Forced Convection

Forced convection refers to the transfer of heat through a fluid (liquid or gas) when an external force, such as a fan or pump, is applied to the fluid to increase the fluid's flow rate. This is in contrast to natural convection, which occurs due to density differences in the fluid caused by temperature variations.

Forced convection is typically more efficient than natural convection because it allows for greater fluid flow and heat transfer rate control. Forced convection is important for the GATE ME exam. It is commonly used in industrial and HVAC (heating, ventilation, and air conditioning) applications.

Newton's Law of Cooling

Newton's law of cooling states that the rate of change of temperature of an object is proportional to the difference between its own temperature and the temperature of its surroundings, with the constant of proportionality being the heat transfer coefficient. This can be mathematically represented as:

$$dT/dt = -h(T-T_s)$$

Where:

- dT/dt is the rate of change of temperature of the object,
- T is the temperature of the object
- T_s is the temperature of the surroundings, and
- h is the heat transfer coefficient.

The convective heat transfer coefficient h strongly depends on the fluid properties and roughness of the solid surface and the type of fluid flow (laminar or turbulent).

$$h = f(\rho, V, D, \mu, C_p, K)$$

This law is based on the assumption that the heat transferred from the object is proportional to the difference in temperature between the object and its surroundings and that the heat transfer coefficient is constant. This law is only approximate and valid for cases where the temperature difference between the object and its surroundings is small, and the heat transfer coefficient is constant.

Boundary Layer in Forced Convection

In forced convection, a boundary layer is formed at the surface of a solid in contact with a fluid or gas in motion. This boundary layer is a thin layer of fluid in which viscosity effects are significant, and the fluid velocity increases from zero at the solid boundary to the free-stream velocity far away from the boundary. The thickness of the boundary layer depends on the fluid velocity and the properties of the fluid, and it can have a significant impact on the overall performance of the system.

In forced convection, an external source, such as a fan or pump, imposes the fluid velocity, resulting in a thinner boundary layer and a higher heat transfer coefficient. The boundary layer in forced convection is different from that of free convection. However, the boundary layer can also cause significant drag and reduce the system's overall efficiency.

Hydrodynamic Boundary layer in Forced Convection

In forced convection, a hydrodynamic boundary layer is a thin fluid in contact with a solid boundary, such as a wall, in which viscosity effects are significant. The fluid velocity in the boundary layer increases from zero at the solid boundary to the free-stream velocity far away from the boundary. The thickness of the hydrodynamic boundary layer increases with the distance along the solid surface and is controlled by the fluid properties and velocity. In forced convection, an external source, such as a fan or pump, imposes the fluid velocity, which can result in a thinner hydrodynamic boundary layer and a higher heat transfer coefficient. However, the hydrodynamic boundary layer can also cause significant drag and reduce the system's overall efficiency. Additionally, the presence of a hydrodynamic boundary layer can also affect the pressure distribution along the surface, which is known as the viscous sublayer.

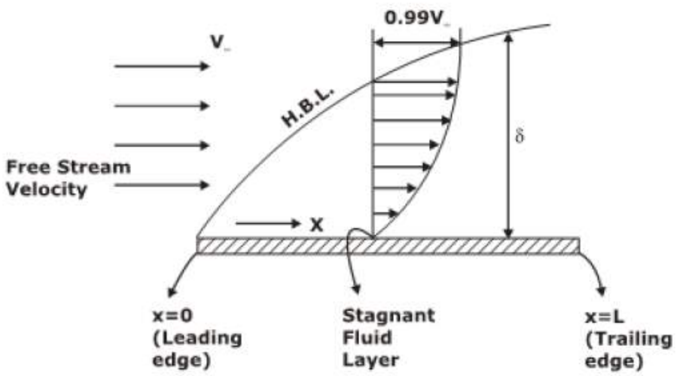
$$\text{Local Reynold's Number } (Re_x) = \frac{V_\infty x \rho}{\mu} = \frac{V_\infty x}{\upsilon}$$

(at any x measured from the leading edge)

If Rex < 5 × 105, then flow is LAMINAR

If Re= > 6.5 to 7 × 105, Then flow is TURBULENT

CASE 1: Flow over flat plates



Hydrodynamic boundary layer

δ → Thickness of Hydrodynamic Boundary Layer at any distance x measured from the plate's leading edge [i.e., x = 0].

$\delta = f(x)$

Thermal Boundary Layer in Forced Convection

In forced convection, a thermal boundary layer is a thin layer of fluid in contact with a solid boundary, such as a wall, in which the temperature gradients are significant. The temperature in the boundary layer increases from the solid surface temperature to the fluid temperature far away from the boundary. The thickness of the thermal boundary layer increases with the distance along the solid surface and is controlled by the fluid properties, the velocity of the fluid, and the heat transfer coefficient.

In forced convection, an external source, such as a fan or pump, imposes the fluid motion, which can result in a thinner thermal boundary layer and a higher heat transfer coefficient. However, the thermal boundary layer can also reduce the heat transfer rate by reducing the temperature gradient between the solid surface and the fluid. The heat transfer rate across the thermal boundary layer can be improved by increasing the fluid velocity, increasing the heat transfer coefficient and reducing the thermal conductivity of the fluid.

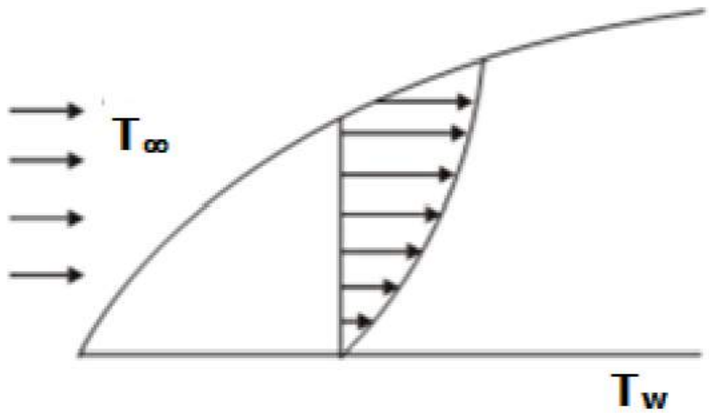
$$\mathbf{T = f\ (x,y)}$$

δt = Thickness of thermal Boundary Layer

$$\boldsymbol{\delta t = f(x)}$$

The Thermal boundary layer thickness is defined as the distance measured from the solid boundary in the y direction at which

$$\mathbf{(T_S - T)/(T_S - T_\infty) = 0.99}$$



A thermal boundary layer ($T_\infty > T_w$)

Nusselt Number (Nu)

$$[Nu] = \frac{\text{conductive heat transfer resistance}}{\text{convective heat transfer resistance}} = \frac{hL}{k_f}$$

Prandtl Number (Pr)

$$[Pr] = \frac{\text{Momentoum diffusivity}}{\text{thermal diffusivity}} = \frac{\nu}{\alpha} = \frac{\mu C_p}{k}$$

Peclet Number

The Péclet number, Pe, is a dimensionless number used in heat and mass transfer problems to compare the effects of convection and conduction. It is defined as the convective heat or mass transfer rate ratio to the conductive heat or mass transfer rate. or in other words, it is the product of Reynold's and Prandtl's number.

Peclet number = Reynold number × Prandtl number.

Stanton Number

The Stanton number, St, is a dimensionless number used in heat transfer problems to describe the heat transfer rate between a fluid and a surface in contact with it. It is defined as the ratio of the heat transfer rate to the product of the fluid velocity, the fluid density, and the fluid's specific heat capacity. Or in other words, it is the ratio of Nusselt number to the Peclet number.

$$\text{S tanton number} = \frac{\text{Nusselt number}}{\text{peclet number}}$$

$$St = \frac{\text{Nusselt number}}{\text{Reynold number} \times \text{Prandtl number}}$$

$$St = \frac{h}{\rho V C_p}$$

Relation between the thermal boundary layer and hydrodynamic boundary layer

$$\frac{\delta_t}{\delta} = \frac{1}{1.026}(Pr)^{-\frac{1}{3}}$$

Applications of Forced Convection

Forced convection is the transfer of heat or mass by a fluid or gas's motion caused by an external source, such as a fan or pump. It is a key mechanism in many industrial and engineering applications, including the following:

- **HVAC systems:** Forced convection is used in heating, ventilation, and air-conditioning systems to circulate air and control the temperature and humidity in buildings.
- **Heat exchangers:** Forced convection is used in heat exchangers to transfer heat from one fluid to another, such as in radiators and condensers in power plants and automobiles.
- **Cooling systems:** Forced convection is used in cooling systems to dissipate heat from electronic devices, such as computer processors and power amplifiers.
- **Chemical processing:** Forced convection is used to mix and heat fluids, such as in distillation columns and reactors.
- **Manufacturing processes:** Forced convection is used in many manufacturing processes, such as casting and welding, to control the temperature and flow of gases and liquids.

Overall, forced convection is an essential mechanism in many industrial and engineering applications and plays an important role in controlling the temperature and flow of fluids.

Limitations of Forced Convection

Forced convection has several limitations, such as high cost and complexity of the operation, noise generation, limited flow rate and pressure drop, and vibration. It may also not be suitable for certain applications such as high-vacuum environments or very high temperatures. Forced convection has several limitations, which include:

1. **Low thermal conductivity:** Materials with low thermal conductivity may not be suitable for forced convection, as they may not be able to transfer heat efficiently.
2. **Cost:** Forced convection systems can be expensive to operate and maintain, especially if they require specialized equipment or frequent maintenance.
3. **Complexity:** Forced convection systems can be complex and may require specialized knowledge and training to operate and maintain.
4. **Limited applications:** Forced convection is not always the best method for transferring heat or mass. It may not be suitable for certain applications, such as in high-vacuum environments or very high temperatures.
5. **Noise:** Forced convection systems can generate noise, which can be problematic in some environments, such as offices or residential areas.
6. **Flow rate and pressure drop:** Forced convection systems may have a limited range of flow rates that they can handle and may have a large pressure drop, which can affect the system's overall performance.
7. **Vibration:** Forced convection systems may generate vibration, which can be a problem in some applications, such as precision equipment or sensitive instruments