<u>Heat Transfer by Convection- Introduction</u>

<u>The Objective:</u> Studying the mechanism of heat transfer through a fluid in the presence of bulk fluid motion.

<u>Introduction:</u>

Heat transfer through a solid is always by conduction, since the molecules of a solid remain at relatively fixed positions. Heat transfer through a liquid or gas, however, can be by conduction or convection, depending on the presence of any ***bulk fluid motion***.
Heat transfer through a fluid is by convection in the presence of bulk fluid motion and by conduction in the absence of it.
Convection heat transfer is complicated by the fact that it involves fluid motion as well as heat conduction. The rate of heat transfer through a fluid is much higher by convection than it is by conduction. In fact, the higher the fluid velocity, the higher the rate of heat transfers.

Convection Classification:

Convection is classified depending on how the fluid motion is initiated as:

- ***Natural convection*** (or ***free convection***).
- ***Forced convection.***

In forced convection: The fluid is forced to flow over a surface or in a pipe by external means such as a **pump** or a **fan.**

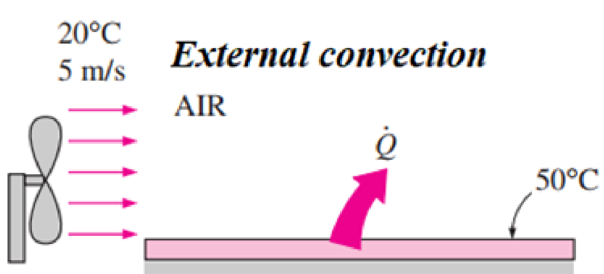
In natural convection: any fluid motion is caused by natural means such as the buoyancy effect, which manifests itself as the rise of warmer fluid and the fall of the cooler fluid (no source of motion).

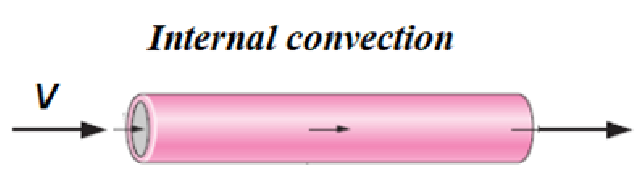
Convection is also classified as:

(depending on whether the fluid is forced to flow over a surface or in a channel).

- ***External convection*:**
The fluid is forced to flow over a surface such as flow over flat plate or turbine blade.
- ***Internal convection*:**

The fluid is forced to flow in a channel such as, flow in channel, pipe, duct.





Experience shows that convection heat transfer strongly depends on the **fluid properties** ***dynamic viscosity*** **μ**, ***thermal conductivity*** ***k***, ***density*** **ρ**, and ***specific heat*** ***Cp***, as well as the ***fluid velocity*** ***V***. It also depends on the ***geometry*** and the ***roughness*** of the solid surface, in addition to the ***type of fluid flow*** (such as being ***laminar*** streamlined or ***turbulent***).

Convection heat transfer is observed to be proportional to the temperature difference and is conveniently expressed by ***Newton's law of cooling*****:**

$\dot{q}_{conv} = h\,(T_s - T_\infty)$ (W/m^2) **[Heat flux]** (1)

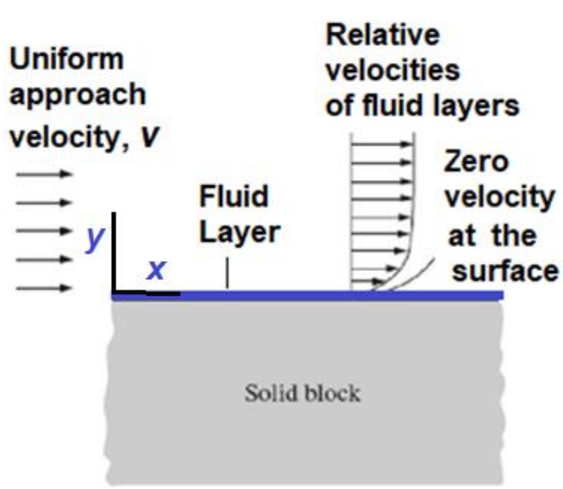
$\dot{Q}_{conv} = h\,A_s\,(T_s - T_\infty)$ (W) **[Rate of heat transfer]** (2)

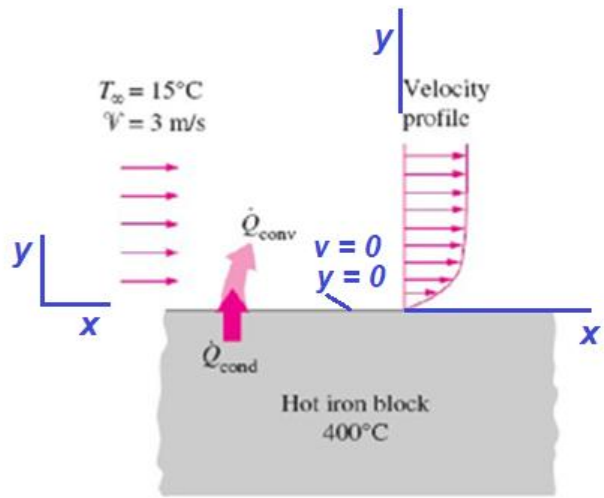
Where: $[\,\dot{q} = \dot{Q}\,/\,A\,]$

h = convection heat transfer coefficient, (W/m^2.°C)
A_s = heat transfer surface area, (m^2)
T_s = temperature of the surface, (°C)
T_∞ = temperature of the fluid sufficiently far from the surface, (°C)

Judging from its **units, the convection heat transfer coefficient** ***h*** can be defined as ***the rate of heat transfer between a solid surface and a fluid per unit surface area per unit temperature difference.***

$$h = \frac{\dot{Q}}{A_s(T_s - T_\infty)} \qquad (\text{W/m}^2.°\text{C}) \qquad (3)$$





When a fluid is forced to flow over a solid surface, it is observed that the fluid in motion comes to a complete stop at the surface and assumes a zero velocity relative to the surface. That is, the fluid layer in direct contact with a solid surface "***sticks***" to the surface and there is ***no slip***. In fluid flow, this phenomenon is known as the ***no-slip condition*****,** and it is due to the ***viscosity of the fluid***.

A fluid and a solid surface will have ***the same temperature at the point of contact***. This is known as ***no-temperature-jump condition*****.**

An implication of the no-slip and the no-temperature jump conditions is that heat transfer from the solid surface to the fluid layer adjacent to the surface is by ***pure conduction***, since the ***fluid layer is motionless***, and can be expressed as:

$$\dot{q}_{\text{conv}} = \dot{q}_{\text{cond}} = -k_{\text{fluid}} \left.\frac{\partial T}{\partial y}\right|_{y=0} \qquad (\text{W/m}^2) \tag{4}$$

Where T represents the temperature distribution in the fluid and

$\left.\frac{\partial T}{\partial y}\right|_{y=0}$ is the temperature gradient at the surface.

This heat is then ***convected away*** from the surface as a result of fluid motion. Note that convection heat transfer from a solid surface to a fluid is merely the conduction heat transfer from the solid surface to the fluid layer adjacent to the surface. Therefore, we can equate **eq.(1) & eq. (4)** for the ***heat flux*** to obtain:

$$\underbrace{h\,(T_s - T_\infty)}_{\text{eq. (1)}} = \underbrace{-k_{\text{fluid}} \left.\frac{\partial T}{\partial y}\right|_{y=0}}_{\text{eq.(4)}}$$

$$h = \frac{-k_{\text{fluid}}(\partial T/\partial y)_{y=0}}{T_s - T_\infty} \qquad (\text{W/m}^2 \cdot {}^\circ\text{C}) \tag{5}$$

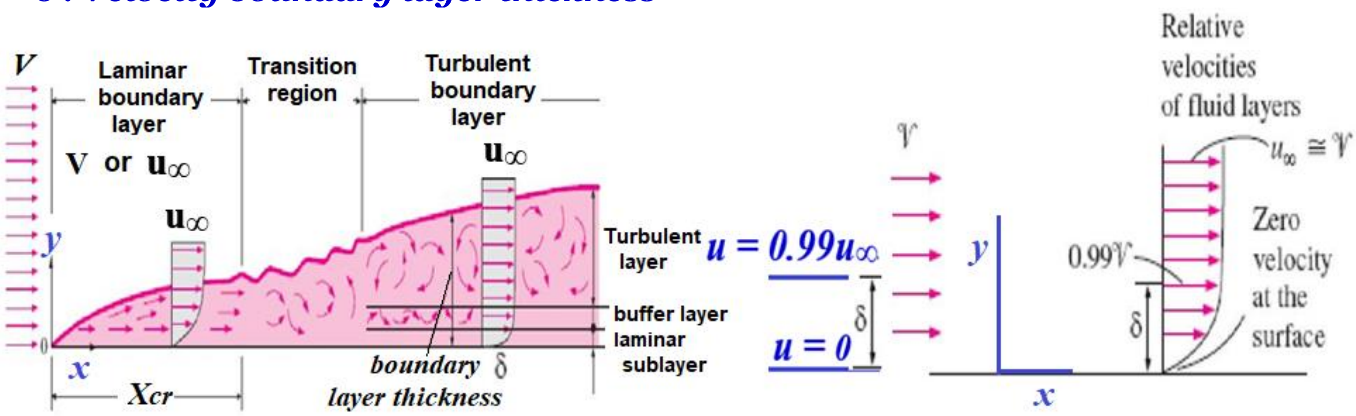
The convection heat transfer coefficient, in general, varies along the flow (or x-) direction. The ***average or mean convection heat transfer coefficient for a surface*** in such cases is determined by properly ***averaging*** the ***local convection heat transfer*** coefficients over the entire surface.

Velocity boundary layer

Consider the ***parallel flow*** of a fluid over a ***flat plate***. The $\boldsymbol{x}$-coordinate is measured along the plate surface from the ***leading edge*** of the plate in the direction of the flow, and $\boldsymbol{y}$ is measured from the surface in the normal direction. The fluid approaches the plate in the $\boldsymbol{x}$-direction with a ***uniform upstream velocity of V*****,** which is practically identical to the free-stream velocity $\boldsymbol{u_\infty}$ over the plate away from the surface. The $\boldsymbol{x}$-component of the fluid velocity, $\boldsymbol{u}$, will vary from **0** at $\boldsymbol{y = 0}$ to nearly $\boldsymbol{u_\infty}$ at $\boldsymbol{y} = \delta$.

The region of the flow above the plate bounded by δ in which the effects of the viscous shearing forces caused by fluid viscosity are felt is called the velocity boundary layer. The ***boundary layer thickness*** δ, is typically ***defined as the distance y from the surface at which u = 0 to a distance at which u = 0.99u∞.*** The hypothetical line of $\boldsymbol{u = 0.99\, u_\infty}$

δ : Velocity boundary layer thickness



divides the flow over a plate into two regions: the ***boundary layer region*****,** in which the ***viscous effects and the velocity changes*** are ***significant***, and the ***inviscid flow region*****,** in which the ***frictional effects are negligible*** and the velocity remains essentially constant.

Friction force per unit area is called ***shear stress*****,** and is denoted by $\boldsymbol{\tau}$**.** Experimental studies indicate that the shear stress for most fluids is proportional to the ***velocity gradient***, and the shear stress at the wall surface is as:

μ : (kg / m.s) , υ : (m^2/ s) $\quad u_\infty$

$$\tau_s = \mu \left. \frac{\partial u}{\partial y} \right|_{y=0} \qquad (\mathrm{N/m^2}) \qquad (6) \qquad \upsilon = \mu / \rho$$

Where the constant of proportionality $\boldsymbol{\mu}$ is called the ***dynamic viscosity*** of the fluid. ***Kinematic viscosity*** is expressed as $\upsilon = \mu / \rho$.

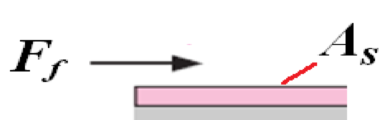
Common units of kinematic viscosity are **m²/s** and ***stoke*** (1 stoke =1cm^2/s = 0.0001 m^2/s).

The determination of the surface shear stress $\boldsymbol{\tau}$ is not practical since it requires a knowledge of the flow velocity profile. A more practical approach in external flow is to relate $\boldsymbol{\tau}$ to the upstream velocity ***V*** as:

$$\tau_s = C_f \, \frac{\rho V^2}{2} \qquad (\mathrm{N/m^2}) \qquad (7)$$

Where ***C*** C_f is the dimensionless ***friction coefficient*****,** whose ***value in most cases is determined experimentally***, and $\boldsymbol{\rho}$ is the density of the fluid. Note that the friction coefficient, in general, will vary with location along the surface. Once the average friction coefficient over a given surface is available, the friction force over the entire surface is determined from

$$F_s = C_f \, A_s \, \frac{\rho V^2}{2} \qquad (\mathrm{N}) \qquad (8)$$



$$\tau_s = \frac{F_s}{A_s} \quad , \quad F_s = \tau_s \cdot A_s$$

Where A_s is the surface area.

The ***Reynolds analogy*** relates the convection coefficient h to the friction coefficient C_f for fluids with ***Prandtl Number***, $P_r \approx 1$, C_p is specific heat at constant pressure, V is fluid velocity, ρ is density, and is expressed as:

$$h = \frac{C_f}{2}\frac{\rho \mathcal{V} C_p}{\mathrm{Pr}^{2/3}} \tag{9}$$

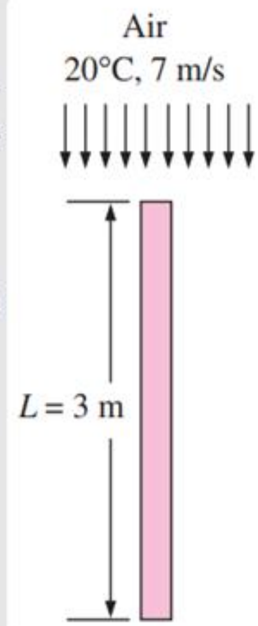
Example:

A **2**m x **3**m flat plate is suspended in a room, and is subjected to air flow parallel to its surfaces along its **3**m long side. The free stream temperature and velocity of air are **20˚C** and **7** m/s. The total drag force acting on the plate is measured to be **0.86 N**. ***Determine*** the average convection heat transfer coefficient for the plate.

Solution:

The properties of air at **20˚C** and pressure 1atm. from tables are:

$$\rho = 1.204 \text{ kg/m}^3, \quad C_p = 1.007 \text{ kJ/kg}\cdot\text{K}, \quad \mathrm{Pr} = 0.7309$$



Analysis The flow is along the 3-m side of the plate, and thus the characteristic length is $L = 3$ m. Both sides of the plate are exposed to air flow, and thus the total surface area is

$$A_s = 2WL = 2(2 \text{ m})(3 \text{ m}) = 12 \text{ m}^2$$

For flat plates, the drag force is equivalent to friction force. The average friction coefficient C_f can be determined from Eq. **(8)**

$$F_f = C_f A_s \frac{\rho \mathcal{V}^2}{2}$$

Solving for C_f and substituting,

$$C_f = \frac{F_f}{\rho A_s \mathcal{V}^2/2} = \frac{0.86 \text{ N}}{(1.204 \text{ kg/m}^3)(12 \text{ m}^2)(7 \text{ m/s})^2/2} = 0.00243$$

Then the average heat transfer coefficient can be determined from the modified Reynolds analogy (Eq. **(9)**

$$h = \frac{C_f}{2}\frac{\rho \mathcal{V} C_p}{\mathrm{Pr}^{2/3}} = \frac{0.00243}{2}\frac{(1.204 \text{ kg/m}^3)(7 \text{ m/s})(1007 \text{ J/kg}\cdot°\text{C})}{0.7309^{2/3}} = 12.7 \text{ W/m}^2\cdot°\text{C}$$

Test:

Q1: What is forced convection? How does it differ from natural convection?

Q2: Is convection caused by winds forced or natural convection?

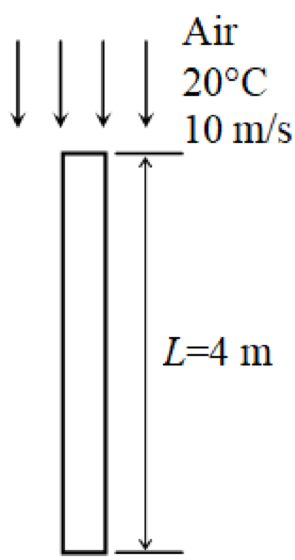
H.W.

A **4**m x **4**m flat plate maintained at a constant temperature of **80˚C** is subjected to parallel flow of air at **1** atm, **20˚C**, and **10 m/s**. The total drag force acting on the upper surface of the plate is measured to be **2.4N**. **Determine** the average ***convection heat transfer coefficient,*** and the ***rate of heat transfer*** between the upper surface of the plate and the air.

The properties of air at **20**°C and **1** atm from tables, are:

ρ = 1.204 kg/m^3, C_p =1.007 kJ/kg.K,   **Pr** = 0.7309

Answer: ***h = 46.54 W/m^2.***°C ,   ***$\dot{Q}$ = 89356W***



Properties of air at 1 atm pressure

Temp. T, °C	Density ρ, kg/m^3	Specific Heat c_p, J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m^2/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m^2/s	Prandtl Number Pr
−150	2.866	983	0.01171	4.158×10^{-6}	8.636×10^{-6}	3.013×10^{-6}	0.7246
−100	2.038	966	0.01582	8.036×10^{-6}	1.189×10^{-5}	5.837×10^{-6}	0.7263
−50	1.582	999	0.01979	1.252×10^{-5}	1.474×10^{-5}	9.319×10^{-6}	0.7440
−40	1.514	1002	0.02057	1.356×10^{-5}	1.527×10^{-5}	1.008×10^{-5}	0.7436
−30	1.451	1004	0.02134	1.465×10^{-5}	1.579×10^{-5}	1.087×10^{-5}	0.7425
−20	1.394	1005	0.02211	1.578×10^{-5}	1.630×10^{-5}	1.169×10^{-5}	0.7408
−10	1.341	1006	0.02288	1.696×10^{-5}	1.680×10^{-5}	1.252×10^{-5}	0.7387
0	1.292	1006	0.02364	1.818×10^{-5}	1.729×10^{-5}	1.338×10^{-5}	0.7362
5	1.269	1006	0.02401	1.880×10^{-5}	1.754×10^{-5}	1.382×10^{-5}	0.7350
10	1.246	1006	0.02439	1.944×10^{-5}	1.778×10^{-5}	1.426×10^{-5}	0.7336
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111
120	0.8977	1011	0.03235	3.565×10^{-5}	2.264×10^{-5}	2.522×10^{-5}	0.7073
140	0.8542	1013	0.03374	3.898×10^{-5}	2.345×10^{-5}	2.745×10^{-5}	0.7041
160	0.8148	1016	0.03511	4.241×10^{-5}	2.420×10^{-5}	2.975×10^{-5}	0.7014
180	0.7788	1019	0.03646	4.593×10^{-5}	2.504×10^{-5}	3.212×10^{-5}	0.6992
200	0.7459	1023	0.03779	4.954×10^{-5}	2.577×10^{-5}	3.455×10^{-5}	0.6974
250	0.6746	1033	0.04104	5.890×10^{-5}	2.760×10^{-5}	4.091×10^{-5}	0.6946
300	0.6158	1044	0.04418	6.871×10^{-5}	2.934×10^{-5}	4.765×10^{-5}	0.6935
350	0.5664	1056	0.04721	7.892×10^{-5}	3.101×10^{-5}	5.475×10^{-5}	0.6937
400	0.5243	1069	0.05015	8.951×10^{-5}	3.261×10^{-5}	6.219×10^{-5}	0.6948
450	0.4880	1081	0.05298	1.004×10^{-4}	3.415×10^{-5}	6.997×10^{-5}	0.6965
500	0.4565	1093	0.05572	1.117×10^{-4}	3.563×10^{-5}	7.806×10^{-5}	0.6986
600	0.4042	1115	0.06093	1.352×10^{-4}	3.846×10^{-5}	9.515×10^{-5}	0.7037
700	0.3627	1135	0.06581	1.598×10^{-4}	4.111×10^{-5}	1.133×10^{-4}	0.7092
800	0.3289	1153	0.07037	1.855×10^{-4}	4.362×10^{-5}	1.326×10^{-4}	0.7149
900	0.3008	1169	0.07465	2.122×10^{-4}	4.600×10^{-5}	1.529×10^{-4}	0.7206
1000	0.2772	1184	0.07868	2.398×10^{-4}	4.826×10^{-5}	1.741×10^{-4}	0.7260
1500	0.1990	1234	0.09599	3.908×10^{-4}	5.817×10^{-5}	2.922×10^{-4}	0.7478
2000	0.1553	1264	0.11113	5.664×10^{-4}	6.630×10^{-5}	4.270×10^{-4}	0.7539