Introduction to Heat Transfer

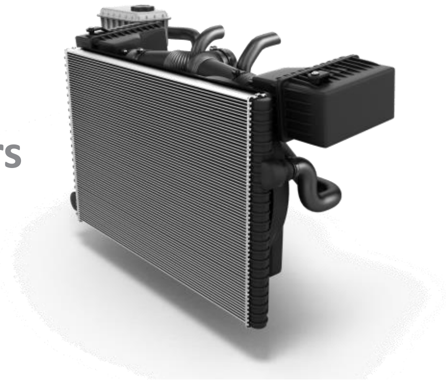
Beyond Viscosity – Lesson 3

Ansys

Intro

- Thermodynamics deals with the end states of a process and does not provide any information related to the nature of the process or the time rate at which it occurs.
- The main objective of this lesson is to extend the thermodynamic analysis by incorporating the study of the modes of heat transfer and calculate heat transfer rates.

Car radiators



Refrigeration systems

Electronics cooling

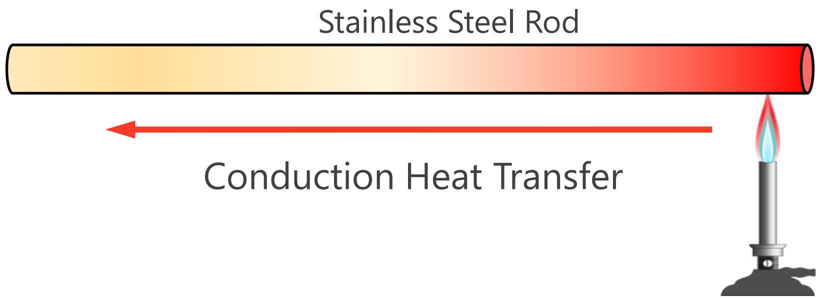
Air-conditioning systems

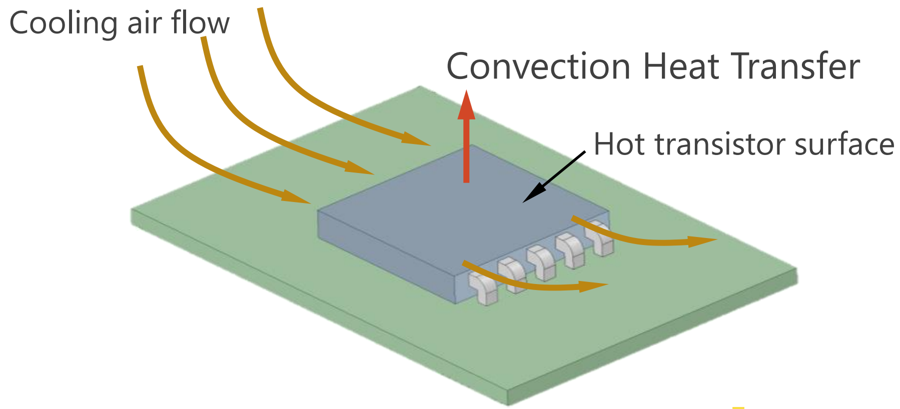
Powerplants

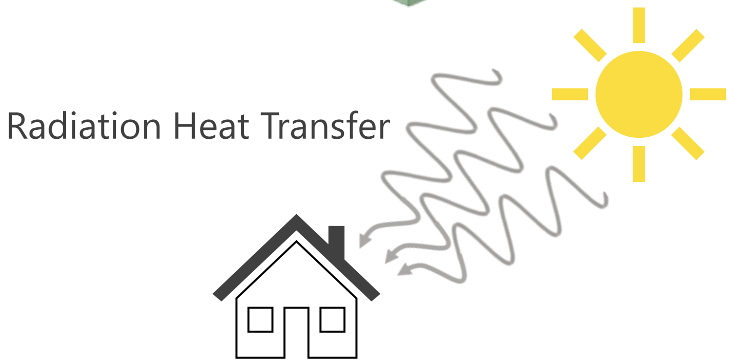
Some application areas of heat transfer

Modes of Heat Transfer

- Heat transfer is thermal energy in transit due to a spatial temperature difference. If there is a temperature difference in a medium or between media, heat transfer will occur.
- *Conduction* is the heat transfer that occurs when the temperature difference exists across a stationary medium.
- *Convection* refers to the heat transfer between a surface and a moving fluid when there is a temperature difference between the two.
- *Radiation* (thermal radiation) is the emission of energy in the form of electromagnetic waves. In the absence of an intervening medium, there is net heat transfer by radiation between two surfaces at different temperatures.

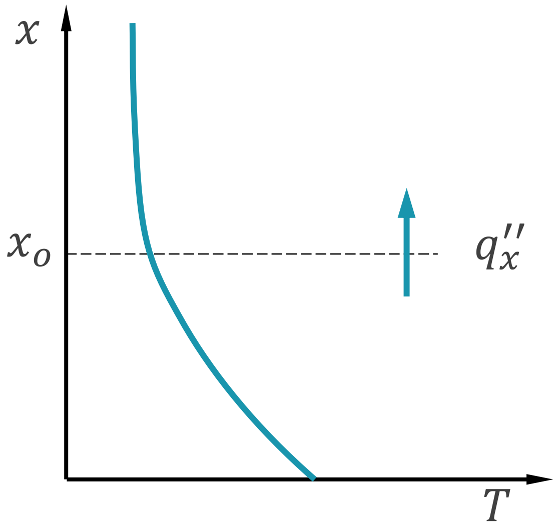


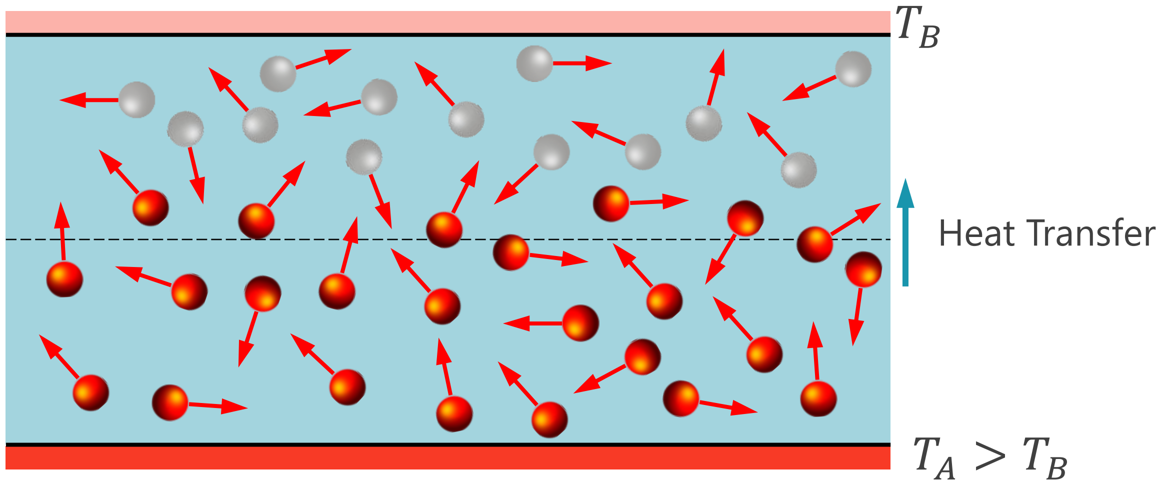




Conduction

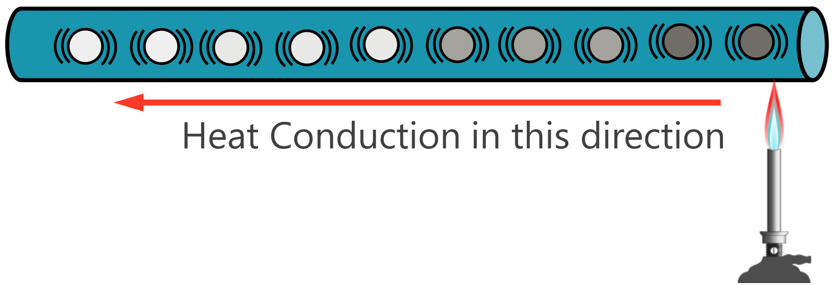
- Conduction is the transfer of energy from more energetic to less energetic particles of a substance via interactions between the particles at molecular levels.
- In order to understand the mechanism of conduction, consider a gas occupying a space between two surfaces being maintained at different temperatures. This leads to a temperature gradient across the gas but without any bulk or macroscopic motion.
- Temperature at any point can be associated with the energy of random translational, internal rotational and vibrational motions of gas molecules.





Conduction (cont.)

- Molecular collisions transfer energy from more energetic molecules to less energetic ones.
- Higher molecular energies are associated with higher temperatures. Thus, in the presence of a temperature gradient, energy transfer by conduction occurs in the direction of decreasing temperature.
- The mechanism of conduction is the same for liquids as the molecules are closely spaced and the molecular interactions are stronger and more frequent than gases.
- In the case of solids, conduction is associated with atomic activity in the form of lattice vibrations. In the case of an electrical conductor, the translational motion of free electrons also contributes to energy transfer.



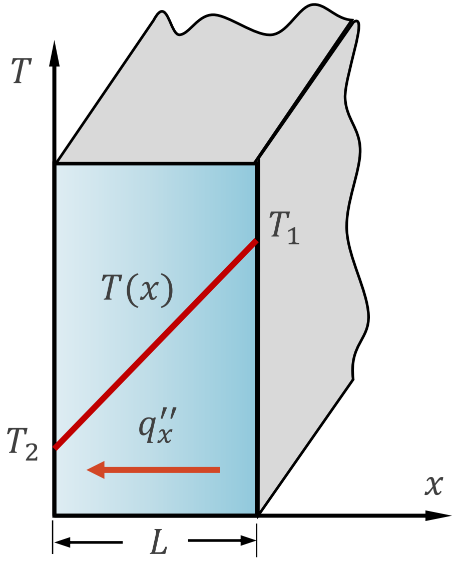
Conduction (cont.)

- Heat transfer process can be quantified in terms of appropriate rate equations which are used to compute the amount of energy being transferred per unit time. In the case of heat conduction, the rate equation is called Fourier's law and for a one-dimensional plane wall is expressed as

$$q_x'' = -k\frac{dT}{dx}$$

Here,

- q_x^''$(W/m$^2) is the heat transfer rate per unit area in the x-direction.
- k is the thermal conductivity (W/mK) and is a characteristic of the wall material.
- The negative sign signifies the fact that the heat transfer is in the opposite direction of the temperature gradient



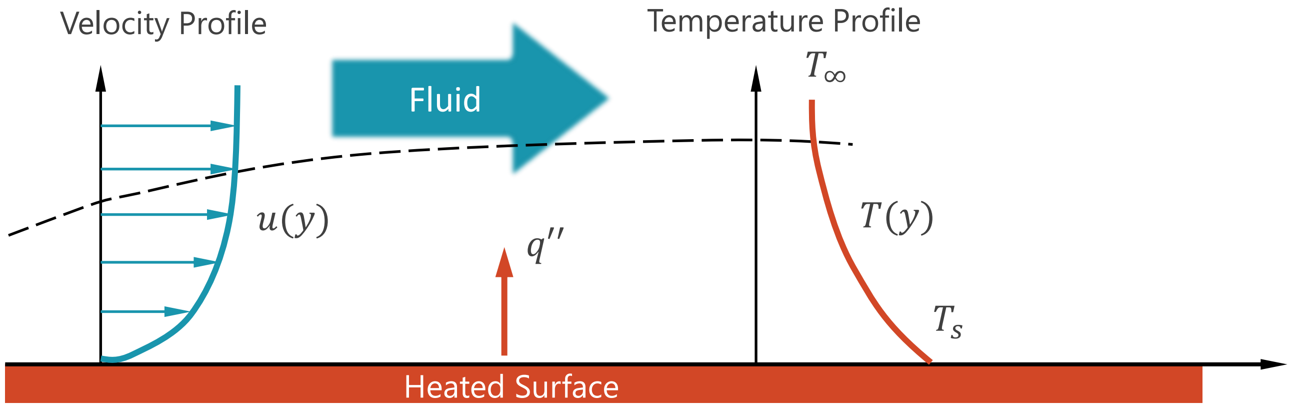
- For steady state conditions, when the temperature gradient is linear, the heat flux is given by:

$$q_x'' = -k\frac{T_2 - T_1}{L} = k\frac{T_1 - T_2}{L} = k\frac{\Delta T}{L}$$

Note that this expression provides the heat flux and the heat transfer rate can be computed by multiplying this with the area, A, of the surface.

Convection

- Convection refers to the energy transfer by a combination of random molecular motion (diffusion) and the bulk (macroscopic) motion of the fluid in the presence of a temperature gradient. Advection refers to the transport only due to the bulk motion of the fluid.
- Convection heat transfer occurs between a fluid in motion and a bounding surface at a different temperature.
- For $T_s > T_\infty$, convection heat transfer occurs from the surface and into the outer flow. If $T_\infty > T_s$, convection heat transfer occurs from the outer flow and into the surface.



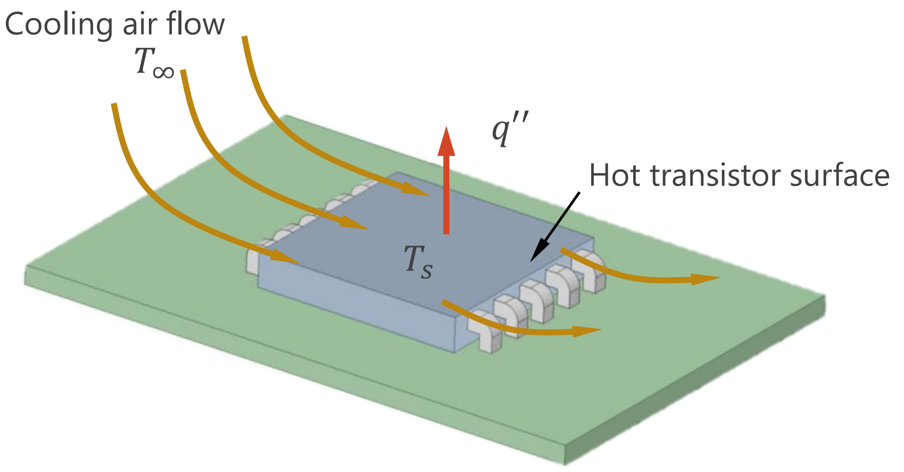
Convection (cont.)

- Similar to the hydrodynamic boundary layer, when the surface and flow temperatures differ, there will be a region of fluid where the temperature will vary from T_s at the surface to T_∞ in the outer flow – called the *thermal boundary layer*.
- Within the boundary layer, convection heat transfer is carried out via both random molecular motion (diffusion) and the bulk motion of the fluid.
- The contribution due to the random molecular motion dominates near the surface where the fluid velocity is low. Due to the no slip condition at the surface, the fluid velocity is zero and heat is transferred via diffusion only.

- The rate of the convection heat transfer process is given by Newton's law of cooling:

$$q'' = h(T_s - T_\infty)$$

where q'' is the convective heat flux (W/m^2), T_S and T_∞ are the temperatures of the solid surface and fluid respectively.

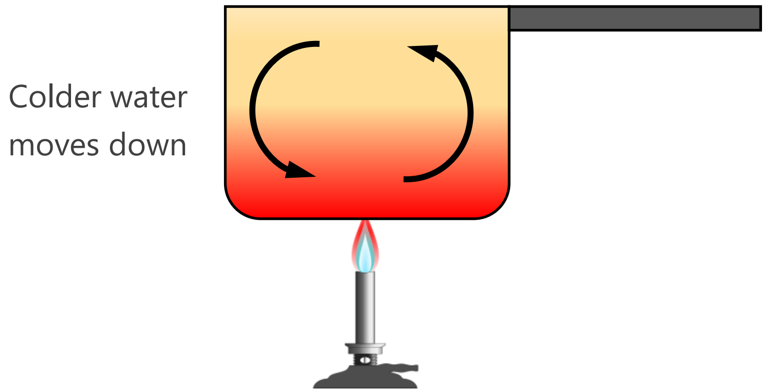


Fan-cooled electronics box – Forced Convection

Convection (cont.)

- $h\ (W/m^2K)$ is the convection heat transfer coefficient, which depends on the conditions in the boundary layer influenced by surface geometry, the nature of the fluid flow and various fluid thermodynamic and transport properties.

- Convection heat transfer can be classified into two categories:
  - *Forced convection*: Flow is caused by external means, such as by a fan, a pump or atmospheric winds
  - *Free (or natural) convection*: Flow is induced by buoyancy forces, caused by density differences due to the temperature variations in the fluid.
- Mixed (combined) forced and free convection can also exist if the velocities associated with forced and free convection modes are comparable.



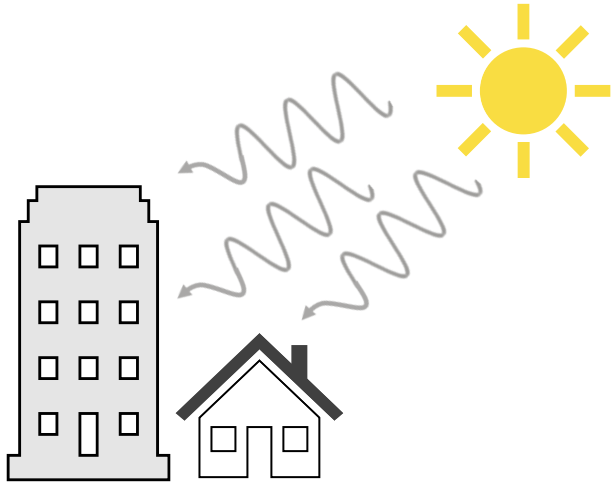
Boiling water – Free Convection

Radiation

- All matter at a nonzero temperature emits thermal radiation.
- This emission is due to changes in the electron configurations of the atoms or molecules, and the energy is transported via electromagnetic waves (or photons).
- Unlike conduction or convection, radiation does not require the presence of a material medium and can occur in vacuum.
- The rate of energy release per unit area (W/m^2) is called the surface emissive power E.
- Stefan-Boltzman law gives the upper limit of the emissive power of an ideal radiator or blackbody:

$$E_b = \sigma T_s^4 \qquad \sigma = 5.67 \times 10^{-8}\ W/m^2K^4$$

where T_s is the absolute temperature of the surface.



Solar radiation

Radiation (cont.)

- The heat flux emitted by a real body is less than that of a black body and is given by

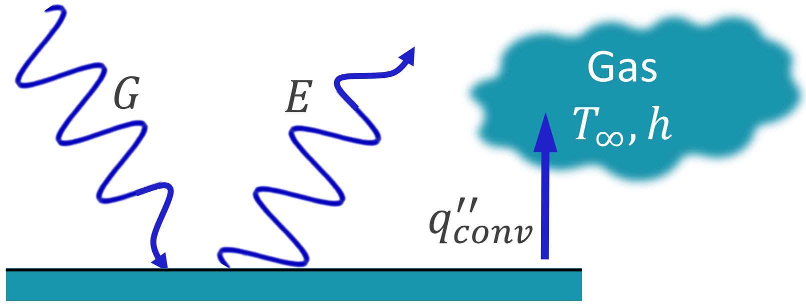
$$E = \varepsilon \sigma T_s^4$$

where $0 \leq \varepsilon \leq 1$ is the emissivity. It is a measure of how effectively a surface emits energy relative to a black body. It depends on the material of the surface and its finish.

- Irradiation, G, is the sum of all incident radiation on a body from its surroundings, a portion or all of which maybe absorbed by the body. The rate at which radiant energy is absorbed per unit surface area can be evaluated using

$$G_{abs} = \alpha G$$

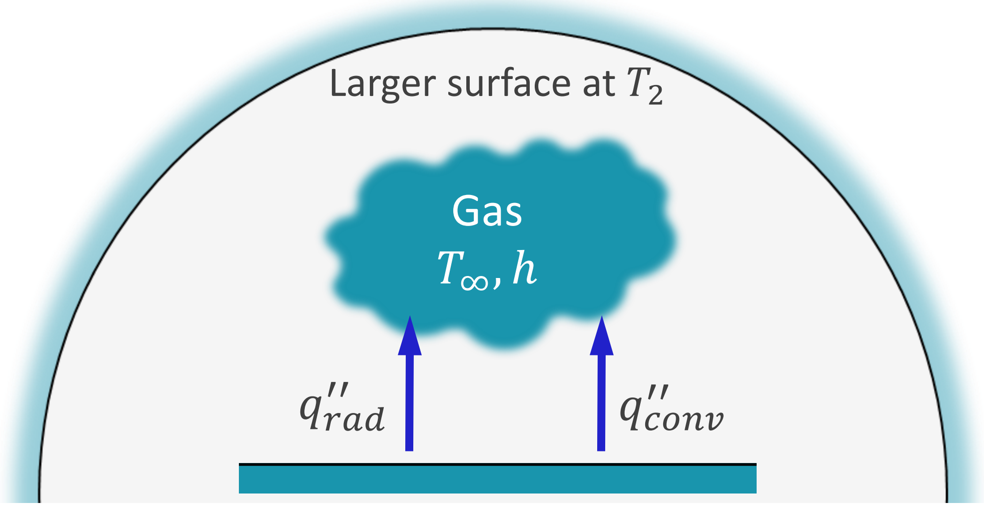
where $0 \leq \alpha \leq 1$ is the absorptivity. If $\alpha < 1$ and the surface is opaque, portions of the irradiation are reflected. However, if the surface is semitransparent, a portion of the irradiation may also be transmitted.



Radiation (cont.)

- Consider the radiation exchange between a small surface at T_1 and a much larger isothermal surface at T_2 completely surrounding the smaller surface. Assuming the surface to be a gray surface (i.e., for which $\alpha = \varepsilon$), then the net rate of radiation heat transfer (per unit area) from the surface can be expressed as:

$$q''_{rad} = \frac{q}{A} = \varepsilon E_b(T_s) - \alpha G = \varepsilon\sigma(T_1^4 - T_2^4)$$



- The above equation represents the difference between the thermal energy being released due to radiation emission and that which is being absorbed.
- The net radiation heat transfer can also be expressed as:

$$q_{rad} = h_r A(T_1 - T_2)$$

where the radiation heat transfer coefficient h_r is

$$h_r \equiv \varepsilon\sigma(T_1 + T_2)(T_1^2 + T_2^2)$$

Summary

- We discussed some preliminaries of heat transfer and briefly described three heat transfer modes:
  - Conduction
  - Convection
  - Radiation

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