Lectures 1&2 : Introduction to Heat Transfer and Principles of Heat Convection

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Heat Transfer vs. Thermodynamics

What is heat transfer?

A simple, yet general, definition provides sufficient response to the question: What is heat transfer?

Heat transfer (or heat) is thermal energy in transit due to a spatial temperature difference.

Whenever a temperature difference exists in a medium or between media, heat transfer must occur.

- Heat transfer and thermodynamics are both concerned with heat, so what is the difference between the two?
- Thermodynamics, usually, gives information about the end state of a process with almost no indication on how the final state has been produced.
- Heat transfer looks deeply into the details of the transfer of thermal energy from one place (medium) to another place (medium) with a lower temperature.

Why do we need to know about heat transfer?

Simply because it is very difficult to find an industry in which heat transfer does not matter!

Oil and gas

Aerospace

Automotive

Electronics

manufacturing

Renewable energy

Textbook for this course

To study more about the fundamentals of heat convection and also for further practice, the following textbooks are highly recommended.

1- T. Bergman, A. S. Lavine, F. P. Incropera, D. P. Dewitt, *Introduction to heat transfer* or *(Fundamentals of heat and mass transfer)*, Sixth edition, 2011, John Wiley & Sons, New York.

2- J. P. Holman, *Heat Transfer*, tenth edition, 2009, McGraw-Hill, New York.

Please note that earlier versions of these books are equally useful. Apart from these two famous textbooks any textbook on heat transfer covers the materials presented in the heat convection lectures.

Structure of this course

- Part I: heat conduction & radiation (Dr Dobson’s part)

- Part II: heat convection and heat exchangers

  - 9 lectures

  - One review lecture and exam preparation session

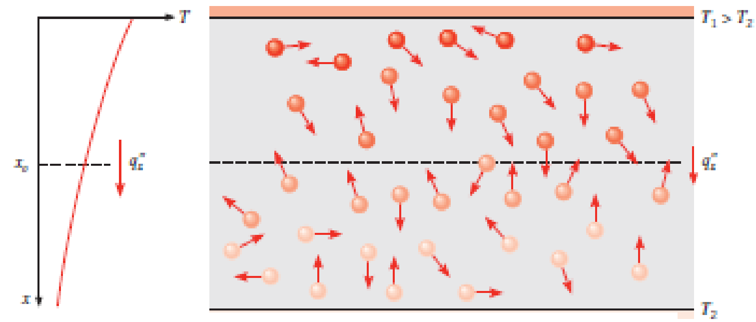
  - Two tutorials and one lab

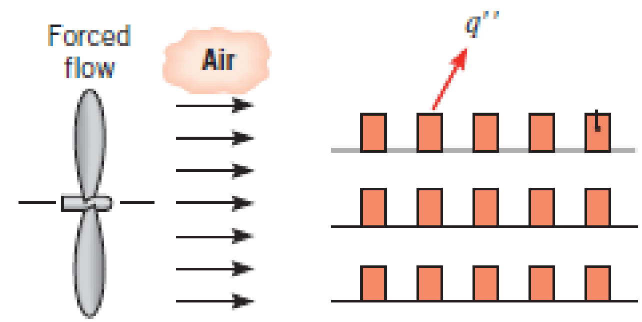
  - The two parts of this course are highly connected

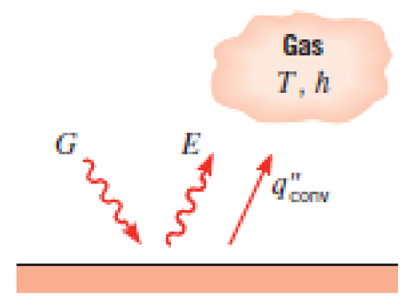
Principal mechanisms of heat transfer

- Heat ***always*** travels from hot to cold place (**second law of thermodynamics**)
  - Hot means higher temperature
  - Cold means lower temperature
- There are three mechanisms of heat transfer:
  1. Heat conduction: happens in solids and fluids and is due to random molecular motion.
  2. Heat convection: happens in fluids only and is mainly due to the motion of a fluid.
  3. Radiation: happens in everywhere (including vacuum) and has an electromagnetic nature.

In this part of the course we are concerned with convection.







Conduction

- When there is a temperature difference in a solid (or fluid) heat is conducted from high temperature region to low temperature region.

- Mathematically, $q = -kA\frac{dT}{dx}$ where

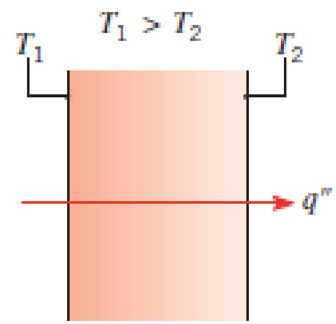
  k: the thermal conductivity of the material [W/m.K]

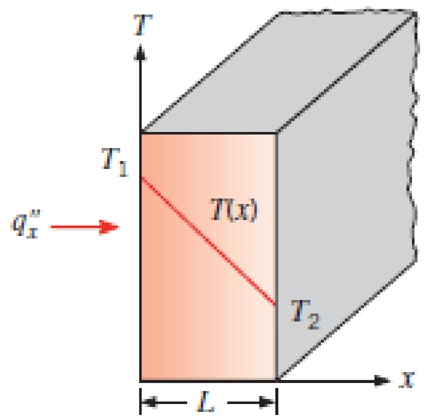
  q: heat transfer rate [W]

  $\frac{dT}{dx}$: temperature gradient [K/m]

  A: the surface area across which heat is being transferred [m^2]

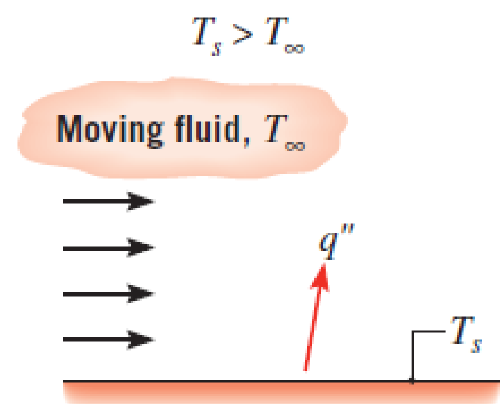
- Note that thermal conductivity is a ***thermo-physical property*** of the material, meaning that as soon as the material type and its temperature are known, the thermal conductivity can be found in tables. (find these tables at the back of your textbook)





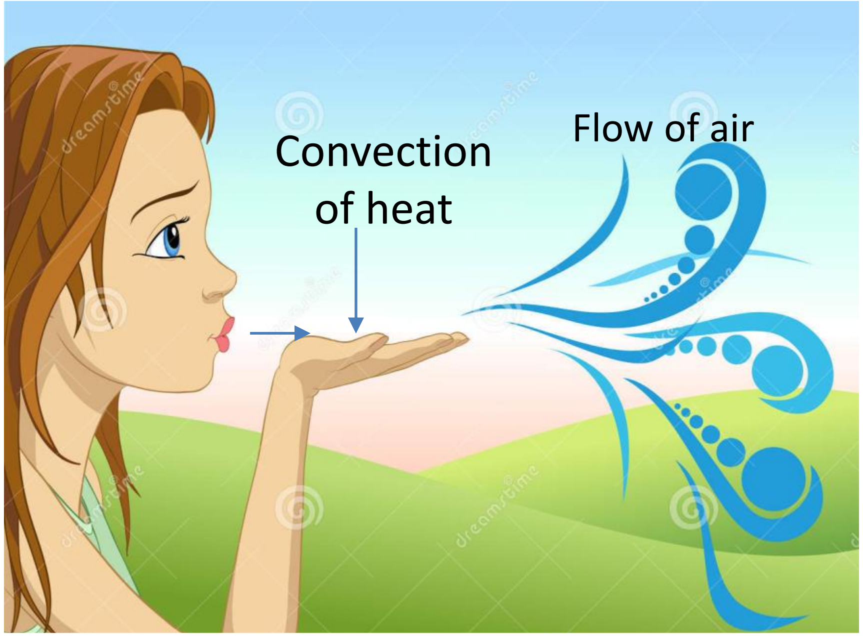
Convection

- If a moving fluid is in contact with a solid or fluid at a different temperature, heat is convected by the moving fluid.
- Note that conduction still exists but usually in moving fluids convection is much stronger than conduction.
- If $T_{solid} > T_{fluid}$ then heat is transferred from solid to fluid if $T_{solid} < T_{fluid}$ then heat goes from fluid to solid.
- Mathematically $\boldsymbol{q = hA\Delta T}$ (Newton's law of cooling) where
  - q: rate of heat transfer [W]
  - h: convection coefficient [W/m^2.K]
  - A: the area over which heat is transferred [m^2]
  - ΔT: is temperature difference between the solid surface and the fluid (i.e. $T_s - T_\infty$)



Heat convection from a hot surface

- Convection coefficient is **<u>not</u>** a thermo-physical property of the fluid. It depends on the thermo-physical properties of the fluid and also the nature of the fluid flow.

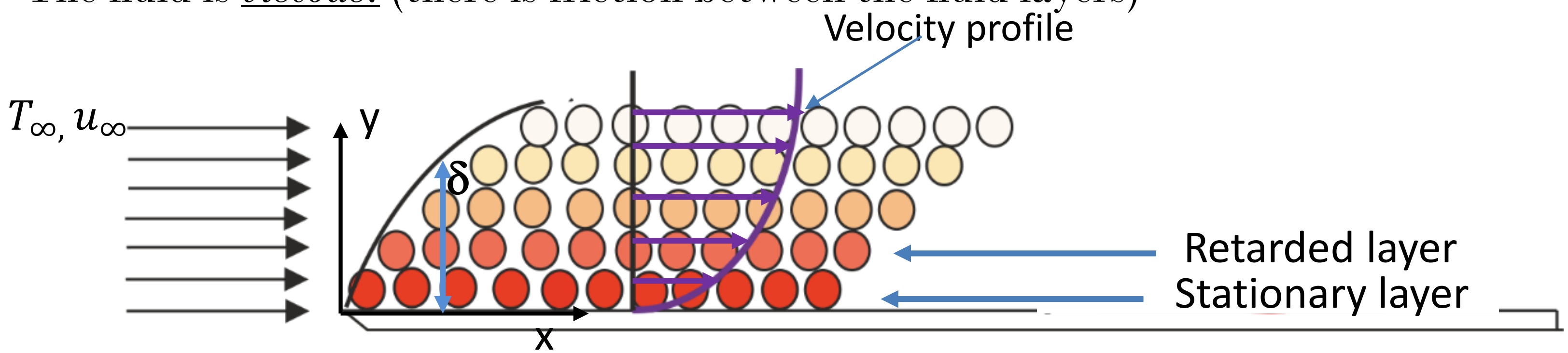


- Blowing stronger will result in feeling colder on her palm
- Blowing stronger $\longrightarrow$ higher velocity of air $\longrightarrow$ higher convection coefficient $\longrightarrow$ higher heat transfer rate from her palm to air $\longrightarrow$ feeling colder

Heat transfer song!

Velocity boundary layer

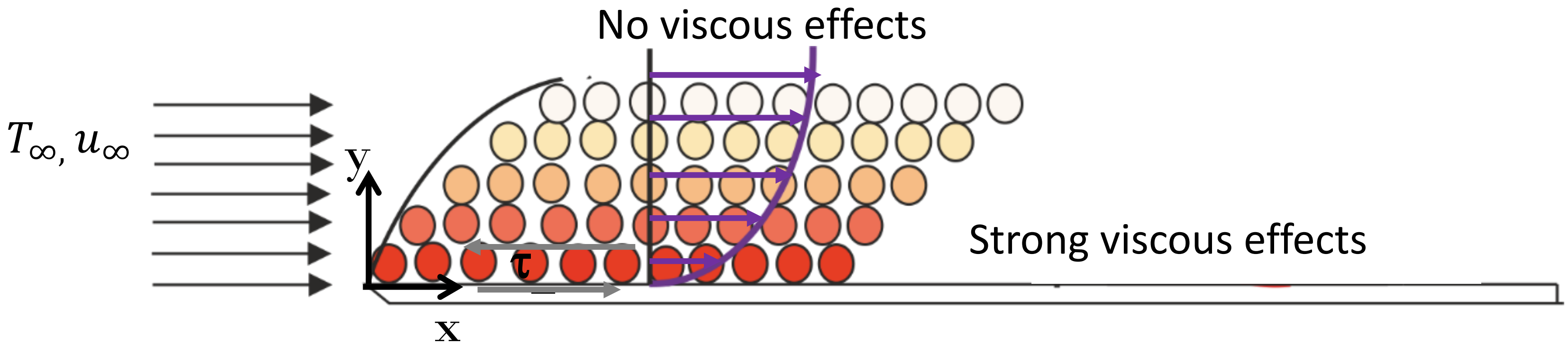
- Consider the following configuration
  - A uniform flow with constant velocity and temperature flows over a flat surface
  - The fluid is ***viscous.*** (there is friction between the fluid layers)



- The first row of molecules sticks to the solid surface (viscosity) $u_{y=0}$=0.
- Friction between the first and second rows: retardation (loss of momentum)
- Friction between the third and second rows: less retardation
- Other layers get similarly retarded.
- At δ (boundary layer thickness) u/u_∞=0.99.

Velocity boundary layer

- Inside the boundary layer, viscosity effects are very significant.
- There is a large velocity gradient within the boundary layer.
- Viscous stress: $\tau = \mu \frac{\partial u}{\partial y}$, in dimensionless from: $C_f = \frac{\tau}{1/2 \rho u_\infty^2}$ (skin friction coefficient)
- No velocity gradient outside the boundary layer $\longrightarrow$ no shear stress



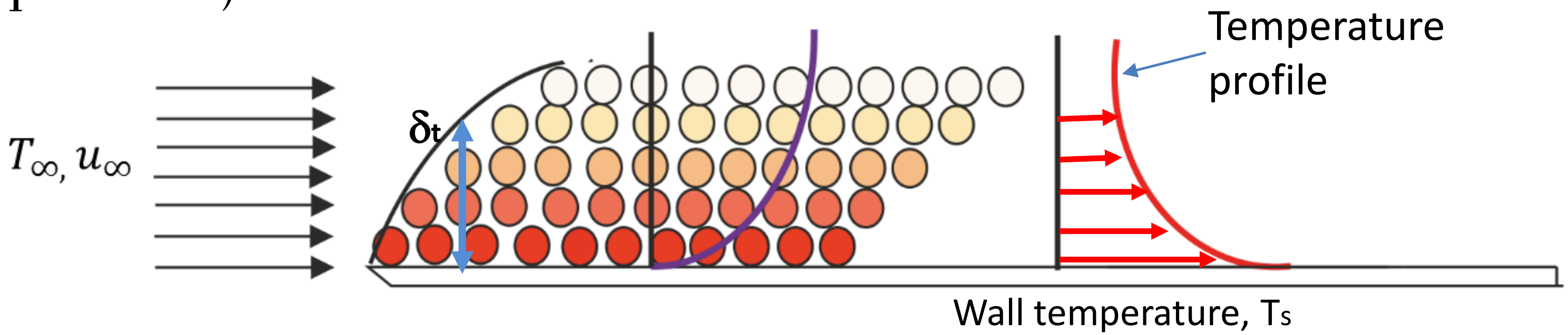
- As the molecules get retarded more fluid penetrates into the BL and so *__boundary layer thickness increases along the surface.__*

- Two distinctive regions in the flow
  - Viscous flow inside the boundary layer
  - *Effectively* non-viscous incompressible flow outside the boundary layer
  - Bernoulli equation holds outside the boundary layer

- We need to know the velocity distribution and shear stress inside the boundary layer.

Thermal boundary layer

- The stationary layer of molecules takes the wall temperature (thermal equilibrium).



- Conduction between the retarded fluid layers
- Strong temperature gradients inside the thermal boundary layer,
- $\frac{T_s - T}{T_s - T_\infty} = 0.99$ at the edge of the thermal boundary layer (δ_t)
- Similar to velocity boundary layer thermal boundary layer thickness grows along the wall.

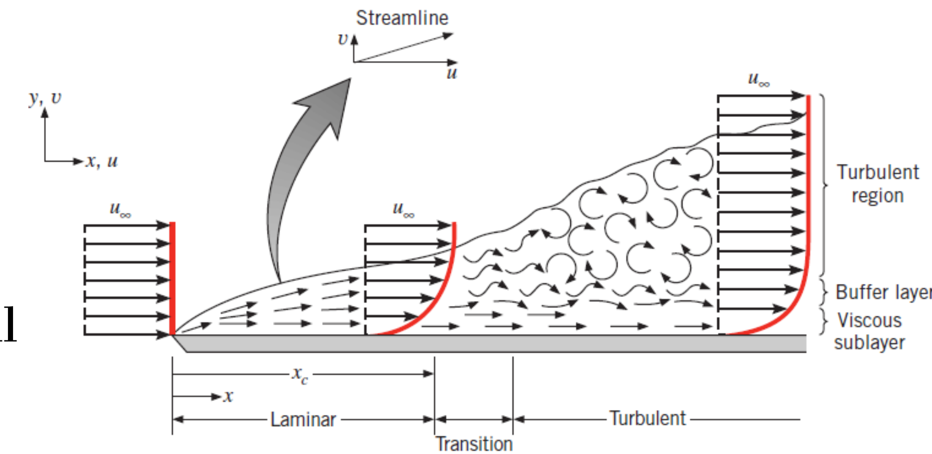
Laminar and turbulent flows

Physical characteristics of laminar and turbulent flows

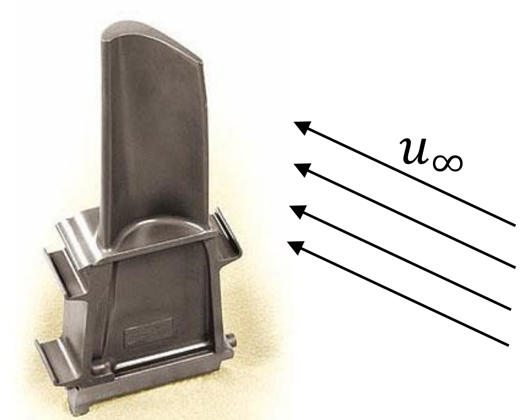
Flow visualisation of laminar turbulent flow in a pipe

Laminar and turbulent boundary layers

- Boundary layers usually include laminar and turbulent regions.
- Laminar boundary layer: flow is highly ordered and, and along well organised streamlines.
- The boundary layer thickness increases in stream-wise direction:
  - ❑ The velocity gradient decreases.
  - ❑ Surface shear stress decreases, viscous forces diminish.
- A transition zone is developed, flow starts to become irregular, and shows a complex behaviour.



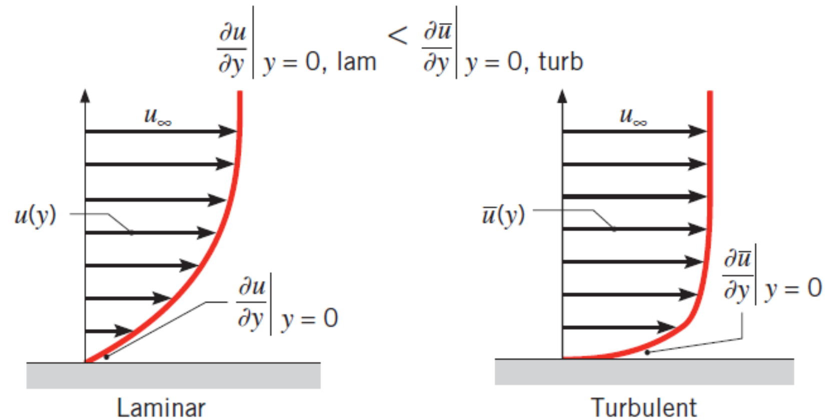
Velocity boundary layer development on a flat plate



Boundary layer formation over a gas turbine blade

Laminar and turbulent boundary layers, contd.

- Turbulent flow involves dis-orderness, chaotic motion, high level of mixing and velocity fluctuations.
  - ❑ The flow remains almost laminar in the vicinity of the wall (viscous or laminar sub-layer).
- Velocity fluctuations in the turbulent boundary layer greatly enhances the transfer of heat.
  - ❑ Higher convection coefficient
- A thicker and relatively flat velocity boundary layers
- Stronger velocity gradient close to the wall compared with laminar flow
- Stronger shear stress compared with laminar boundary layer

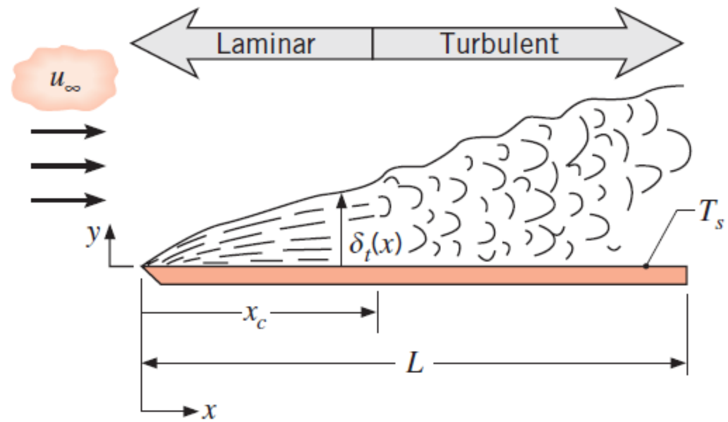


Comparison between laminar and turbulent boundary layers

Laminar and turbulent boundary layers

- Reynolds number is an essential dimensionless number in boundary layers:

$$Re_x = \frac{\rho u_\infty x}{\mu}$$



x_c: the critical length for which the transition to turbulent begins.

- $\boldsymbol{Re_c} = \frac{\rho u_\infty x_c}{\mu} = \mathbf{5 \times 10^5}$ is the critical *Reynolds* number for flow over a surface.
- $\boldsymbol{Re_c}$ is the value of Re_x for which transition begins, $\boldsymbol{Re_x} < \boldsymbol{Re_c} \longrightarrow$ flow is laminar.
- Heat transfer characteristics are significantly different in the turbulent region.

It is essential to determine if the flow under investigation is laminar or turbulent.

Nusselt number

- Newton's law of cooling $q = hA(T_s - T_\infty)$ where h is the *convection heat transfer coefficient*.
- Conduction heat flux in the stationary layer $q = -k_f A \frac{\partial T}{\partial Y}$ at y=0
- Combining the two: $h = \frac{-k_f \frac{\partial T}{\partial y}}{T_s - T_\infty}$.
- The problem of heat convection is mostly about finding the value of h.
- The dimensionless coefficient of convection is called *Nusselt* number and, is defined as $\boldsymbol{Nu} = \frac{\boldsymbol{h.L}}{\boldsymbol{k_f}}$ in which,
    - h is coefficient of convection,
    - L is the characteristic length defined according to the problem configuration.
    - k_f is the thermal conductivity of fluid.

Ernst Kraft Wilhelm Nußelt, 1882-1957.

Nusselt number correlations

- Calculation of Nusselt number often requires applying advanced computational techniques to solve the governing equation of fluid flow and heat transfer. This, although possible, is quite involved.
- We can, however, show analytically (Nusselt did this for the first time) that in forced convection $Nu = Nu(Re, Pr)$, where

  Re is the flow Reynold number defined as Re= $\frac{U.L}{\nu}$.

  Pr is the Prandtl number defined as $Pr = \frac{\nu}{\alpha}$, where ν is the kinematic viscosity and α is the thermal diffusivity, $\alpha = \frac{k_f}{\rho C_p}$ of the fluid.
- Note that *Pr* number is a thermo-physical property of the fluid and *Re* number is a characteristic of the flow.
- Since $Nu = Nu(Re, Pr)$ experimental studies can be conducted on various flow configurations and heat transferring flows to find *empirical correlations for Nusselt number.*