)^{1/3}$=414.43

$\bar{h} = \frac{\overline{Nu}k}{L} = \frac{414.43\times0.03025}{2} = 6.27W/m^2.^oC$

$\dot{Q} = A\bar{h}(T_s - T_\infty) = (1\times2)6.27(120-40) = 1002.93W$

Ex.4 **Air at 27^{o}C and 100kPa flows over a plate with temperature 60^{o}C at a speed of 2m/s from the laminar flow long. Calculate the heat transferred per 1m width. The properties at the film temperature are ν=17.36x10^{-6}m^2/s, k=0.02749W/m.^{o}C, Cp=1.005kJ/kg.K, R=0.287kJ/kg.K, Pr=0.7.**

Solution: Air T_∞=27^{o}C, T_s=60^{o}C u=2m/s over a flat plate in laminar region

Analysis: for region of laminar flow

$Re_c = 5 \times 10^5 = \frac{u \times L}{\nu} = \frac{2 \times L}{17.36 \times 10^{-6}} \rightarrow L = 4.34m$

$Nu_L = 0.664(Re)^{0.5}(Pr)^{1/3} = 0.664(5 \times 10^5)^{1/2}(0.7)^{1/3} = 416.887$

$\bar{h} = \frac{\overline{Nu}.k}{L} = \frac{416.887 \times 0.02749}{4.34} = 2.64W/m^2.°C$

$\dot{Q} = \bar{h}A(T_s - T_\infty) = 2.6(4.34 \times 1)(60 - 27) = 372.37W$

Ex.5 **Air at 20°C is flowing over a flat plate which is 200mm width and 500mm long. The plate is maintained at 100°C. Find the heat loss per hour from the plate if the air is flowing parallel to 500 mm side with 2m/s velocity. What will be the effect on heat transfer if the flow is parallel to 200mm side? The properties at film temperature are ν=18.97x10^{-6}m^2/s, k=0.025W/m.K and Pr=0.7.**

For turbulent flow over flat plate where $Re_L > 5x10^5$

The following relation is used

$$\mathbf{\overline{Nu} = 0.036(Re_L)^{4/5}(Pr)^{1/3}}$$

Solution: Air T_∞=20°C, flow over flat plate W=0.2 L=0.5m T_s=100°C u=2m/s

Analysis: $Re_l = \frac{u \times L}{\nu} = \frac{2 \times 0.5}{18.97 \times 10^{-6}} = 0.527 \times 10^5$ the flow is laminar

$\overline{Nu} = 0.664(Re)^{1/2}(Pr)^{1/3} = 0.664(0.527 \times 10^5)^{1/2}(0.7)^{1/3} = 135.344$

$\bar{h} = \frac{\overline{Nu}.k}{L} = \frac{135.344 \times 0.025}{0.5} = 6.77W/m^2.°C$

$\dot{Q} = (0.2 \times 0.5)6.77(100 - 20) = 54.137W = 194.9kJ/h$

If the flow along the width of the blat

$Re_l = \frac{u \times L}{\nu} = \frac{2 \times 0.2}{18.97 \times 10^{-6}} = 0.21 \times 10^5$ the flow is also laminar

$\overline{Nu} = 0.664(Re)^{1/2}(Pr)^{1/3} = 0.664(0.21 \times 10^5)^{1/2}(0.7)^{1/3} = 85.61$

$\bar{h} = \frac{\overline{Nu}.k}{L} = \frac{85.61 \times 0.025}{0.2} = 10.7W/m^2.°C$

$\dot{Q} = (0.2 \times 0.5)10.7(100 - 20) = 85.61W = 308.2kJ/h$

Heat Transfer for combination of Laminar and turbulent Flow

$$\overline{\boldsymbol{Nu}} = (\boldsymbol{Pr})^{1/3}\left[\mathbf{0.664}(\boldsymbol{Re_c})^{1/2} + \mathbf{0.036}\{(\boldsymbol{Re_L})^{0.8} - (\boldsymbol{Re_c})^{0.8}\}\right]$$

Assuming that the transition occurs at critical Reynolds number $Re_c=5x10^5$

$$\overline{\boldsymbol{Nu}} = (\boldsymbol{Pr})^{1/3}\left[\mathbf{0.664}\left(\mathbf{5} \times \mathbf{10^5}\right)^{1/2} + \mathbf{0.036}(\boldsymbol{Re_L})^{0.8} - \mathbf{0.036}\left(\mathbf{5} \times \mathbf{10^5}\right)^{0.8}\right]$$

$$\overline{\boldsymbol{Nu}} = (\boldsymbol{Pr})^{\frac{1}{3}}\left[\mathbf{0.664}\left(\mathbf{5} \times \mathbf{10^5}\right)^{\frac{1}{2}} + \mathbf{0.036}(\boldsymbol{Re_L})^{0.8} - \mathbf{0.036}\left(\mathbf{5} \times \mathbf{10^5}\right)^{0.8}\right]$$

Or $\overline{\boldsymbol{Nu}} = (\boldsymbol{Pr})^{\frac{1}{3}}[\mathbf{0.036}(\boldsymbol{Re_L})^{0.8} - \mathbf{836}]$

Other relation for heat transfer coefficient

$$\boldsymbol{St}.(\boldsymbol{Pr})^{2/3} = \frac{C_{fx}}{2}$$

Where Stanton number= St=$\frac{h_x}{\rho.Cp.u}$

And C_{fx} local friction coefficient

Ex. 6**. Air flows over a heated plate at a velocity of 50m/s. The local skin friction coefficient at a point on a plate 0.004. Estimate the local heat transfer coefficient at this point. The following properties of air are givin:**

$\rho=0.88kg/m^3$, $\mu=2.286x10^{-5}kgm/s$, Cp=1.001kJ.kg.K k=0.035W/m.K

Solution: flow over flat heated plate with u=50m/s and $C_{fx}=0.004$

we know that $\boldsymbol{St}.(\boldsymbol{Pr})^{2/3} = \frac{C_{fx}}{2}$

St=$\frac{h_x}{\rho.Cp.u} = \frac{h_x}{0.88\times1001\times50} = \frac{h_x}{44044}$

And $Pr = \frac{\mu.Cp}{k} = \frac{2.286\times10^{-5}\times1001}{0.035} = 0.654$

By subsitituting in $\boldsymbol{St}.(\boldsymbol{Pr})^{2/3} = \frac{C_{fx}}{2}$

$\frac{h_x}{44044}(0.654)^{2/3} = \frac{0.004}{2} \rightarrow h_x = 116.9W/m^2.K$

Ex 7. The crankcase of an I.Cengine measuring 80cmx20cm may be idealized as flat plate. The engine runs at 90km/h and the crankcase is cooled by the air flowing past it at the same speed. Calculate the heat loss from the crank surface maintained at 85°C, to the ambient air at 15°C. Due to road indused vaibration, the boundary layer becomes turbulent from the leading edge itself.

Solution: A=0.8x0.2=0.16m^2 T_s=85°C, T_∞=15°C, u=90km/h=90$\times \frac{1000}{3600} = 25m/s$

L=0.8m W=0.2

The film temperature $T_m = \frac{T_s+T_\infty}{2} = \frac{85+15}{2} = 50°C$

The Properties at film temperature k=0.02824W/m.k, ν=17.95x10^{-6}m^2/s Pr=0.698

$Re_L = \frac{uL}{\nu} = \frac{25\times0.8}{17.95\times10^{-6}} = 11.14\times10^5$

It turbulent and because of vibration the turbulent along the crank surface

The $\mathbf{\overline{Nu} = 0.036(Re_L)^{4/5}(Pr)^{1/3}}$

$$\overline{Nu} = 0.036(11.14\times10^5)^{4/5}(0.698)^{1/3} = 2197$$

$$\bar{h} = \frac{\overline{Nu}k}{L} = \frac{2197\times0.02824}{0.8} = 77.55W/m^2.K$$

$$\dot{Q} = A\bar{h}(T_s - T_\infty) = 0.16\times77.55\times(85-15) = 868.56W$$

Ex. 8 **Air at 20°C and 101.3kPa flows over a flat plate at 40m/s. The plate is 1m long and is maintained at 60°C . Assuming unit depth, calculate the heat transfer from the plate. Using the following correlation:**

$Nu_L = (Pr)^{0.33}[0.037(Re_L)^{0.8} - 850]$

Solution: T_∞=20°C, u=40m/s, L=1m, w=1m, T_s=60°C

Film temperature $T_f = \frac{T_\infty+T_s}{2} = \frac{20+60}{2} = 40°C$

The properties at film temperature are ρ=1.128kg/m^3, Cp=1.005kJ/kg.K, k=0.0275W/m.K ν=16.96x10^{-6}m^2/s

$$Pr = \frac{\mu.Cp}{k} = \frac{\rho \times \nu \times Cp}{k} = \frac{1.128 \times 16.96 \times 10^{-6} \times 1005}{0.0275} = 0.699$$

$$Re_L = \frac{u.L}{\nu} = \frac{40 \times 1}{16.96x10^{-6}} = 23.585 \times 10^5$$

$$Nu_L = (Pr)^{0.33}[0.037(Re_L)^{0.8} - 850]$$

$$Nu_L = (0.699)^{0.33}[0.037(23.585 \times 10^5)^{0.8} - 850] = 3365.59$$

$$\bar{h} = \frac{Nu \times k}{L} = \frac{3365.59 \times 0.0275}{1} = 92.55W/m^2.K$$

$$\dot{Q} = A\bar{h}(T_s - T_\infty) = (1 \times 1)92.55 \times (60 - 20) = 3702.14W$$

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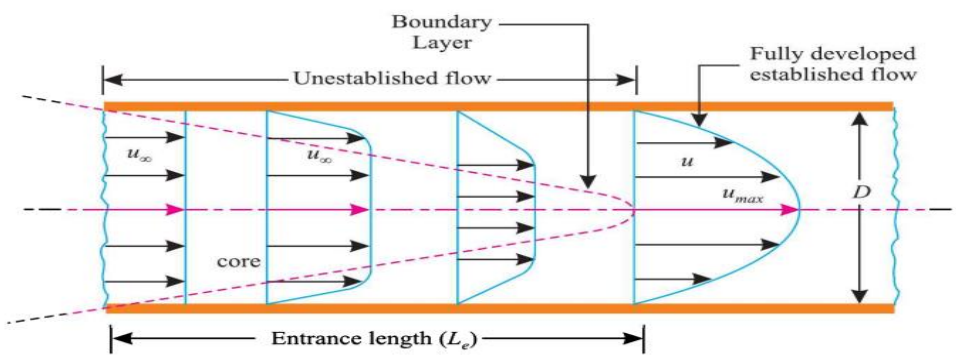
Flow in tube

Laminar flow in tube

The flow is also described by Reynolds Number

The Reynolds number is defined by the diameter of tube instead of its length



$$Re_d = \frac{d.u.\rho}{\mu} = \frac{d.u}{\nu}$$

The flow is laminar $Re_d<2300$

And Nu= constant for laminar flow in tube

For constant surface temperature Nu=3.65

For constant heat flux Nu=4.364

And $Nu = \frac{Nu.k}{d}$

Hydraulic diameter: for non-circular tubes we use the hydraulic diameter which is

$D_h = \frac{4A}{P}$

It used for any non-circular tube-like square, rectangular, the space between two tubes and so on.

Turbulent Flow in tube

The flow in tube be turbulent if Re_d>2300

And for that $\overline{Nu} = 0.023(Re)^{0.8}(Re)^{1/3}$

And $\bar{h} = \frac{k.\overline{Nu}}{d}$

The above expression is valid for $10^4 < Re < 10^5 : 0.5 < Pr < 100 : \frac{L}{d} > 60$

The properties of fluid are evaluated at Film temperature T_f

This relation may be

For heating becomes $\overline{Nu} = 0.023(Re)^{0.8}(Re)^{0.4}$

And for cooling $\overline{Nu} = 0.023(Re)^{0.8}(Re)^{0.3}$

Ex. 9. **Lubricating oil at a temperature of 60°C enters 1cm diameter tube with a velocity of 3m/s. The tube surface is maintained at 40°C. Assuming that the oil has following average properties calculate the tube length required to cool the oil to 45°C. ρ=865kg/m³, k=0.14, Cp=1.78kJ/kg.K. assume the flow is laminar and Nu=3.657**

Solution: d=1cm=0.01m, T_∞=60°C, $T_{\infty 2}$=45°C T_s=40°C u=3m/s

for laminar flow the value of Nu is given

$$h = \frac{Nu.K}{d} = \frac{3.657 \times 0.14}{0.01} = 51.2 W/m^2.K$$

$$\dot{m} = \rho A u = \rho \frac{\pi}{4} d^2 u = 865 \frac{\pi}{4} (0.01)^2 \times 3 = 0.2038 kg/s$$

$$\dot{Q} = \dot{m} Cp (T_{\infty 2} - T_{\infty 1}) = 0.2038 \times 1.78(45 - 60) = -5.442 kW = -5442 W$$

$$\dot{Q} = hA\theta_m$$

A=πdL $\quad \theta_m = \frac{\theta_2-\theta_1}{ln\frac{\theta_2}{\theta_1}} = \frac{(T_s-T_{\infty1})-(T_s-T_{\infty2})}{ln\frac{(T_s-T_{\infty1})}{(T_s-T_{\infty2})}} = \frac{(40-60)-(40-45)}{ln\frac{(40-60)}{(40-45)}} = \frac{-20+5}{ln\frac{-20}{-5}} = -10.82^{o}C$

$\dot{Q} = hA\theta_m \rightarrow -5442 = 51.2 \times (\pi \times 0.01L)(-10.82)$

L=312.68m

Ex. 10. **When 0.5 kg of water per minute is passed through a square tube of side length 20mm, it is found to be heated from 20°C to 50°C. The heating is accomplished by condensing steam on the surface of the tube and subsequently the temperature of the tube is maintained at 85°C. Determine the length of the tube required for fully developed flow.**

Take the thermo-physical properties of water at 60°C as:

ρ=983.2kg/m^3, Cp=4.178kJ/kg.K, k=0.659W/m.°C, ν=0.478x$10^{-6}$$m^2$/s

Solution: square tube of side length B=20mm $\dot{m}$=0.5kg/min=0.00833kg/s

$T_{\infty1}$=20°C, T_∞=50°C, T_s=85°C.

It to determine the length of the tube

Analysis: the bulk temperature is $T_\infty = \frac{T_{\infty1}+T_{\infty2}}{2} = \frac{20+50}{2} = 35^{o}C$

The film temperature $T_f = \frac{T_s+T_\infty}{2} = \frac{85+35}{2} = \frac{120}{2} = 60^{o}C$

The properties of water at T_f=60°C are given as ρ=983.2kg/m^3, Cp=4.178kJ/kg.K, k=0.659W/m.°C, ν=0.478x$10^{-6}$$m^2$/s.

The hydraulic diameter $\boldsymbol{D_h = \frac{4A}{P} = \frac{4B^2}{4B} = B}$

$u = \frac{\dot{m}}{\rho A} = \frac{\dot{m}}{\rho B^2} = \frac{0.008333}{983.2\times(0.02)^2} = 0.0212m/s$

$Re_d = \frac{d.u}{\nu} = \frac{0.02\times0.0212}{0.478\text{x}10^{-6}} = 887.03$

The flow is laminar for that Nu=3.65

$h = \frac{Nu.k}{d} = \frac{3.65\times0.659}{0.02} = 120.27W/m^2.K$

$\frac{T_s-T_{\infty2}}{T_s-T_{\infty1}} = e^{-\frac{hAL}{\dot{m}Cp}} \rightarrow \frac{85-50}{85-20} = e^{-\frac{120.27\times0.02^2}{0.00833\times4178}L}$

L=447.83m

Ex. 11. **A surface condenser consists of two hundred thin walled circular tubes (each tube is 22.5mm in diameter and 5m long) arranged in parallel, through which water flows. If the mass flow rate of water through the bank is 160kg/s and its inlet and outlet temperature are known to be 21°C and 29°C respectively, calculate the average heat transfer coefficient associated with flow of water.**

Solution: Tube numbers n=200 d=22.5mm=0.0225m, L=5m, $\dot{m}$=160kg/s T_1=21°C, T_2=29°C,

It is to find the heat transfer coefficient

Analysis: to find the bulk temperature which is $T_b=\frac{T_1+T_2}{2}=\frac{21+29}{2}=25$°C

The properties of water at bulk temperature are ρ=996.65kg/m³, μ=0.862x10⁻³kg/m.s, k=0.6079W/m.°C, Cp=4178J/kg.°C

$$Pr=\frac{\mu Cp}{k}=\frac{0.862\times10^{-3}\times4178}{0.6079}=5.92$$

Mass transfer in one tube is $\dot{m}_1=\frac{\dot{m}}{n}=\frac{160}{200}=0.8kg/s$

$\dot{m}_1=\rho u\frac{\pi}{4}d^2\rightarrow0.8=996.25\times u\times\frac{\pi}{4}(0.0225)^2$ →u=2.019m/s

$$Re_d=\frac{\rho ud}{\mu}=\frac{996.65\times2.019\times0.0225}{0.862\times10^{-3}}=52539.34$$

For flow is turbulent

$$\overline{Nu}=0.023(Re)^{0.8}(Pr)^{0.4}=0.023(52539.34)^{0.8}(5.92)^{0.4}=280.13$$

$$\bar{h}=\frac{Nu\times k}{d}=\frac{280.13\times0.6079}{0.0225}=7568.5W/m^2.°C$$

Ex 12. **A tube 5m long is maintained at 100°C by steam jacketing. A fluid flows through the tube at the rate of 2940kg/h at 30°C. The diameter of tube is 2cm. Find out average heat transfer coefficient. Take the following properties of the fluid:**

ρ=850kg/m³, Cp=2000J/kg.K, ν=5.1x10⁻⁶m²/s and k=0.12W/m.K

Solution: L=5m, D=2cm=0.02m, $\dot{m}$ =2940kg/h

$$\dot{m} = \frac{\pi}{4} d^2 u\rho \rightarrow \frac{2940}{3600} = \frac{\pi}{4}(0.02)^2 u \times 850$$

$$u = 3.06 m/s$$

Then $Re_d = \frac{u.d}{\nu} = \frac{3.06\times0.02}{5.1\times10^{-6}} = 11993.22$

Re >2300

$$Pr = \frac{\mu Cp}{k} = \frac{\rho\nu CP}{k} = \frac{850\times5.1\times10^{-6}\times2000}{0.12} = 72.25$$

$$\overline{Nu} = 0.023(Re)^{0.8}(Pr)^{1/3} = 0.023(11993.22)^{0.8}(72.25)^{1/3} = 175.6$$

$$\bar{h} = \frac{\overline{Nu}k}{d} = \frac{175.6\times0.12}{0.02} = 1053.6 W/m^2.\text{K}$$

Ex 13. **In a straiht tube of 60mm diameter, water is flowing at a velocity of 12m/s. The tube surface temperature is maintained at 70°C and the flowing water is heated from the inlet temperature 15°C to an outlet temperature of 45°C. Taking the physical properties of water at its mean bulk tamperature, calculate the following: 1) The heat transfer coefficient from the tube surface to the water, 2) The heat transferred, and 3) The length of the tube**.

The thermo-physical properties of water at 30°C are:

ρ=995.7kg/m^3, Cp=4.174kJ/kg.K, k=61.718x10^{-2}W/m.°C, ν=0.805x10^{-6}m^2/s.

Solution: straight tube d=60mm=0.06m u=12m/s T_s=70°C T_{c1}=15°C, T_{c2}=45°C

It is to found h, Q, L

Analysis: to find the Re

$$Re = \frac{ud}{\nu} = \frac{12\times0.06}{0.805\times10^{-6}} = 894410$$

$$Pr = \frac{\rho\nu Cp}{k} = \frac{995.7\times0.805\times10^{-6}\times4174}{0.61718} = 5.421$$

$$Nu = 0.023(Re)^{0.8}(Pr)^{0.4} = 0.023(894410)^{0.8}(5.421)^{0.4} = 2609.66$$

$$h_i = \frac{Nu.k}{d} = \frac{2609.66\times.61718}{0.06} = 26843 W/m^2.°\text{C}$$

$$\dot{m}_w = \rho u \frac{\pi}{4} d^2 = 995.7 \times 12 \times \frac{\pi}{4} \times 0.06^2 = 33.78 kg/s$$

$\dot{Q} = \dot{m}_w Cp_w (T_{c2} - T_{c1}) = 33.78 \times 4174(45 - 15) = 4230345.5$W

$\Delta T_m = \frac{(T_s - T_{c1}) - (T_s - T_{c2})}{ln\frac{(T_s - T_{c1})}{(T_s - T_{c2})}} = \frac{(70-15)-(70-45)}{ln\frac{(70-15)}{(70-45)}} = 38.05$°C

$\dot{Q} = Ah\Delta T_m = \pi dLh\Delta T_m \rightarrow 4230345.5 = \pi \times 0.06L \times 26843 \times 38.05$

L=22m.

Ex. 14 **Water is flowing at the rate of 50kg/min through a tube of inner diameter 2.5cm. The inner surface of the tube is maintained at 100°C. If the temperature of water increases from 25°C to 55°C, find the length of the tube required**.

Properties of water at film temperature are ρ=977.8kg/m^3, Cp=4187J/kg.K, k=0.6672W/m.K, μ=405x10^{-6}kg/m.s

Solution: water m=50kg/min=0.8333kg/s, d_i=2.5cm=0.025m, T_s=100°C, T_{c1}=25°C, T_{c2}=55°C.

It is to find length of the tube

$\dot{Q} = \dot{m}Cp(T_{c2} - T_{c1}) = 0.8333 \times 4187(55 - 25) = 104675W$

$\Delta T_m = \frac{(T_s - T_{c1}) - (T_s - T_{c2})}{ln\frac{(T_s - T_{c1})}{(T_s - T_{c2})}} = \frac{(100-25)-(100-55)}{ln\frac{(100-25)}{(100-55)}} = 58.73$°C

$\dot{m} = \rho Au = \rho \frac{\pi}{4} d^2 u \rightarrow 0.8333 = 977.8 \times \frac{\pi}{4}(0.025)^2 u$

$u = 1.736m/s$

$Re = \frac{\rho ud}{\mu} = \frac{977.8 \times 1.736 \times 0.025}{405x10^{-6}} = 104789.2$

$Pr = \frac{\mu.Cp}{k} = \frac{405x10^{-6} \times 4187}{0.6672} = 2.54$

$Nu = 0.023(Re)^{0.8}(Pr)^{0.4} = 0.023(104789.2)^{0.8}(2.54)^{0.4} = 346.75$

$h = \frac{Nu.k}{d} = \frac{346.75 \times 0.6672}{0.025} = 9254.2W/m^2.$°C

$\dot{Q} = Ah\Delta T_m = \pi dLh\Delta T_m \rightarrow 104675 = \pi \times 0.025L \times 9254.2 \times 58.73$

L=2.452m

Empirical correlations used for turbulent flow (ross flow) over cylinder

The following empirical correlation is widely used for flow over cylinder

$\overline{Nu} = C(Re)^n(Pr)^n$

Where C and n are taken from the following table

No.	Re	C	n
1	0.4→4	0.989	0.330
2	4→40	0.911	0.385
3	40→4x10^3	0.683	0.466
4	4x10^3→4x10^4	0.193	0.618
5	4x10^4→4x10^5	0.026	0.805

Also Churchill and Bernstein have suggested the following comprehensive empirical correlation which covers the entire range of Re and wide range of Pr

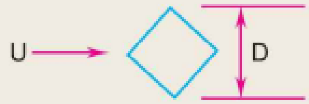
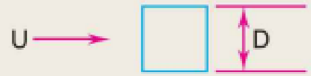
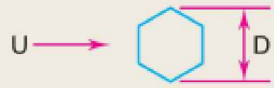
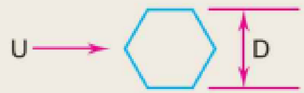
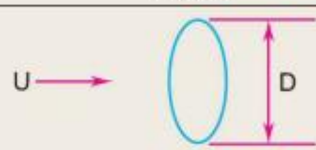
$$\overline{Nu} = 0.3 + \frac{0.62(Re)^{0.5}(Pr)^{1/3}}{[1+(0.4/Pr)^{2/3}]^{0.25}}\left[1+\left(\frac{Re}{28200}\right)^{5/8}\right]^{0.8}$$

Non-Circular Cylinders

For non-circular cylinder the following correlation is used

$$\overline{Nu} = C(Re)^n(Pr)^n$$

D =characteristic length and C and n are given in table below

S.No.	Geometry	Re	C	n
1.	 Square	$5 \times 10^3 - 10^5$	0.246	0.588
2.	 Square	$5 \times 10^3 - 10^5$	0.102	0.675
3.	 Hexagon	$5 \times 10^3 - 1.95 \times 10^4$ $1.95\times10^4 - 10^5$	0.16 0.0385	0.638 0.782
4.	 Hexagon	$5 \times 10^3 - 10^5$	0.153	0.638
5.	 Vertical plate	$4 \times 10^3 - 1.5 \times 10^4$	0.228	0.731
6.	 Ellipse	$2.5 \times 10^3 - 1.5 \times 10^4$	0.224	0.612
7.	 Ellipse	$3 \times 10^3 - 1.5 \times 10^4$	0.085	0.804

Ex. 15. **The following data relate to a metallic cylinder of 20mm diameter and 120mm in length heated internally by an electric heater and subjected to cross flow of air in a low speed wind tunnel.**

Temperature of free stream=25^{o}C; Velocity of free stream=16.5m/s; Average temperature of cylinder surface =130^{o}C; Power dissipation by heater=100W.

If 12% of power dissipation is lost through the insulation end pieces of the cylinder, calculate the experimental value of the convective heat transfer coefficient. Compare this value with that obtained by using the correlation:

$$\overline{Nu} = 0.26(Re)^{0.6}(Pr)^{0.36}\left(\frac{Pr}{Pr_s}\right)^{0.25}$$

Where all thermo-physical properties except Pr_s are evaluated at the mean bulk temperature (free stream) of air. Pr_s is evaluated at the average temperature of cylinder. The thermo-physical properties of air at 25°C are: k=0.0263W/m°.C, $\nu=15.53\times10^{-6} m^2/s$ Pr=0.702, Pr_s=0.685 at 130°C

Solution: d=20mm=0.02m L=120mm=0.12m T_a=25°C, T_s=130°C, Q=100W loss=12%

u=16.5m/s

Analysis: we can find the heat transfer coefficient directly as below

$$\dot{Q} = Ah\Delta T \rightarrow 100(1-0.12) = \pi dLh\Delta T$$

$$h = \frac{88}{\pi\times0.02\times0.12\times(130-25)} = 111.156 W/m^2.°C$$

Now to calculate the heat transfer coefficient from the above correlation

$$Re = \frac{u.d}{\nu} = \frac{16.5\times0.02}{15.53\text{x}10^{-6}} = 21249.2$$

$$\overline{Nu} = 0.26(21249.2)^{0.6}(0.702)^{0.36}\left(\frac{0.702}{0.685}\right)^{0.25} = 90.933$$

$$\bar{h} = \frac{Nu.k}{d} = \frac{90.933\times0.0263}{0.02} = 119.577 W/m^2.°C$$

Or we can use $\overline{Nu} = C(Re)^n(Pr)^{1/3} = 0.193(Re)^{0.618}(Pr)^{1/3}$

$$\overline{Nu} = 0.193(21249.2)^{0.618}(0.702)^{1/3} = 81.03$$

$$h = \frac{Nu.k}{d} = \frac{81.03\times0.0263}{0.02} = 106.55$$

Ex. 16. **A refrigerated truck is moving on a high way at 90km/h in a desert area where the ambient air temperature is 50°C. The body of the truck may be considered as a rectangular box measuring 10m (length)x4m (width) x3m (height). Assume that the boundary layer on the four walls is turbulent, the heat transfer takes place only from the four surfuces and the wall surface of the track is maintianed at 10°C. Neglecting heat transfer from the front and back and assuming the flow to be parallel to 10m long side, calculate the following: (i) The heat loss from the four surfaces.**

Properties of air at 30^{o}C: ρ=1.165kg/m^3. Cp=1.005kJ/kg.K, k=0.02673W/m^2.k, ν=16x10^{-6}m^2/s, Pr=0.701.

Solution: refrigerated truck, u=90km/h, T_∞=50^{o}C, L=10m, W=4m, h=3m, T_s=10^{o}C

Requirement: heat transfer by convection

Analysis: u_∞=90x$\frac{1000}{3600} = 25m/s$

$Re_l = \frac{u.L}{\nu} = \frac{25\times10}{16\times10^{-6}} = 15.625 \times 10^6$ The flow is turbulent

$\overline{\mathrm{Nu}} = 0.036(\mathrm{Re_L})^{4/5}(\mathrm{Pr})^{1/3} = 0.036(15.625 \times 10^6)^{4/5}(0.701)^{1/3} = 18194$

$\bar{h} = \frac{\overline{Nu}.k}{L} = \frac{18194\times0.02673}{10} = 48.632W/m^2.^oC$

$\dot{Q} = (A)\bar{h}(T_\infty - T_s) = (Perimeter \times L)48.632(50 - 10) = (2 \times 7 \times 10)1945.3$

$\dot{Q} = 272.344kW$