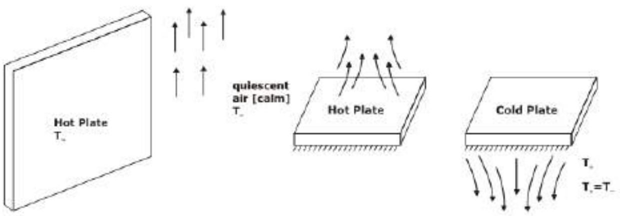
Free Convection

Free convection is a natural heat transfer mechanism that happens when a fluid (liquid or gas) is heated from below and cooled from above, resulting in a temperature gradient that causes the fluid to circulate. The fluid motion is driven by the density differences created by temperature variations within the fluid, as warm fluid is less dense and tends to rise, while cool fluid is denser and tends to sink. Free convection can occur in closed and open systems, and it plays a significant role in many natural and industrial processes, including heating and cooling systems, meteorology, and geophysics.

Free convection over different geometries



In any free convection heat transfer,

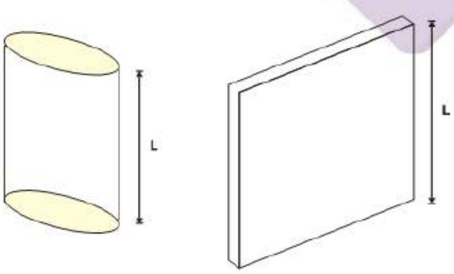
$$\mathbf{h = f(g, \beta, \Delta T, L, \mu, \rho, C_p, k)}$$

- μ, ρ, C_p, k = Thermo-physical Properties of fluid
- β = Isobaric volume expansion coefficient of fluid [per kelvin]

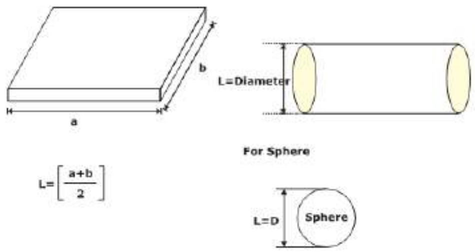
$$\beta = (1/V)(\partial V/\partial T)_{P=C} \text{ [per Kelvin]}$$

Characteristic dimension for various dimensionless numbers:

For vertical plates, vertical cylinders.



For horizontal plate for horizontal cylinder



Characteristic dimension for various geometries

Grashof Number (Gr)

The Grashof number, Gr, is a dimensionless number used in heat transfer and fluid flow problems to describe the relative importance of buoyancy forces to viscous forces. It is defined as the ratio of the buoyancy force to the viscous force in a fluid.

where

- g= gravitational acceleration, m/s^2
- β= coefficient of volume expansion, 1/K
- δ= characteristic length of the geometry, m
- v= kinematic viscosity of the fluid, m^2/s

Grashof Number(Gr) replaces Reynolds Number (Re) in free convection heat transfer.

Therefore, in any free convection heat transfer,

Heat transfer coefficient

$$Nu = f\ (Gr\ Pr)$$

product of Gr Pr is called Rayleigh Number (Ra)

$$Nu = C\ (Gr \times Pr)m$$

C m are constants which vary from case to case.

- m = 1/4 for Laminar Flow
- m = 1/3 for Turbulent Flow

The flow during free convection heat transfer is decided as Laminar or Turbulent based on the value of the (Gr Pr) product.

- If Gr Pr < 109 Then, flow is Laminar
- If Gr Pr > 109 Then, flow is Turbulent

Convection is the mechanism of heat transfer that occurs between a solid surface and the surrounding fluid in the presence of bulk fluid motion.

Convection is classified as Natural (or free) and Forced convection depending on how the fluid motion is initiated.

Reynold Number (Re)

The Reynolds number (Re) is a dimensionless number used in fluid mechanics to characterize the relative importance of fluid inertia to viscous forces. It determines whether a fluid flow is laminar or turbulent and is defined as the ratio of inertial forces to viscous forces. The equation for the Reynolds number is:

Re = (inertial forces) / (viscous forces) = (density * velocity * characteristic length) / (viscosity)

It measures the ratio of inertial forces to viscous forces in a fluid and is used to predict the transition between the laminar and turbulent flow. The value of the Reynolds number can vary depending on the fluid and the specific flow conditions, but generally, a Reynolds number less than 2300 represents laminar flow, while a Reynolds number greater than 4000 represents turbulent flow.

The Reynolds number is important in many engineering applications, including fluid dynamics, heat transfer, and mass transfer. The value of the Reynolds number is used to predict the flow behaviour of a fluid, which can have significant implications for the design and performance of many types of systems and equipment, such as pipes, heat exchangers, and pumps.

Reynold's number is defined as:

Re = Inertia Force/Viscous Force
$Re = \rho Vl/\mu = Vl/v$
where:

- ρ = Density of fluid
- V = Velocity of fluid passing through length (l)
- v = Kinematic viscosity
- μ = Dynamic viscosity

Critical Reynold Number: The number used to show the boundary layer changes from laminar to turbine flow is called the critical Reynolds number.

(a) For flat plate

- Re < 5 × 105 (laminar)
- Re > 5 × 105 (turbulent)

(b) For circular pipes

- Re < 2300 (laminar flow)
- 2300 < Re < 4000 (transition of flow from Laminar to turbulent)
- Re > 4000 (turbulent flow)

Stanton Number (St)

The Stanton number (St) is a dimensionless number used in heat transfer to characterize the relative importance of convective heat transfer to conductive heat transfer in a fluid. It is used to determine the heat transfer coefficient of a fluid and is defined as the ratio of the convective heat transfer coefficient to the product of the fluid's thermal conductivity and characteristic length. The equation for the Stanton number is:

$$St = (h * L) / (k)$$

where h is the convective heat transfer coefficient, L is the characteristic length, and k is the thermal conductivity of the fluid.

It is a measure of the ratio of convective heat transfer to conductive heat transfer in a fluid and is used to predict the heat transfer behaviour of a fluid. The value of the Stanton number can vary depending on the fluid and the specific flow conditions, but generally, a low value of the Stanton number represents a high heat transfer rate and vice versa.

The Stanton number is important in many engineering applications, including heat exchangers, combustion, and thermodynamics. The value of the Stanton number is used to predict the heat transfer behavior of a fluid, which can have significant implications for the design and performance of many types of systems and equipment, such as boilers, heat exchangers, and solar collectors.

St = heat transfer coefficient / Heat flow per unit temperature rise

St = Nu/(Re*Pr)

Grashof Number (Gr)

The Grashof number (Gr) is a dimensionless number used in fluid mechanics and heat transfer to characterize the relative importance of buoyancy forces to viscosity forces in a fluid. It determines whether a fluid flow is affected by natural convection and is defined as the ratio of buoyancy forces to viscosity forces. Where g is the acceleration due to gravity, Beta is the thermal expansion coefficient of the fluid, Th and Tc are the temperatures at the hot and cold surfaces, L is a characteristic length, and viscosity is the dynamic viscosity of the fluid.

It is a measure of the ratio of buoyancy forces to viscosity forces in a fluid and is used to predict the natural convection behaviour of a fluid. The value of the Grashof number can vary depending on the fluid and the specific flow conditions, but generally, a large value of the Grashof number represents a fluid flow affected by natural convection, while a small value of Grashof number represents a fluid flow not affected by natural convection.

The Grashof number is important in many engineering applications, including heat exchangers, combustion, and thermodynamics. The value of the Grashof number is used to predict the natural convection behaviour of a fluid, which can have significant implications for the design and performance of many types of systems and equipment, such as boilers, heat exchangers, and solar collectors.

Gr = [Inertia force* buoyancy Force]/ viscous Force

where, β = Coefficient of volumetric expansion = 1/T

The ratio of inertia force × Buoyancy force/(viscous force)2in mathematical terms is written as:

$$Gr = \frac{\left(\rho V^2 L^2\right) \times \rho g \beta \left(T_w - T_\infty\right) L^3}{\left(\mu V L\right)^2} = \frac{\rho^2 g \beta \left(T_w - T_\infty\right) L^3}{\mu^2} = g \beta L^3 \left(T_w - T_\infty\right) / \nu^2$$

- The magnitude of the Grashof number shows that the flow is laminar or turbulent.
- Grashof number (Gr) > 109, the flow is turbulent and
- If the Grashof number is less than 108, the flow is laminar.
- For 108 < Gr < 109, which shows the transition range.

Prandtl Number (Pr)

The Prandtl number (Pr) is a dimensionless number used in fluid mechanics and heat transfer to characterize the relative importance of momentum diffusivity to thermal diffusivity in a fluid. It is used to determine the rate of heat transfer in a fluid and is defined as the ratio of momentum diffusivity (viscosity) to thermal diffusivity (thermal conductivity).It is a measure of the ratio of momentum diffusivity to thermal diffusivity in a fluid, and is used to predict the heat transfer behavior of a fluid. The value of the Prandtl number can vary depending on the fluid and the specific flow conditions, but generally, a high Prandtl number represents a fluid that is more viscous than thermal conductive and vice versa.

The Prandtl number is important in many engineering applications, including heat exchangers, combustion, and thermodynamics. It is used to predict the heat transfer behavior of a fluid, which can have significant implications for the design and performance of many types of systems and equipment, such as boilers, heat exchangers, and solar collectors. Additionally, Prandtl number is also used to determine the fluid's thermal boundary layer thickness.

$$\mathrm{Pr} = \frac{\text{Momentum diffusivity through the fluid}}{\text{Thermal diffusivity through the fluid}}$$

$$\mathrm{Pr} = \mu C_p / k = \nu / \alpha$$

$$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\mu / \rho}{k / \rho c_p} \Rightarrow \mathrm{Pr} = \frac{\mu c_p}{k}$$

where

- μ: dynamic viscosity of the fluid
- v = kinematic viscosity
- α = thermal diffusivity
- For liquid metal: Pr < 0.01
- For air and gases: Pr ≈1
- For water: Pr ≈10
- For heavy oil and grease: Pr > 105
- It provides a measure of the relative effects of momentum and energy transport by diffusion in velocity and thermal boundary layers, respectively. Higher Pr means higher Nu, and it shows higher heat transfer.
- The physical significance of this number considers both momentum and energy propagation through the system. It is considered a physical parameter which depends on the properties of the medium.
- The relative magnitudes of momentum and thermal diffusion in the fluid are given by Prandtl Number (Pr):
  For Pr = 1, Thermal boundary layer thickness (δt)=momentum boundary layer (δ)
  For Pr << 1 (Liquid metals), δt>>δ
- The product of Grashof (Gr) and Prandtl number (pr) is the Rayleigh number (Ra).
  Ra = Gr × Pr.

Rayleigh Number (Ra)

The Rayleigh number (Ra) is a dimensionless number used in the study of convection in fluids. It represents the ratio of buoyancy forces to viscous forces in a fluid and is used to determine whether a fluid will exhibit natural convection or not.where g is the acceleration due to gravity, beta is the thermal expansion coefficient of the fluid, deltaT is the temperature difference across the fluid, H is the height of the fluid, nu is the kinematic viscosity of the fluid, and alpha is the thermal diffusivity of the fluid.

A high Rayleigh number indicates that buoyancy forces are strong relative to viscous forces, and natural convection is likely to occur. A low Rayleigh number indicates that viscous forces are strong relative to buoyancy forces, and natural convection is unlikely to occur. Grashof number (Gr) and Prandtl number (Pr) product is Known as the Rayleigh Number(Ra). It is used for free convection.

$$Ra = Gr.Pr; Ra = \frac{g\ \beta\ l^3\ \Delta t}{\nu.\alpha}$$

where:

- g: Acceleration due to gravity
- β: Thermal expansion coefficient
- v: Kinematic viscosity
- α: Thermal diffusivity
- Pr: Prandtl number
- Gr: Grashof number

In free or natural convection:

- For laminar flow: 104 < Ra < 109
- For turbulent flow: Ra > 109.

Applications of Free Convection

Free convection, also known as natural convection, is the movement of fluid caused by differences in density due to temperature variations. It occurs without the need for an external force, such as a pump or fan. Free convection has a variety of applications in different fields:

1. **Heat transfer:** In industrial processes, natural convection is often used for heat transfer in devices such as heat exchangers, boilers, and coolers.
2. **Building design:** In architectural and building design, natural convection is used to improve indoor air quality by providing ventilation through windows and vents, which also helps to cool the building.
3. **Fluid dynamics:** Free convection is also studied in fluid dynamics to understand the behavior of fluids under different conditions, such as in geophysical and astrophysical flows.
4. **Solar energy:** Free convection is used in solar thermal systems to transfer heat from the collector to a storage tank.
5. **Natural cooling systems:** The natural convection currents can be used in natural cooling systems to cool buildings by using the natural ventilation of the building to cool the air.
6. **Cooling of electronic devices:** Natural convection is used in electronic devices to cool the electronic components, by providing natural flow of air over the electronic components.
7. **Food and Beverage Industry:** Natural convection is used in Food and Beverage Industries for Drying, pasteurization, fermentation and other processes.

Limitations of Free Convection

Free convection, also known as natural convection, is a cost-effective and energy-efficient method of heat transfer. However, there are some limitations to its use:

1. **Low heat transfer coefficient:** The heat transfer coefficient for natural convection is generally lower than that for forced convection, meaning that it may not be able to transfer heat as quickly or efficiently.
2. **Limited temperature range:** Natural convection is most effective at transferring heat within a limited temperature range. Beyond this range, the efficiency of heat transfer decreases.
3. **Dependence on fluid properties:** The effectiveness of natural convection is heavily dependent on the properties of the fluid being used, such as its density, viscosity, and thermal conductivity.
4. **Dependence on geometry:** The effectiveness of natural convection is also dependent on the geometry of the system, including the shape and size of the fluid-containing container and the location of heat sources and sinks.
5. **Limited in high-temperature applications:** Natural convection is not suitable for high-temperature applications due to the high thermal conductivity of the fluid leading to low thermal gradient.
6. **Vulnerability to external factors:** Natural convection is vulnerable to external factors such as wind, which can disrupt the natural flow of the fluid and affect the efficiency of heat transfer.
7. **Limited in low-gravity environments:** Natural convection is not suitable for low-gravity environments, such as outer space, because the buoyancy force that drives natural convection is dependent on gravity.