Chapter 2

Forced Convection

CHAPTER HIGHLIGHTS

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- *Laminar Flow*
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- *Stanton Number*
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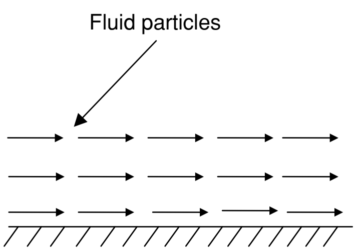
Introduction

Convection can be categorized in two parts.

1. **Forced convection:** It is convection heat transfer where fluid motion is imparted by external means like, pump, fan, compressor etc.
2. **Natural or free convection:** It is the convection heat transfer where the fluid moves due to density difference caused by the heat transfer between solid surface and fluid. In both type of convections (forced and free) flow can be either laminar or turbulent.

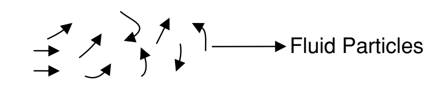
Laminar Flow

It is defined as the type of flow in which the fluid particles move along a well defined path or streamline. In laminar flow, fluid layers slide smoothly one over the other as shown in the figure below.



Turbulent Flow

If the fluid particles move in a zigzag way having no fixed direction, then flow is said to be turbulent. In turbulent flows, the eddies formation takes place which are responsible for high energy loss.



Boundary Layer

Consider flow of a fluid over a thin stationary plate at velocity v_α as shown in Figure 1 (no slip condition).

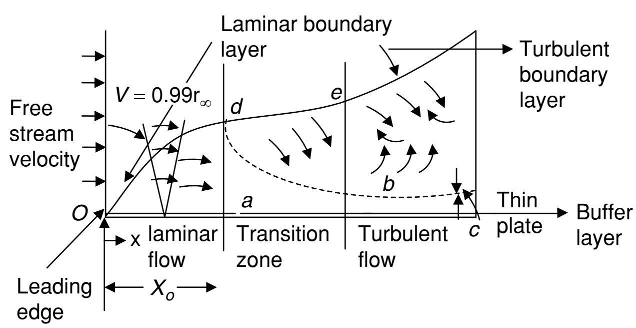


Figure 1 Velocity boundary layer growth due to flow over a plate.

When real (viscous) fluid flow over a stationary plate a layer of fluid which is in contact with the boundary surface, adheres to it on account of viscosity and condition of no slip occurs. The velocity of fluid at leading edge relative to plate becomes zero.

The adjacent layers also slow down to a lower and lower extent from the boundary surface in y-direction and there exist a velocity gradient due to viscous effect of the fluid layers over the surface in which there is a slowing down is defined as velocity boundary layer or hydro dynamic boundary layer where viscous shear takes place. In these, layers the velocity of flow increases from zero velocity at the surface to the free stream velocity at the edge of the boundary layer. The thickness of the boundary layer δ is defined as the boundary layer thickness. It is the distance from the stationary plate to the layer whose velocity is $0.99x$ free stream velocity.

The thickness of the boundary layer increases due to continuous retardation flow. The flow is laminar initially. The velocity variation is parabolic in laminar flow region. In laminar region, viscous forces are larger compared to inertia forces. But after a certain distance along the plate layers mix into each other and flow becomes turbulent. In turbulent flow, the inertia force becomes larger. The region between laminar and turbulent zones is known as transition zone.

Boundary Layer Thickness (δ)

The distance from the solid surface, to the layer measured in Y direction in which the velocity ($v = 0.99\ v_{\alpha}$) is known as boundary layer thickness same as δ. Special features of a boundary layer are as given below

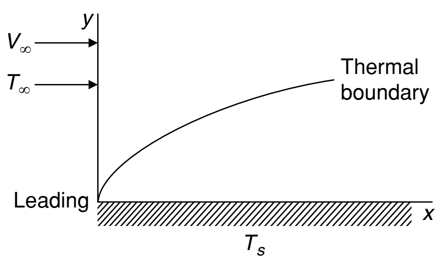
1. As distance from leading edge increases, δ increases.
2. δ Decreases as velocity of fluid increases.
3. As kinematic viscosity (v) increases δ increases.
4. As shear stress increases δ decreases

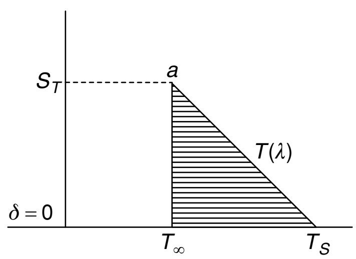
$$\left[\tau = \mu\left(\frac{V}{\delta}\right)\right].$$

5. If Reynolds number > 4000 flow is turbulent. (for pipe).
6. If $R_e < 2000$, flow is laminar (for pipe).

Thermal Boundary Layer

When a fluid flow over a hot plate surface there will be development of thermal boundary layer like hydrodynamic boundary layer



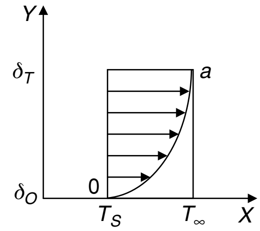


Consider the flow of liquid over a plate, when the free stream temperature is T_α and the surface temperature is T_s in case $T_s > T$ as shown in F_{guage}. The fluid particles at adjacent layer to plate will get the same temperature as of plate where the fluid particles have zero velocity. It should be noted that, at leading edge the temperature of the fluid and plate are the same.

$$T_s = T$$

The fluid particles coming in contact with the surface will exchange heat energy with the adjacent layers of fluid and so on. As a result, a thermal gradient is set up in the fluid layers, thereby a temperature profile is developed in the fluid flow. The heat is transferred by conduction.

As the fluid moves along the plate surface the temperature profile developed as the temperature variations T_s at the surface to the fluid temperature T_α in Y direction. When plate is cold in comparison of fluid, then



The region over the surface having temperature variation in the direction perpendicular to surface is called the thermal boundary layer.

The thickness of thermal boundary layer δ_1 at any point along the flow direction is defined as a distance δ from the plate surface at which the temperature difference ($T_s - T$) is 0.99 times ($T_s - T_\infty$), mathematically.

When $T_s > T_\infty$

$$\frac{\theta}{\theta_\infty} = \frac{T_s - T_\delta}{T_s - T_\infty}$$

Relation between thermal and hydrodynamic boundary layer can be found by Prandtl number.

Dimensionless Numbers

Nusselt Number (N_u)

$$N_u = \frac{hL}{K}$$

$N_u = \dfrac{h \cdot A \cdot \Delta T}{K \dfrac{A \cdot \Delta T}{L}}$, where K is the thermal conductivity of the fluid.

$$= \frac{\text{Rate of heat transfer by convection}}{\text{Rate of heat transfer by conduction}}$$

ΔT is the temperature difference between wall surface and fluid. This N_u is the measure of energy transfer by convection occurring at the surface. Larger the value of N_u, larger will be the rate of heat transfer by convection.

Reynolds Number (R_e)

Reynolds number signifies the ratio of inertia force to viscous force.

$$\text{Also, } R_e = \frac{\rho VL}{\mu} = \frac{VL}{\left(\frac{\mu}{\ell}\right)} = \frac{VL}{\nu}$$

In forced convection, Reynolds number characterizes the type of flow. Whether it is laminar or turbulent flow is proportional to velocity and density of fluid thus, for higher values of ρ and V, higher will be the Reynolds number. It signifies that the inertia forces are higher. The flow is turbulent. If Reynolds number is low viscous force is higher and the flow is laminar.

Critical Reynolds number $(R_e)_{\text{cr}}$. It represents the number where the boundary layer changes from laminar to turbulent flow for flat plate

$$R_e < 5\times 10^5 \text{ (laminar) } R_e = \frac{\rho VL}{\mu}$$

$$R_e > 5 \times 10^5 \text{ (turbulent)}$$

For circular plates

$$R_e < 2000 \text{ laminar } R_e = \frac{\rho V}{D\mu}$$

$$R_e > 4000 \text{ (turbulent)}$$

The value of R_e in between laminar and turbulent shows a transition state where laminar boundary changes to turbulent boundary.

Prandtl Number (P_r)

It can be written as

$$(P_r) = \frac{\mu C_p}{k} = \frac{\text{kinematic viscocity } (V)}{\text{Thermal diffusivity}}$$

$$= \frac{\frac{\mu}{\ell}}{\frac{K}{\ell Q}}$$

$$P_r \frac{V}{\alpha} = \frac{\text{Momentum diffusivity through the fluid}}{\text{Thermal diffusivity through the fluid}}$$

Prandtl number signifies the ratio of momentum diffusivity to the thermal diffusivity. It provides a measure of relative effectiveness of momentum and energy transport, by diffusion in hydro-dynamic and the thermal boundary layers, respectively. Higher P_r means higher N_u and it shows higher heat transfer (as $N_u \propto$ to $\bar{h}$).

Prandtl number for various materials
Liquid metals $P_r < 0.01$
For air and gases $P_r = 1$
For water $P_r = 10$
For heavy oils and greases $P_r > 10^5$.

Stanton Number (S_t)

It is the ratio of heat transfer coefficient to flow of heat per unit temperature rise due to the velocity of fluid

$$S_t = \frac{h}{\rho VC_p} = \frac{h}{\rho VC_p} \times \left(\frac{L}{k} \times \frac{k}{L}\right) \times \frac{\mu}{\mu}$$

$$= \frac{h \cdot \frac{L}{k}}{\left(\frac{\rho \cdot v \cdot L}{\mu} \times \frac{\mu C_p}{k}\right)}$$

$$= S_t = \frac{N_u}{R_e \times P_r}$$

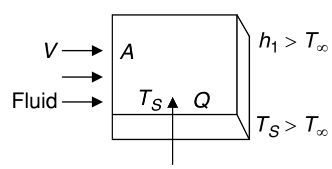
The temperature of fluid varies from surface up to the thermal boundary layer thickness. For convective heat transfer analysis the mean temperature of surface and that of fluid is taken, so that mean heat transfer coefficient can be calculated

$$T_{\text{mean}} = \frac{T_s + T_\infty}{2}$$

Effective Convection Heat Transfer Coefficient

Consider a flow of fluid past a flat plate at velocity, v, the plate having surface area A and surface temperature T_s and fluid temperature T_∞.

According to Newton's law of cooling the heat flux (heat transfer rate per unit area) is given by equation $q = h_L (T_s - T_\infty)$,



Heat transfer by convection over a plate where h_L represents the local heat transfer coefficient. 'h' does not depend upon the type of fluid flow, thermal properties, and dimensions of surface but it depend upon density, velocity, viscosity length, specific heat and thermal conductivity of fluid. Since these things vary from point to point on the surface, the rate of heat transfer and convective heat transfer vary along the surface. Average heat transfer coefficient is

$$h = \frac{1}{L}\int_0^L h_L \cdot dx \text{ where } L \text{ is length of plate}$$

(Formula used in forced convection)

1. $N_{ux} = 0.332\,(R_{e_x})^{0.5}\,(P_r)^{0.33}$ for flat plate
2. $N_{ua} = 0.664\,(R_{ea})^{0.5}\,(P_r)^{0.33}$ for flat plate
3. $N_{ua} = 0.023\,(R_e)^{0.8}\,(P_r)^{0.33}$ for tubes.

Solved Examples

Example 1: A metal slab 5 mm thick is exposed to a stream of air so that heat transfer by convection occurs from the slab to the air. If the thermal conductivity of the metal is 48 W/mK and convective heat transfer coefficient on the slab surface is 32 W/m^{2}K the biot no. is

(A) 0.0036 (B) 0.0017
(C) 0.0012 (D) 0.0008

Solution:
Explanation

$$\text{Biot No} = \frac{hL}{k}$$

Which 'h' is the convective heat transfer coefficient 'K' the conductivity of the slab and 'L' the characteristics length?

Characteristic length is $\frac{V}{A}$.

If ℓ and b are the length and breadth of the slab then

$$L = \frac{\ell \times b \times 5}{2(\ell \times b)}$$

$$= \frac{5}{2}\text{ mm} = \frac{5}{2} \times 10^{-3}\text{ m}$$

$$\text{Biot no} = \frac{hL}{K}$$

$$= \frac{32 \times \frac{5}{2} \times 10^{-3}}{48}$$

$$\frac{5}{3} \times 10^{-3} = 1.667 \times 10^{-3}$$

$$= 0.0017.$$

Example 2: A flat plate of dimension 80×40 cm^2 is exposed to an air stream at 27°C. The flat plate is maintained at a uniform temperature of 100°C. Velocity of air flow is 3 m/s. The properties of air are ρ = 1.2 kg/m^3, K = 0.03 W/mK $P_r = 0.7$; $\nu = 16 \times 10^{-6}$ m^2/s. If the air is flowing parallel to the 80 cm side the heat lost from the plate is

(A) 184 W (B) 250 W
(C) 320 W (D) 200 W

Solution:
The heat transfer by convection depends on the convective heat transfer co-efficient which is not given. Since air flows past the plate, it depends on Reynold number.

$R_eN = \frac{Vd}{\nu}$ Reynold No at the end of the plate $x = 0.8$

$$R_{e_x} = \frac{3 \times 0.8}{16 \times 10^{-6}} = 0.15 \times 10^6$$

Since it is less than 10^9
Nusselt number at $x = 0.8$

$$N_{u_x} = 0.332(\text{R}_{e_x})^{\frac{1}{2}}(P_r)^{\frac{1}{3}}$$

$$= 0.332(0.15 \times 10^6)^{\frac{1}{2}}(0.7)^{\frac{1}{3}}$$

$$= 114$$

$$N_{u_x} = \frac{h_x L}{k} = 114$$

$$\therefore\ h_x = \frac{114 \times k}{L} = \frac{114 \times 0.03}{0.8}$$

$$= 4.275\text{ W/m}^2\text{ K}$$

∴ Average value of convection heat transfer coefficient is

$$h = 2h_x = 8.55\text{ W/m}^2\text{ K}$$

∴ Heat transfer from one side of the plate is $Q = hA\Delta T$

$$= 8.55 \times 0.8 \times 0.4\ (100 - 27)$$

$$= 199\text{ W} \approx 200\text{ W}.$$

Example 3: A metal plate is exposed to stream of air flow at temperature 25°C. The temperature of the metal plate is 75°C. In order to evaluate the heat loss from the plate, the Nusselt No: $\frac{hL}{K}$ is evaluated.

Here 'K' represents

(A) Thermal conductivity of the metal plate
(B) Thermal conductivity of air
(C) Average thermal conductivity of metal and air
(D) The thermal conductivity lowest between the metal and air

Solution:
It is thermal conductivity of the fluid.

Example 4: Air at 20°C and 1 bar flows over a plate 75 cm long at a velocity of 35 m/s. Determine the heat loss per meter of the plate if it in maintained at 60°C.

Use the following equation for finding average heat transfer coefficient if the boundary is turbulent

(A) 2170 W (B) 2090 W
(C) 2260 W (D) 2180 W

Solution:

$$N_{u_a} = P_r^{\frac{1}{3}}[0.037 R_e^{0.8} - 850]$$

Properties of air taken at $(60 + 20)/2 = 40$°C are listed below

$\mu = 2 \times 10^{-5}$ kg/ms,
$K = 0.0272$ W/m°C
$C_p = 1.007$ kJ/kg°C, $P_r = 0.7$.

Density of air is given by $= \rho = \frac{P}{RT} = \frac{1 \times 10^5}{287 \times 313}$

$$= 1.13\text{ kg/cg/m}^3$$

$$(R_e)_x = L = \frac{\rho LU}{\mu} = \frac{1.13 \times 0.75 \times 35}{2 \times 10^{-5}} = 1.48 \times 10^6$$

The boundary layer is turbulent as $R_e > 5 \times 10^5$

$$N_{ua} = \frac{h_a L}{k} = (0.7)^{\frac{1}{3}}$$

$$[(0.037 \times (1.48 \times 10^6)^{0.8} - 850] = 2074$$

$$h_a = \frac{2074}{1} \times \frac{0.0272}{0.75} = 75.5 \text{ W/m}^2$$

$$Q = h_a A\,(T_w - T_a)$$

$$= 75.5\,(0.75 \times 1)\,(60 - 20)$$

$$= 2260 \text{ W.}$$

Example 5: A flat plate 100 cm wide and 150 cm long is to be maintained at 90°C in air with a free stream temperature of 10°C. Determine the velocity at which the air must flow over the flat plate along 150 cm side so that the rate of energy dissipation from the plate is 3.75 kW. Properties of air at 50°, $\rho = 1.09$ kg/m^3

$k = 0.02$ W/m°C, $C_p = 1007$

J.kgK, $P_r = 0.7$ $\mu = 2.03 \times 10^{-5}$ kg/ms

Solution:

Heat flow from the plate to air is given by $Q = h_a A\,(T_\omega - T_a)$

$$= 3750 = h_a \times 1 \times 1.5\,(90 - 10)$$

$$h_a = \frac{3750}{1.5 \times 80} = 31.25 \text{ W/m}^2 - \text{c}°$$

Considering the flow is turbulent, the average heat transfer coefficient is given by

$$h_a = \frac{k}{L}[0.036(R_{e_l})^{0.8} - 836](P_r)^{0.33}$$

$$31.25 = \frac{0.028}{1.5}[(0.036(R_{e1})^{0.8} - 836)](0.7)^{0.33}$$

$R_{e_l} = 12.5 \times 10^5 > 5 \times 10^5$

Therefore assumption of turbulent flow is correct

$$R_{e_l} = \frac{\rho L U}{\mu}$$

$$U = \frac{R_e \mu}{\rho L} = \frac{(12.5 \times 10^5) \times 2.03 \times 10^{-5}}{1.09 \times 1.5}$$

$$= 15.5 \text{ m/s}$$

Direction for questions 6 and 7:

Example 6: Air at 35°C at atmospheric pressure of flow over a flat plate at a speed of 1.2 m/s. Calculate the boundary layer thickness at a distance of 15 cm and 30 cm from the leading edge of the plate

$V = 16 \times 10^{-6}$ m^{2}s,

$\mu = 18.6 \times 10^{-6}$ kg/ms

(A) 8.57 mm, 9.28 mm (B) 6.57 mm, 9.28 mm
(C) 6.57 mm, 6.25 mm (D) 8.57 m, 6.25 mm

Solution:

$$R_{e_x}\,(\text{at} = 0.15 \text{ m}) = \frac{Ux}{\nu}\frac{1.2 \times 0.15}{16 \times 10^{-6}}$$

$$= 11.25 \times 10^3$$

$$\delta\,(x = 0.15 \text{ m})$$

$$= \frac{4.64x}{\sqrt{R_{e_x}}} = \frac{4.64 \times 0.15}{\sqrt{11.25 \times 10^3}}$$

$$= (x_1 = 0.15) = 6.57 \text{ mm}$$

$$R_{e_x}\,(\text{at } x = .3 \text{ m}) = \frac{Ux}{\nu} = \frac{1.2 \times 0.3}{16 \times 10^{-6}}$$

$$= 22.5 \times 10^3$$

$$\delta_2 = (\text{at } x = 0.3)\frac{4.64x}{\sqrt{22.5 \times 10^3}}$$

$$= \frac{4.64 \times 0.3}{\sqrt{22.5 \times 10^3}}$$

$$\delta_2 = 9.28 \text{ mm.}$$

Example 7: Air at 35°C at atmospheric pressure flow over a flat plate at speed of 1.2 m/s. For the above boundary layers thickness at a distance of 15 cm and 30 cm from leading edge the mass of air flow, when $\rho = 1.16$ kg/m^3

(A) 8.48 kg/h (B) 6.75 kg/h
(C) 7.25 kg/h (D) 5.35 kg/h

Solution:

$$\delta_m = \frac{5}{8}\rho U(\delta_2 - \delta_1)$$

$$= \frac{5}{8} \times 1.16 \times 1.2(9.28 - 6.57) \times 10^{-3}$$

$$= 2.35 \times 10^{-3} \text{ kg/s}$$

$$2.35 \times 10^{-3} \times 3600 = 8.48 \text{ kg/h.}$$

Direction for questions 8 and 9:

Example 8: Air at 27°C and at atmospheric pressure flows over a flat plat at a speed of 2 m/s. Assuming the length of the plate along the flow of air is 2 m. Determine R_e, P_r and N_u number when properties of air at mean temperature of 60°C.

$\rho = 1.06$ kg/m^3, $C_p = 1.005$ kJ/kg K

$K = 0.0285$ W m/K, $\mu = 20.03 \times 10^{-6}$kg/m^{-5},

$\nu = 18.9 \times 10^{-6}$ m^2/s

(A) 2.11×10^5, 0.612, 125
(B) 2.11×10^6, 0706, 165
(C) 2.11×10^5, 0.612, 142
(D) 2.11×10^5, 0.706, 135

Solution:

$$\text{Reynolds Number } R_e = \frac{UL}{\nu}$$

$$= \frac{2 \times 2}{18.9 \times 10^{-6}}$$

$$2.11 \times 10^5$$

$$Re = 2.11 \times 10^5$$

$$\text{Prandtl Number } P_r = \frac{\mu C_p}{k}$$

$$= 20.03 \times 10^{-6} \times \frac{1005}{0.0285}$$

$$= 0.706$$

$$\text{Nusselt No} = N_u = \frac{hL}{k}$$
$$= 0.332 \times R_e^{0.5} \times P_r^{.33} = 135.$$

Example 9: Find the average heat transfer per unit length when plate maintained at 93°C.

(A) 506.88 W/m (B) 408 W/m
(C) 380 W/m (D) 560 W/m

Solution:

$$h\ell = \frac{135 \times 0.0285}{2} = 1.92 \text{ W/m}^2\text{K}$$
$$h_{av} = 2h\ell = 2 \times 1.92 = 3.84 \text{ W/m}^2\text{K}$$
$$Q = A \cdot h_{av}(T_\omega - T_a)$$
$$= 2 \times 1 \times 3.84\,(93 - 27)$$
$$Q = 506.88 \text{ W/m}.$$

Direction for questions 10 and 11: Air at 20°C flows over a plate 1 m wide and 2 m long at a velocity of 100 m/s. A fan is placed before the plate so that flow of air turbulent upstream an over the plate is,

Example 10: The thickness of the boundary layer at trailing edge of the plate

(A) 15.2×10^{-6} (B) 28.9×10^{-3}
(C) 15.6×10^{6} (D) 14.134×10^{6}

Assume properties of air at 20°C, $k = 0.025$ w/mk $v = 14.15 \times 10^{-6}$ m^2/sP_r = 0.72 take $N_u = 0.037 \times R_e^{0.8}\,(P_r)^{1/3}$ for turbulent flow and $\delta = \dfrac{0.39x}{\sqrt{R_{e_x}}}$ for turbulent flow

Solution:

To calculate mean value of h, we have to put $x = L$ in equation $N_{u_x} = \dfrac{hx}{K}$

Then
$$\overline{Nu} = \frac{\bar{h}L}{K}$$
$$R_{e_L} = \frac{vL}{\nu} = \frac{100 \times 2}{14.15 \times 10^{-6}}$$
$$= 14.134 \times 10^6.$$

Since, $R_{eL} > 5 \times 10^5$, flow is turbulent, thickness of boundary layer δ at $x = L = 2$ m

For turbulent flow

$$\delta = \frac{0.39x}{R_e^{0.2}} = \frac{0.39 \times 2}{(14.134 \times 10^6)^{0.2}} = 0.02898 \text{ m}.$$

Example 11: Average value of heat transfer coefficient for the entire surface of plate

(A) 315 W/m^{2}K (B) 217.65 W/m^{2}K
(C) 407 W/m^{2}K (D) 380 W/m^{2}K

Solution:

Average value of heat transfer coefficient

$$N_u = 0.037\,(R_e)^{0.8}\,(P_r)^{1/3}$$
$$0.037 \times (14.134 \times 10^6)^{.8} \times (.72)^{\frac{1}{3}}$$
$$= 17412$$
$$N_u = \frac{hL}{k} = \frac{h \times 2}{0.025}$$
$$h = 217.65 \text{ W/m}^2\text{K}.$$

Empirical Correlation for Forced Convection

If it is given that forced convection then determine nature of flow laminar or turbulent by Reynolds number.

Laminar Flow Over Flat Plate

1. $R_{e_x} = \rho \dfrac{Vx}{\mu}$

   Where x is the distance from leading edge along the length of the plate
2. $\delta = \dfrac{5x}{\sqrt{R_{e_x}}}$
3. $N_{u_x} = 0.332(R_{e_x})^{\frac{1}{2}} \times P_r^{\frac{1}{3}}$

$$Nu_x = \frac{h_x \cdot x}{Kf} \text{ (}Kf\text{ is thermal conductivity of fluid)}$$

Here, Nu_x and h_x are Nusselt number and local heat transfer co-efficient respectively $\overline{Nu} = \dfrac{\bar{h}L}{kf} = 0.664(R_{e_L})^{\frac{1}{2}} \times P_r^{\frac{1}{3}}$

Bar (–) represents average value

Laminar Flow Inside Tubes

$$N_U = \frac{hd}{k}$$

For constant heat flux $N_U = 4.36$

For constant wall temperature $N_U = 3.66$

Mean temperature $T_m = \dfrac{T_1 + T_0}{2}$

1. $\delta = \dfrac{0.37x}{(R_{e_x})^{\frac{1}{5}}}$
2. $N_{U_x} = 0.0288(R_e)^{.8}\,P_r^{\frac{1}{3}}$
3. $N_U = .036(R_{e_L})^{.8}\,P_r^{\frac{1}{3}}$
4. $N_U = 0.023 R_e^{.8}\,P_r^{\frac{1}{3}}$

General Notes

1. In laminar flow, Nusselt is not a function of $R_e^{0.8}$.
2. In turbulent flow, Nusselt is proportional to $R_e^{0.8}$.
3. In turbulent flow the velocity at a point varies about an average value.
4. The local value of convection co-efficient in laminar flow over a flat plate will decrease along the length.
5. In flow over flat plate over length L the average convection co-efficient will not be equal to $\dfrac{4}{3}h_L$.

6. In convection temperature and velocity gradient vary only in the boundary layer.
7. Along the thickness the boundary layer velocity and temperature gradients decrease.
8. The thickness of the hydrodynamic boundary layer is defined as the distance of the layer at which velocity gradient is nearly zero, from the surface of the plate.
9. In a laminar flow, the average convection coefficient along the length will decrease.
10. In a laminar flow the velocity at a location with respect to time is constant.
11. In turbulent flow the velocity at a point randomly chosen will be equal to the mean velocity.
12. In laminar flow, momentum and heat transfer is mainly by molecular diffusion.
13. In laminar flow there is no macroscopic mixing between layers.
14. In turbulent flow momentum and heat transfer is due to macroscopic mixing between layers.
15. If thermal diffusivity equals momentum diffusively, then the ratio of thermal and velocity boundary layer thickness will be equal to one.
16. The ratio of momentum diffusivity to thermal diffusivity is called Prandtl number.
17. Flow transition is generally judged by Reynolds number.
18. Thickness of hydrodynamic boundary layer in laminar flow is $= \dfrac{5x}{\sqrt{R_{e_x}}}$.
19. Thickness of hydrodynamic layer in turbulent flow is $0.381 \times R_{e_x}^{-vs.}$
20. In a liquid metal flow over a flat plate, thermal boundary layer will be thicker than hydrodynamic boundary layer.
21. In viscous oil flow over a flat plate the thermal boundary layer will be thinner than hydrodynamic boundary layer,
22. In laminar flow over flat plates the convection coefficient will be proportional to the distance raised to the power of –0.5.
23. In turbulent flow over flat plates the convection coefficient will be proportional to the distance raised to the power of –0.2,
24. In flow over a flat plate temperature and velocity gradients above the boundary layer is zero.
25. In the case of flow over flat plate the Reynolds number along the length will increase continuously,
26. The value of transition Reynolds number in the case of flow over flat plate is 5×10^5,
27. In pipe flow the analogy method of convection analysis relates Stanton number to friction factor,
28. In flow over bank of tubes effective way to increase heat transfer rate is to reduce the pitch.
29. In flow over spheres and cylinders. The characteristic length used in the calculation of dimensionless number is diameter,
30. In flow through non circular sections hydraulic mean diameter replaces diameter.
31. In flow through pipes conditions of flow is decided by the conditions at entry.
32. In fully developed flow through pipes the convection coefficient is constant.
33. In the case of liquid metal the flow in pipes can be considered as slug flow.

Example 12: For fully developed turbulent flow in a pipe with heating, the Nusselt number N_U, varies with Reynolds number R_e and Prandalt number (P_r) as

(A) $R_e^{0.5} (P_r)^{1/2}$ (B) $(R_e)^{0.8} \times (P_r)^{0.2}$
(C) $(R_e)^{0.8} (P_r)^{0.4}$ (D) $(R_e)^{0.8} (P_r)^{0.3}$

Solution:

Example 13: Consider the following statements is respect of automobile engine with thermosyphon coding

1. Heat transfer from gases to cylinder walls takes place by convection and radiation.
2. Most of the heat transfer from radiator to atmosphere takes place by radiation.
3. Most amount of heat transfer from radiator to atmosphere take place by convection.
4. Heat transfer from cylinder walls takes place conduction, and convection. The correct statements are:

(A) 1, 2 and 4 (B) 1, 3 and 4
(C) 2, 3 and 4 (D) 1 and 2

Solution:

Example 14: Water is passed through the annulus formed by the two tubes of 6 cm and 4 cm in diameter at a velocity of 0.5 m/sec of the inlet temperature of water is 20°C and 4 cm diameter tube temperature is maintained at 80°C.

Find the heat transfer coefficient between the water and small tube surface.

Take following properties of water at 50°C

$\rho = 988$ kg/m^3, $C_P = 4200$ J/kg K

$K = 0.557$ W/mK,

$v = 0.55 \times 10^{-6}$ m^2/sec

(A) 2632 W/m^2 (B) 3112 W/m^2
(C) 2830 W/m^2 (D) 3916 W/m^2

Solution:

$$R_e = \frac{(D-d)Um}{v}$$

$$= \frac{2}{100} \times \frac{0.5}{0.55 \times 10^{-6}} = 1.82 \times 10^4$$

$$P_r = \frac{\rho v C_P}{K}$$

$$= 988 \times 0.55 \times \frac{10^{-6} \times 4200}{.557} = 4.14$$

$$N_u = 0.023\,(R_e)^{.8}\,P_r^{0.33}$$

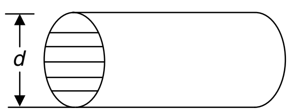
$$= 0.023\,(1.82 \times 10^4)^{.0.8}\,(4.14)^{0.33}$$
$$= 94.5$$
$$h \times \frac{(D-d)}{K} = 94.5$$
$$h = \frac{94.5 \times .557}{\frac{2}{100}} = 2632 \text{ W/m}^2\text{K}.$$

Flow Through the Duct

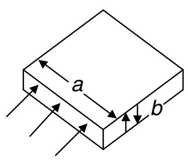
The calculation when flow takes place inside the plate or duct. For this we use equivalent diameter

$$D_{equ} = \frac{4A_c}{P}$$

(a) $D_{equ} = \dfrac{4 \times \dfrac{\pi d^2}{4}}{\pi d} = d$



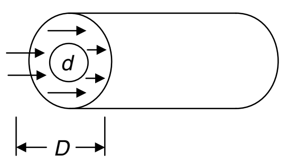
(b) $D_{equ} = \dfrac{4 \times ab}{2(a+b)}$



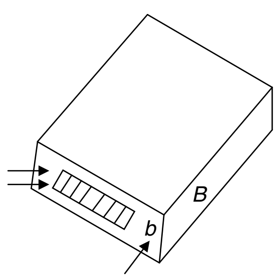
$$D_{equ} = \frac{2ab}{(a+b)}$$

(c) $D_{equ} = \dfrac{4 \times \dfrac{\pi}{4}(D^2 - d^2)}{(\pi D + \pi d)}$

$D_{\text{equ}} = D - d$



(d) $D_{equ} = \dfrac{4 \times (LB - Lb)}{2[(L+B)+(L+b)]}$



Example 15: Air at 30°C flowing along a heated plate at 144°C with velocity of 3 m/s. The plate is 2 m long. Heat transferred from first 40 cm from leading edge is 2 kw. Determine width of the plate

Properties of air

$\rho = 0.998$ kg/m^3, $C_p = 1.009$ kJ/kg-K

$\nu = 20.76 \times 10^{-6}$ m^2/s,

$K = 0.03$ W/m-K

Use following correlation

$N_{u_x} = 0.332\, R_e^{0.5}\, P_r^{0.33}$

Solution:

Given $T_\alpha = 20°C$ $T_s = 134°C$ $V = 3$ m/s. $L = 40$ cm $= .4$ m ($x = L = 0.4$ m), $Q = 2$ kW

Let b be the width of plate.

To determine width of the plate, we should find the area A of heat transfer. Since A = width × length (length is given as .4 m)

Area can be found out from $Q = h\,A\,\Delta T = h\,A\,(T_s - T_\alpha)$. Since Q and ΔT are known we should find out h which can be find out from given N_{UX} relation

$$R_{e_{0.4}} = \frac{VL}{\upsilon} = \frac{3 \times 0.4}{20.76 \times 10^{-6}}$$
$$= 0.57803 \times 10^5$$
$$\text{And } P_r = \frac{\mu C_p}{K} \text{ since } \frac{\mu}{\rho} = \nu\mu = \rho\nu$$

Hence

$$P_r = \frac{\rho_V C_P}{K} = \frac{.998 \times 20.76 \times 10^{-6} \times 1009}{0.03}$$
$$= 0.697$$
$$\text{Also } N_U = 0.332\, R_e^{.5}\, P_r^{0.33}$$
$$= 70.86$$
$$N_U L = \frac{h_L L}{K};\; h = \frac{N_\mu L k}{L}$$
$$h_L = \frac{70.86 \times 0.03}{0.4} = 5.313 \text{ W/m}^2\text{K}$$

We know that

$h_{av} = 2\,h_L$ (only in this case)

$= 2 \times 5.313$

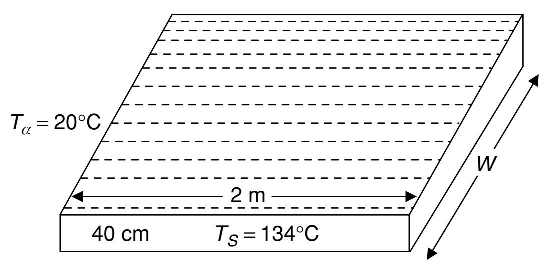
$= 10.626$ W/m^2-K

Have $Q = h\,A\,(T_s - T_\alpha)$

$= 2 \times 10^3$

$= 10.626\,(0.4 \times b) \times (144 - 30)$

Width $b = 4.12$ m



Example 16: For a fluid having Prandtl number equal to unity the relation between hydrodynamic boundary layer thickness δ_1 and thermal boundary layer thickness δ_1 is

(A) $\delta = \delta_t$ (B) $\delta > \delta_t$

(C) $\delta < \varepsilon_t$ (D) $\delta_t = \delta\frac{1}{3}$

Solution:

$$\frac{\delta_t}{\delta} = \frac{1}{(P_r)^{\frac{1}{3}}} \text{ as } P_r = 1$$

$$\delta_t = \delta.$$

Example 17: The Nusselt number is related to Reynolds number in laminar and turbulent flows respectively as

(A) $R_e^{\frac{-1}{2}}$ and $R_e^{0.8}$ (B) $R_e^{\frac{1}{2}}$ and $R_e^{-0.8}$

(C) $R_e^{-\frac{1}{2}}$ and $R_e^{-0.8}$ (D) For laminar flow

$N_U = .332\, R_e^{\frac{1}{2}} P_r^{\frac{1}{3}}$, For turbulent flow,

$N_U = 0.0288\, R_e^{0.8} P_r^{\frac{1}{3}}$

Solution: (D)

Example 18: Match the following list.

List-I	List-II
A. Nusselt number	**1.** Convection
B. log mean area	**2.** Conduction
C. Conduction through a cylindrical wall	**3.** Hyperbolic curve
D. Conduction through a spherical wall	**4.** logarithmic curve

Codes:

	a	b	c	d
(A)	1	2	4	3
(B)	2	1	3	4
(C)	1	2	4	3
(D)	2	1	3	4

Solution: (A)

Example 19: The value of biot number is very small (<0.01) when

(A) Convective resistance of a fluid surface of the body is negligible

(B) Conductive resistance with in the body is negligible

(C) Conductive resistance of the fluid is negligible

(D) None of these

Solution:

$$\text{Biot number} = \frac{hL}{k}$$

i.e., $\dfrac{\left(\dfrac{L}{K}\right)}{\dfrac{1}{h}} = \dfrac{\text{Conductive resistance}}{\text{Convective resistance}}$

Biot is very small conductive resistance is very low. This case is known as 'Lumped Heat Transfer'.

$$\frac{\text{Conductive resistance with in the body}}{\text{Convective resistance of fluid at surface}}$$

Formula Used for Solving Problems

Laminar Flow

1. $\dfrac{\delta}{x} = \dfrac{4.64}{\sqrt{R_{e_x}}}$ (Vor Karman) $= \dfrac{5}{\sqrt{R_{e_x}}}$ (Blassius)
2. $\dfrac{\delta}{\delta t} = (P_r)^{\frac{1}{3}}$
3. m_x (mass flow through boundary layer at a section $x = x$)
4. ∂_m (mass flow between two sections)

   $= \dfrac{5}{8}\rho U\left(\bar{d}_2 - \delta_1\right)$ where $\bar{d}_2 > \delta_1$
5. $C_{tx} = 0.664\ (P_{ex})^{-1/2}$
6. $C_{f_a} = 1.328\ (R_e \ell)^{-1/2}$
7. $\tau_x = C_{f_a}\dfrac{\rho U^2}{2}$
8. $\tau_x = 0.332\,\mu\dfrac{U}{L}\sqrt{R_{e_x}} = 0.332\rho U^2 \times (R_{e_x})^{\frac{-1}{2}}$
9. $\tau_x = 0.664\,\mu\dfrac{U}{L}\sqrt{R_{e_\ell}} = 0.664\rho U^2 (R_{e_L})^{\frac{1}{2}}$
10. $F = \tau_a A = 0.664\,\mu\, U\, W\sqrt{R_{e_\ell}} = 0.664 A\rho U^2 (R_{e_l})^{\frac{-1}{2}}$

Turbulent Flow

1. $\dfrac{\delta}{x} = \dfrac{0.39}{(\text{Re}_x)^{\frac{1}{5}}}$
2. $C_{fx} = 0.0576\ (R_{e_x})^{-1/5}$
3. $C_{f_a} = 0.072\ (R_{e_y})^{-1/5}$
4. $\tau_a = Cf_a\rho\dfrac{U^2 2}{}$
5. $F = \tau_a A$
6. $N_{u_x} = 0.0288\ (R_{e_x})^{0.8}\ (P_r)^{-1/5}$
7. $N_{u_a} = 0.036\ (R_{el})^{0.8}\ P_r^{1/3}$

Exercises

Practice Problems I

Direction for questions 1 to 20: Select the correct alternative from the given choices.

1. Engine oil at 80°C flows a over a horizontal flat plate at 40°C for cooling purpose, the flow velocity being 2 m/s. Determine at a distance of 0.4 m from the edge the thermal boundary layer thickness
   (A) 2 mm (B) 4 mm
   (C) 3 mm (D) 2.5 mm

   The film temperature is (80 + 40)/2 = 60°C, Kinematic Viscosity = 83×10^{-6}m^2/s, $P_r = 1050$. Thermal conductivity = 0.1407 W/mK

Direction for questions 2 and 3: Air at 20°C flows over a flat plate having a uniform heat flux of 800 W/m^2. The flow velocity is 4 m/s and length of the plate is 1.2 m

2. Determine (a) the value of heat transfer coefficient is

   $v = 19.42 \times 10^{-6}$, $K = 0.02593$ W/mK,

   $P_r = 0.695$, $N_u = 0.453\ [R_{e_x} P_r]^{0.5}$
   (A) 10.2 (B) 9.16
   (C) 8.9 (D) 12.1
3. The temperature of the plate as the air leaves the plate
   (A) 108.54°C (B) 112°C
   (C) 130°C (D) 195°C
4. For a flow over a flat plate the hydrodynamic boundary layer thickness is 0.5 mm. The dynamic viscosity is 30×10^{-6} Pa-s. Specific heat is 2.0 kJ/kg K and thermal conductivity is 0.05 W/mK. The thermal boundary layer thickness would be
   (A) 0.1 mm (B) 0.53 mm
   (C) 1 mm (D) 2 mm
5. A flat plate thickness 5 cm, the thermal conductivity 1 W/m-k convective heat transfer coefficients on its two flat faces of 15 W/m^{2}K and 20 W/m^{2}K. The overall heat transfer co-efficient for such a flat plate is
   (A) 6.026 W/m^{2}K (B) 6.33 W/m^{2}K
   (C) 20 W/m^{2}K (D) 30 W/m^{2}K

Direction for questions 6 and 7: A commercial aero plane is modeled as a flat plate which is 1.5 m wide and 8 m long in size. It is maintained at 20°C. The aero plane is flying at a speed of 850 km/s air at 0°C and 60 cm of Hg pressure. The properties of air at average temperature 10^{0}C $K = 2.511 \times 10^{-2}$ W/mK. $v = 14.16 \times 10^{-6}$ m^2/s $P_r = 0.705$

For laminar flow, $N_u = 0.64\ N_u^{1/2}\ P_r^{1/3}$, for turbulent flow,

$N_u = 0.036\ R_e^{0.8}\ P_r^{0.33}$

6. Heat transfer coefficient is in W/m^{2}K
   (A) 401 (B) 295
   (C) 353 (D) 318
7. Heat loss from wing if flow is made to parallel to width of using is
   (A) 200 kW (B) 153 kW
   (C) 287.2 kW (D) None of these

Direction for questions 8 and 9: An electrically heated sphere of 1.5 cm diameter is cooled in quiescent medium of air at 320 K. In order to maintain the surface temperature of the sphere at 385 K

$D = 1.5 \times 10^{-2}$ m

$T_\infty = 273 + 20 = 293$ K

The properties of air

Kinematic viscosity

$n = 2.076 \times 10^{-5}$ m^2/s

Prandtl number $P_r = 0.697$

Thermal conductivity $k = 0.03$ W/m-K

Coefficient of thermal expansion

$\beta = 2.86 \times 10^{-3} \times K^{-1}$

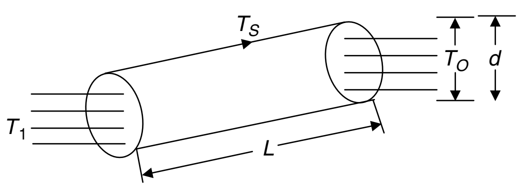
Use of the relationship

$$\bar{N}_u = 2 + 0.43 R_{a_D}^{\frac{1}{4}}$$

8. Grashof number is
   (A) 14281.3 (B) 19234
   (C) 15379.8 (D) Cannot be determined
9. Amount of heat to be supplied by electrical heater
   (A) 0.578 W (B) 0.729 W
   (C) 1.034 W (D) 2.32 W

Direction for questions 10 and 11: Consider steady one dimensional heat flow in a plate of 20 mm thickness with a uniform heat generation 80 MW/m^3. The left and right faces are kept at constant temperature of 160°C and 120°C respectively. The plate has a constant thermal conductivity of 200 W/mK.

10. The location of maximum temperature within the plate from its left face is
    (A) 15 mm (B) 10 mm
    (C) 5 mm (D) Zero
11. Maximum temperature within the plate in °C is
    (A) 160 (B) 165
    (C) 200 (D) 250
12. When liquid metal flows through the pipe shown in figure, the details of flows as shown in the given data



Given, properties of liquid metal

$\mu = 1.35 \times 10^{-3}$ kg/ms

$C_P = 150$ j/kg K

$P_r = 0.011$
$K = 16$ W/mK
$\mathring{m} = 5$ kg/s
$d = 6$ cm
$T_1 = 400°C$
$T_s - T_\infty = 30°C$
$T_0 = 450°C$ Correlation is
$N_u = 4.82 + 0.0185 \times (R_e; P_r)^{0.83}$
Calculate lengths of tube

(A) 2.5 m (B) 1 m
(C) 3 m (D) 4 m

13. 65 kg/mm of water is heated from 20°C to 80°C passing through the duct of 3 cm × 2 cm. The duct is heated by condensing the steam on its outer surface. Find out the length of duct required. Properties of water

$\rho = 995$ kg/m^3, $\mu = 7.65 \times 10^{-4}$ kg/m − s, C_p = 4.174 kJ/kgK, k = 0.623 W/mK, Conductivity of duct material = 35 W/mK use the following correlations, N_u = .023 $R_e^{0.8} P_r^{0.4}$ for turbulent flow, $N_u = 4.36$ for laminar flow

(A) 5.51 (B) 8 m
(C) 6 m (D) 7.51 m

Direction for questions 14, 15 and 16: Lubricating oil at a temperature of 60°C enters into a 1 cm diameter tube with a velocity of 3 m/s. The tube surface is to maintain at 30°C.

14. Find the heat gained by the oil at 45°C. Take properties of oil

$\rho = 865$ kg/m^3
$C_p = 1.75$ kJ/kgK

(A) 5355 W (B) 2257.25 W
(C) 2257.25 W (D) 4457.25 W

15. Determine the Reynolds number, Prandtl no, and Nusselt no for above data. Given $K = 0.12$ W/mK, $\nu = 9 \times 10^{-6}$m^2/s

(A) 62.5, 3333, 113.5 (B) 53.1, 2777, 112.5
(C) 52.1, 3333, 105.5 (D) 51.1, 2810, 115.4

16. Heat transfer coefficient for which the oil is flowing

(A) 690.8 W/m^{2}K (B) 649.2 W/m^{2}K
(C) 572.23 W/m^{2}K (D) 750 W/m^{2}K

17. Liquid mercury flow through a long tube 2.5 cm ID with a velocity of 0.9 m/s. Calculate R_e, P_r and N_u.
Following properties of mercury are given

$\rho = 12870.$ kg/m^3
$C_p = 135$ J/kg K
$K = 12$ W/mK
$\mu = 0.0016$ kg/ms

(A) 1.809×10^5, 0.018, 98.15
(B) 2×10^5, 0.028, 112.63
(C) 1×10^5, .028, 110.20
(D) 2×10^{-5}, 0.18, 106.78

18. Liquid Ammonia flows in a duct of section of equilateral triangle of 1 cm side. The average bulk temperature is 25°C and duct wall is at uniform temperature of 55°C. Fully developed laminar flow with Reynolds number of 1200 is maintained Calculate the average value of heat transfer for 1 m length. For fully developed flow, the triangular section laminar flow $N_u = 2.47$ (from tables) and $K = 0.521$ W/m^{2}K

(A) 200.6 W/m (B) 280.3 W/m^{2}K
(C) 215.3 W/m (D) 256.4 W/m

19. The velocity of water flowing through the tube 2.2 cm diameter is 2 m/s .On the steam condensing at 150°C the outside surface of tube heats the water from 15°C to 60°C over the length of tube. Determine the mass flow rate and heat gained by the water is passing through the tube Properties of water at mean temperature as

$\rho = 990$ kg/m^3 $C_p = 4.2$ kJ/kgK

(A) 31.3×10^3 W, 0.55 kg
(B) 41.1×10^3W, 0.49 kg
(C) 51.1×10^3W, 0.43 kg
(D) 142×10^3W, 0.753 kg

20. The velocity of water flowing through a tube of 2.2 cm dia is 2 m/s. The outside surface of tube is heated by steam, condensing at 150°C and heat water from 15°C to 60°C over the length of tube. Properties of water at mean temperature is $\rho = 990$ kg/m^3, $C_p = 4.2$ kJ/kgK. Determine R_e, P_r and N_u for the following properties of water is given at mean temperature.

$K = 0.5418$ W/mK, $\mu = 700 \times 10^{-6}$ kg/ms

(A) 7.2×10^4, 6.4,309 (B) 8×10^4, 5.2,309
(C) 4×10^4, 3.2,309 (D) 6.2×10^4, 5.43,308.71

Practice Problems 2

Direction for questions 1 to 30: Select the correct alternative from the given choices.

1. When there is a flow of fluid over a flat plate of length 'L' the average heat transfer coefficient is given by (N_{u_x} = local Nusselt number, other symbols have the usual meaning).

(A) $\int_o^L h_x d_x$ (B) $\frac{d}{d_x}(h_x)$
(C) $\frac{1}{L}\int_o^L h_x d_x$ (D) $\frac{K}{L}\int_o^L N_u d_x$

2. A fluid flowing over a flat plate has the following properties Dynamic viscosity 25×10^{-6} kg/ms. Specific heat = 2.0 kJ/kgK Thermal conductivity 0.05 W/mK.

The hydrodynamic boundary layer thickness is measured to be 0.6 mm. The thickness of thermal boundary layer would be

(A) 0.6 mm (B) 0.5 mm
(C) 1.0 mm (D) None of the above

Direction for questions 3 to 12: Air at 20° and at atmospheric pressure is flowing over a flat plate, with a velocity of 4 m/sec along the length. If the plate is 30 cm wide and 60°C, calculate the following at $x = 30$ cms along the length. Data properties of air at mean temperature 40°C

$\rho = 1.128$ kg/m^3, $\mu = 19.1 \times 10^{-6}$ kg/ms, $C_p = 1007$ J/kgK, $K = 0.0237$ W/mK.

3. Boundary layer thickness
(A) 5.228 mm (B) 6.35 mm
(C) 4.88 mm (D) 3.43 mm

4. Local friction coefficient
(A) 2.494×10^{-3} (B) 2.894×10^{3}
(C) 3.22×10^{-3} (D) 2.483×10^{-3}

5. Average friction coefficient
(A) 0.523 (B) 0.004988
(C) 0.428 (D) 0.00585

6. Local heat transfer coefficient
(A) 6.19 W/m^{2}K (B) 2.8 W/m^{2}K
(C) 7.2 W/m^{2}K (D) 4.3 W/m^{2}K

7. Average shear stress
(A) 0.23 N/m^2 (B) 0.5 N/m^2
(C) 0.45 N/m^2 (D) 0.3 N/m^2

8. Thickness of thermal boundary layer
(A) 8.84 mm (B) 6.19 mm
(C) 6 mm (D) 9.003 mm

9. Total heat loss for the length of the plate 30 cm along the flow
(A) 35.8 W (B) 73 W
(C) 44.56 W (D) 51.6 W

10. Total drag force on the plate
(A) .011 N (B) 0.210 N
(C) .021 N (D) 0.25 N

11. Total mass flow through boundary
(A) .38 kh/h (B) 41.83 kg/h
(C) 48 kg/h (D) 61.4 kg/h

12. Average heat transfer coefficient

The properties of air at mean temperature 40°C are as below.

$\rho = 1.128$ kgm^3, $\mu = 19.1 \times 10^{-6}$ kg/m^3 $C_p = 0.0273$ W/mgK, K = 0.0273 W/mK

(A) 5 W/m^{2}K (B) 13 W/m^{2}K
(C) 12.38 W/m^{2}K (D) 11.65 W/m^{2}K

13. Two plates spaced 150 mm apart are maintained at 1000°C and 70°C. The heat transfer will take place mainly by
(A) Convection
(B) Free convection
(C) Forced convection
(D) Radiation and convection

14. At thermal equilibrium
(A) Absorptivity is greater than emissivity
(B) Absorptivity is less than emissivity
(C) Absorptivity is equal to emissivity
(D) Sum of absorptivity and emissivity is unity

Direction for questions 15 and 16: Air at 25°C, flows over a thin plate with a velocity of 2.5 m/s. The plate is 2 m long and 1 m wide. At 25°C, the density of air is 1.2 kg/m^3 and kinematic viscosity is 15×10^{-6} m^2/s, Prandtl number for air = 0.69.

15. The thermal boundary layer at the trailing edge of the plate along the length
(A) 2.5 cm (B) 3.2 cm
(C) 2.1 cm (D) 1.96 cm

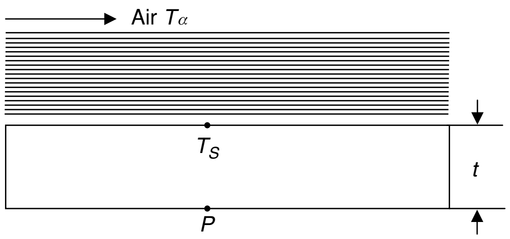
16. Total drag force experienced by the plate
(A) 0.0172 N (B) 0.0285
(C) 0.0331 (D) Zero

17. For flow over a plate the hydrodynamic boundary layer thickness is 0.5 mm. The dynamic viscosity is 25×10^{-6} kg/ms, specific heat is 2.0 kJ/kgK and thermal conductivity is 0.05 W/mK. The thermal layer thickness would be
(A) .1 mm (B) 0.5 mm
(C) 1 mm (D) 2 mm

18. A fluid of thermal condutivity 1.0 W/mK flows in fully developed flow of with Reynolds number 1500. Through a pipe of diameter 10 cm. The heat transfer coefficient for uniform heat flux and uniform wall temperature boundary conditions are respectively
(A) 36.57 and 43.64 W/m^{2}K
(B) 43.64 and 36.57 W/m^{2}K
(C) 43.64 W/m^{2}K for both the cases
(D) 36.57 W/m^{2}K for both the cases

19. Prandtl number of a flowing fluid greater than unity indicates that hydrodynamic boundary layer thickness is
(A) Greater than thermal
(B) Less than thermal boundary layer
(C) Equal to thermal boundary layer
(D) None of the above

Direction for questions 20 and 21: Air having temperature 250°C flows over a plate whose surface temperature is 50°C. For plate $L = 10$ cm $b = 5$ cm, $t = 2$ cm, $K = 10$ W/mK Value of heat transfer coefficient at distance x from leading edge is $h(x) = C_o e^{\frac{X}{L}}$ Here, C_o is a constant



20. Value of average heat transfer coefficient is

(A) $\bar{h} = 1.71,\ C_o = 2$ (B) $\bar{h} = 0.85,\ C_o = 0.5$

(C) $\bar{h} = 3.43,\ C_o = 1$ (D) None of these

21. At steady state, the temperature of point P will be (if $C_o = 15$)

(A) 5.1°C (B) 45°C

(C) 39.74°C (D) 50°C

22. A plate is maintained at 84°C and this surface is facing air having temperature of 30°C, then what will be the value of coefficient of volumetric expansion β?

(A) 325 /k

(B) 0.0192 k

(C) 3.300×10^{-3} k

(D) None of these

Direction for questions 23 and 24: A flat is 2 m long 0.8 m wide and 3 mm thick. Density of plate is 3000 kg/m^3 specific heat of plate material is 700 J/kgK. Its initial temperature is 80°C. A stream of air at 20°C blow over both surfaces of the plate along its width at a velocity of 2 m/s

Properties of air $\rho = 1.09$ kg/m^2

$K = 0.28$ W/m-K $P_r = 0.698$

$\mu = 2.03 \times 10^{-5}$kg/m-s

$$N_u = 0.664(R_e)^{\frac{1}{2}}(P_r)^{\frac{1}{3}}$$

23. Rate of heat dissipation from plate

(A) 586 W (B) 586 kW

(C) 1173 W (D) 1173 kW

24. Initial rate of cooling is

(A) .0058°C/s

(B) 0.0116^2

(C) 0.0116°C/s

(D) None of these

Direction for questions 25 and 26: The pressurized water enters the tube of diameter 50 mm with constant surface heat flux of 2000 W/m^2 at mass flow rate of 0.01 kg/sec and 20°C.

25. What is the tube length (ℓ) required to obtain an exit temperature of 80°C. C_p of Water = 4.187 kJ/kg°K

(A) 8 m (B) 11.09 m

(C) .0066 m (D) 3.32 m

26. What is the surface temperature of out let of the tube where local convection co-efficient at the tube outlet is 48.7 W/m^{2}K

(A) 121.06°C (B) 101.06°C

(C) 81.06°C (D) 61.06°C

Direction for questions 27 and 28: Air at 27°C and pressure 10^5 N/m^2 flows over a flat plate at a speed of 2 m/s. For air $m = 19.8 \times 10^{-6}$ kg/ms at 27°C.

Properties of air at mean temperature of (27 + 60)/2 = 43.5°C are listed below

$\upsilon = 17.36 \times 10^{-6}$ m^2/s

$C_p = 1006$ J/kg

$R = 287$ Nm/kgK

$K = 0.02749$ W/mK

$P_r = 0.7$

27. Find the boundary layer thickness at 40 cm from leading edge of the plate.

(A) 0.68 cm (B) 0.75 cm

(C) 0.27 cm (D) 0.13 cm

28. Calculate the heat transfer per hour if the plate is maintained at 60°C.

(A) 400 kJ/h (B) 390 kJ/h

(c) 388 kJ/h (D) 1318 kJ/h

29. A thin plate of length 2 m and width 1.2 m is exposed to a flow of air parallel to surface along 2 m side. The velocity and temperature of the free stream flow of air are 3 m/s and 20°C respectively. The plate surface temperature is 80°C. The amount of heat transferred is

(Take the following properties of air at 20°c)

$v = 15.06 \times 10^{-6}$ m^2/s, $K = 2.59 \times 10^{-2}$ W/m°C, $P_r = 0.703$

(A) 70 W (B) 694 W

(C) 710 W (D) 650 W

30. A flat plate of length 100 cm is exposed to air flow parallel to its surface. The velocity and temperature of the free stream air flow are 80 m/s and 10°C. At turbulising grid is placed upstream of the plate resulting in that the fluid is in turbulent flow in the boundary layer over the whole length of the plate. Calculate the mean heat transfer coefficient and thickness of hydrodynamic boundary layer at the end of the plate. $\delta = \dfrac{0.37x}{5\sqrt{R_{e_x}}}$

Take the following properties of the air at 10°C $v = 14.16 \times 10^{-6}$ m^2/s, $K = 2.51 \times 10^{-2}$ W/m−°C

(A) 198 W/m^{2}C, 1.66 cm

(B) 280 W/m^2 2.1 cm

(C) 311 W/m^{2}C, 3 cm

(D) 4.2 m^{2}C, 1.8 cm

PREVIOUS YEARS' QUESTIONS

Direction for questions 1 and 2: An un-insulated air conditioning duct of rectangular cross section 1 m × 0.5 m, carrying air at 20°C with a velocity of 10 m/s, is exposed to an ambient of 30°C. Neglect the effect of duct construction material. For air in the range of 20–30°C, data are as follows: thermal conductivity = 0.025 W/mK; viscosity = 18 μPa.s; Prandtl number = 0.73; density = 1.2 kg/m^3. The laminar flow Nusselt number is 3.4 for constant wall temperature conditions and, for turbulent flow, $N_u = 0.023\ R_e^{0.8}\ P_r^{0.33}$.

1. The Reynolds number for the flow is **[2005]**
   (A) 444 (B) 890
   (C) 4.44×10^5 (D) 5.33×10^5
2. The heat transfer per metre length of the duct, in watts, is: **[2005]**
   (A) 3.8 (B) 5.3 (C) 89 (D) 769
3. The temperature distribution within the thermal boundary layer over a heated isothermal flat plate is given $y\dfrac{T - T_w}{T_\infty - T_w} = \dfrac{3}{2}\left(\dfrac{y}{\delta_t}\right) - \dfrac{1}{2}\left(\dfrac{y}{\delta_t}\right)^3$ where T_w and T_∞ are the temperatures of plate and free stream respectively, and y is the normal distance measured from the plate. The local Nusselt number based on the thermal boundary layer thickness δ_t is given by **[2007]**
   (A) 1.33 (B) 1.50 (C) 2.0 (D) 4.64
4. A coolant fluid at 30°C flows over a heated flat plate maintained at a constant temperature of 100°C. The boundary layer temperature distribution at a given location on the plate may be approximated as $T = 30 + 70\exp(-y)$, where y (in m) is the distance normal to the plate and T is in °C. If thermal conductivity of the fluid is 1.0 W/mK, the local convective heat transfer coefficient (in W/m^{2}K) at that location will be **[2009]**
   (A) 0.2 (B) 1
   (C) 5 (D) 10
5. The ratios of the laminar hydrodynamic boundary layer thickness to thermal boundary layer thickness of flows of two fluids P and Q on a flat plate are $\dfrac{1}{2}$ and 2 respectively. The Reynolds number based on the plate length for both the flows is 10^4. The Prandtl and Nusselt numbers for P are $\dfrac{1}{8}$ and 35 respectively. The Prandtl and Nusselt numbers for Q are respectively. **[2011]**
   (A) 8 and 140 (B) 8 and 70
   (C) 4 and 70 (D) 4 and 35

Direction for questions 6 and 7: Water (specific heat, C_p = 4.18 kJ/kgK) enters a pipe at a rate of 0.01 kg/s and a temperature of 20°C. The pipe, of diameter 50 mm and length 3 m, is subjected to a wall heat flux q_W^n in W/m^2:

6. If $q_w'' = 2500x$, where x is in m and in the direction of flow ($x = 0$ at the inlet), the bulk mean temperature of the water leaving the pipe in ºC is **[2013]**
   (A) 42 (B) 62
   (C) 74 (D) 104
7. If $q_w'' = 5000$ and the convection heat transfer coefficient at the pipe outlet is 1000 W/m^{2}K, the temperature in °C at the inner surface of the pipe at the outlet is **[2013]**
   (A) 71 (B) 76 (C) 79 (D) 81
8. The non-dimensional fluid temperature profile near the surface of a convectively cooled flat plate is given by $\dfrac{T_w - T}{T_w - T_\infty} = a + b\dfrac{y}{L} + c\left[\dfrac{y}{L}\right]^2$, where y is measured perpendicular to the plate, L is the plate length, and a, b and c are arbitrary constants. T_W and T_∞ are wall and ambient temperatures, respectively. If the thermal conductivity of the fluid is k and wall heat flux is q″ the Nusselt number $Nu = \dfrac{q''}{T_w - T_\infty}\dfrac{L}{k}$ is equal to **[2014]**
   (A) a (B) b
   (C) $2c$ (D) $(b + 2c)$
9. For laminar forced convection over a flat plate, if the free stream velocity increases by a factor of 2, the average heat transfer coefficient **[2014]**
   (A) Remains same
   (B) Decreases by a factor of $\sqrt{2}$
   (C) Rises by a factor of $\sqrt{2}$
   (D) Rises by a factor 4
10. Water flows through a tube of diameter 25 mm at an average velocity of 1.0 m/s. The properties of water arer = 1000 kg/m^3, $\mu = 7.25 \times 10^{-4}$ N.s/m^2, $K = 0.265$ W/mK, $P_r = 4.85$. Using $N_u = 0.023\ R_e^{0.8} P_r^{0.4}$, the convective heat transfer coefficient (in W/m^2.K) is __________. **[2014]**
11. For flow of viscous fluid over a flat plate, if the fluid temperature is the same as the plate temperature, the thermal boundary layer is **[2015]**
    (A) thinner than the velocity boundary layer
    (B) thicker than the velocity boundary layer
    (C) of the same thickness as the velocity boundary layer
    (D) not formed at all
12. In the laminar flow of air (Pr = 0.7) over a heated plate, if δ and δ_T denote, respectively, the hydrodynamic and thermal boundary layer thickness, then **[2015]**
    (A) $\delta = \delta_T$ (B) $\delta > \delta_T$
    (C) $\delta < \delta_T$ (D) $\delta = 0$ but $\delta_T \neq 0$

13. The ratio of momentum diffusivity (v) to thermal diffusivity (a), is called: **[2015]**
(A) Prandtl number (B) Nusselt number
(C) Biot number (D) Lewis number

14. One side of a wall is maintained at 400 K and the other at 300 K. The rate of heat transfer through the wall is 1000 W and the surrounding temperature is 25°C. Assuming no generation of heat within the wall, the irreversibility (in W) due to heat transfer through the wall is ________. **[2015]**

15. A fluid (Prandtl number, $P_r = 1$) at 500 K flows over a flat plate of 1.5 m length, maintained at 300 K. The velocity of the fluid is 10 m/s. Assuming kinematic viscosity, $u = 30 \times 10^{-6}$ m^2/s, the thermal boundary layer thickness (in mm) at 0.5 m from the leading edge is ______. **[2016]**

Answer Keys

Exercises

Practice Problems 1

1. A	**2.** B	**3.** D	**4.** B	**5.** A	**6.** D	**7.** B	**8.** A	**9.** A	**10.** C
11. B	**12.** A	**13.** D	**14.** A	**15.** A	**16.** D	**17.** A	**18.** A	**19.** D	**20.** D

Practice Problems 2

1. C	**2.** A	**3.** A	**4.** A	**5.** B	**6.** A	**7.** C	**8.** A	**9.** C	**10.** A
11. D	**12.** C	**13.** D	**14.** C	**15.** D	**16.** A	**17.** B	**18.** B	**19.** A	**20.** B
21. C	**22.** C	**23.** C	**24.** C	**25.** A	**26.** A	**27.** C	**28.** D	**29.** B	**30.** A

Previous Years' Questions

1. C	**2.** D	**3.** B	**4.** B	**5.** A	**6.** B	**7.** D	**8.** B	**9.** C
10. 4600 to 4625		**11.** D	**12.** C	**13.** A	**14.** 247 to 249		**15.** 6 to 6.25	