Lecture 9

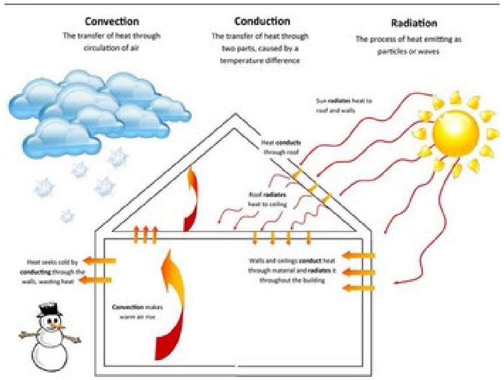
Introduction on Heat Transfer

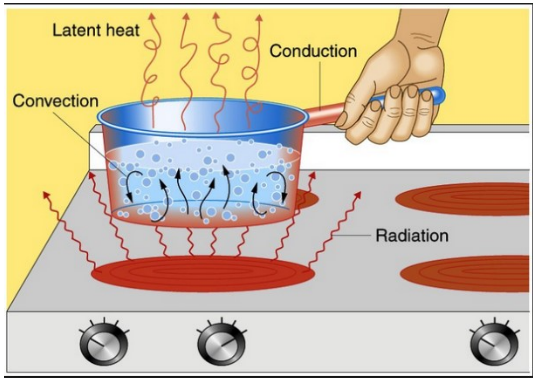
Learning Objectives

- To understand
  - Understand basic concept of heat transfer.
  - Understand how thermodynamics and heat transfer are related to each other.
  - Understand the basic mechanisms of three modes of heat transfer, which are conduction, convection, and radiation, and Fourier's law of heat conduction, Newton's law of cooling, and the Stefan–Boltzmann law of radiation
  - Learn how to analyse heat transfer process
  - Understand concepts of thermal resistance
  - Implement heat transfer circuit analysis

Introduction

- Heat Transfer Applications
  - Heat transfer is commonly encountered in engineering systems and other aspects of life, and one does not need to go very far to see some.





Introduction

- Heat Transfer (传热学)
  - Heat is a form of energy that can be transferred from one system to another as a result of temperature difference.
  - Heat is the energy associated with the random motion of atoms and molecules.
  - Heat transfer deals with the determination of the rates of such energy transfers, and thus the time of cooling or heating, as well as the variation of the temperature.
  - The transfer of energy as heat is always from the higher-temperature medium to the lower-temperature one.
  - Heat transfer stops when the two mediums reach the same temperature.
  - Generally, we assume the continuum assumption is valid

Introduction

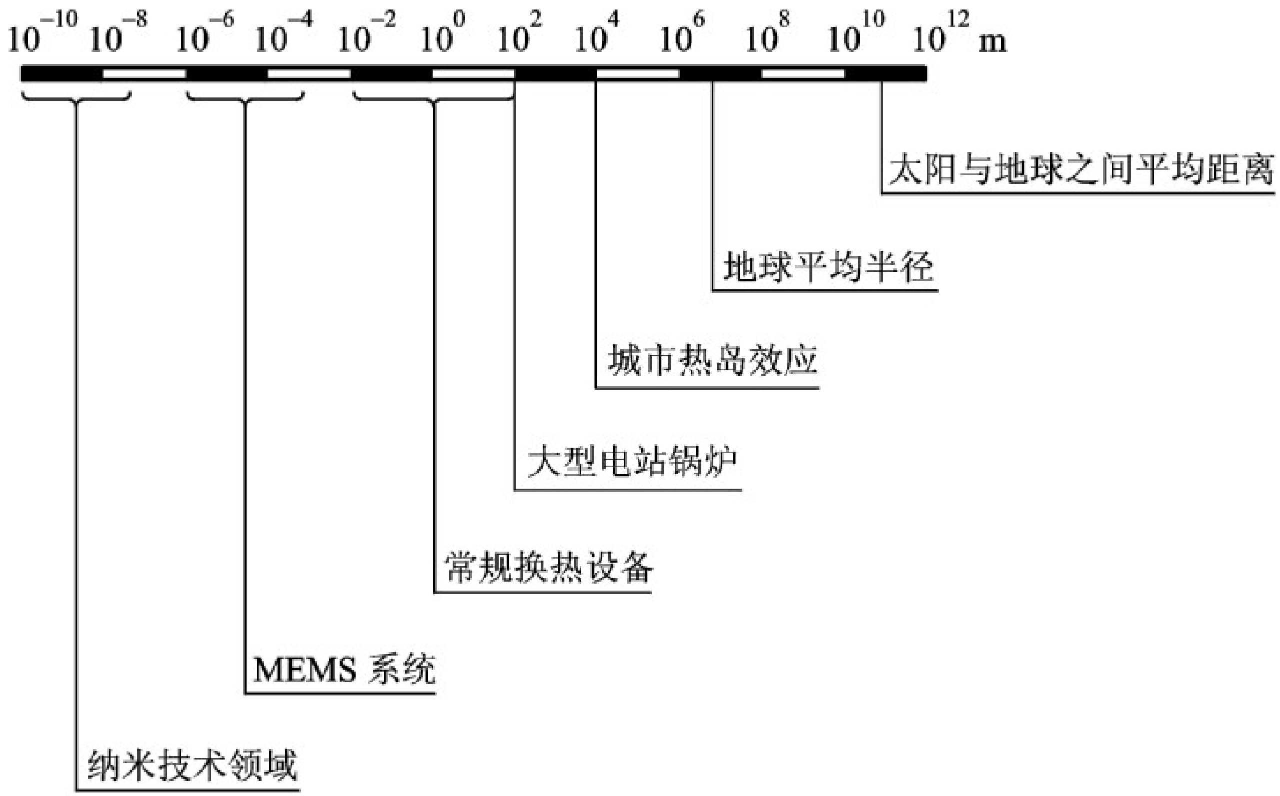
- Thermodynamics (工程热力学)
  - Thermodynamics is a branch of science concerned with heat and temperature and their relation to energy and work.
  - Thermodynamics describes how thermal energy is converted to and from other forms of energy and how it affects matter.
  - Thermodynamics is concerned with the amount of heat transfer as a system undergoes a process from one equilibrium state to another.

Introduction

- Relationship between heat transfer & thermodynamics
  - Thermodynamics: system at equilibrium state.
  - Heat transfer: system at non-equilibrium state (temperature difference).
  - The physical quantities in thermodynamics do not include the dimension time (T).
  - The main variables in heat transfer include the dimension T^{-1}: the main concern is the rate of energy transfer
  - Basic laws in thermodynamics are widely applied in the heat transfer
    - First law : The internal energy of an isolated system is constant.
    - Second law: Heat cannot flow from a colder location to a hotter location

Introduction

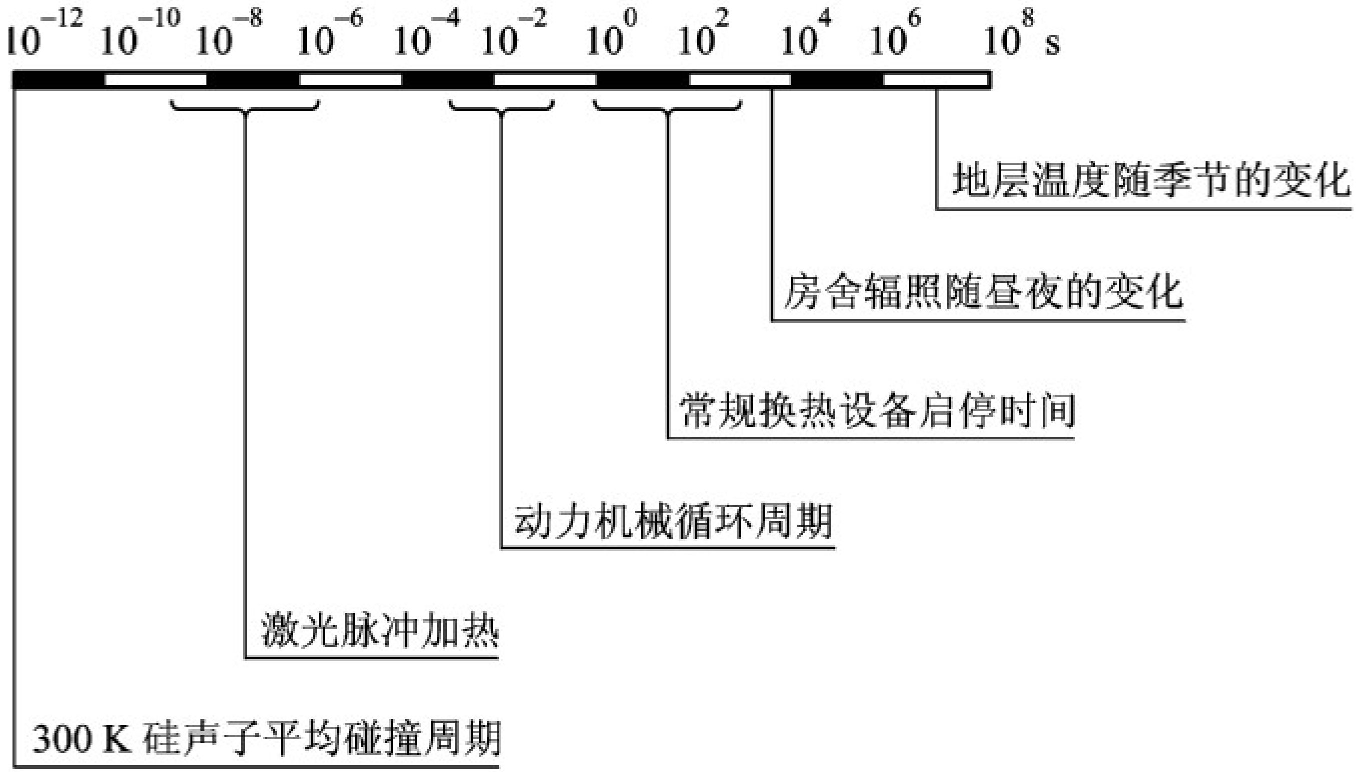
- Length Scale for Heat Transfer



  - Spanning 20 orders of magnitude

Introduction

- Time Scale for Heat Transfer



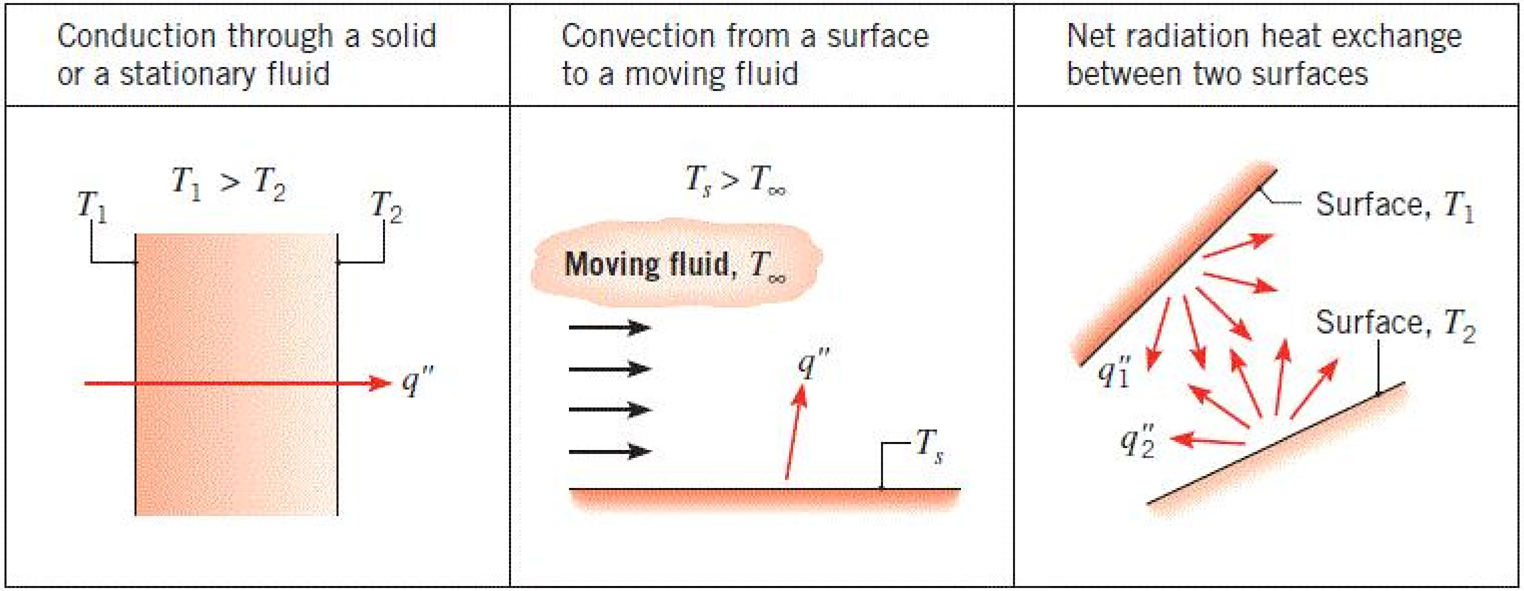
  - Spanning 20 orders of magnitude

Introduction

- Three modes of heat transfer
  - Heat transfer is energy transfer due to a temperature difference in a medium or between two or more media
  - Different types of heat transfer processes are called different modes of heat transfer
  - Conduction: heat transfer is due to a temperature gradient in a stationary medium or media.
  - Convection: heat transfer occurs between a surface and a moving fluid at different temperatures.
  - Radiation: heat transfer occurs due to emission of energy in the form of electromagnetic waves by all bodies above absolute zero temperature.

Introduction

- Three modes of heat transfer

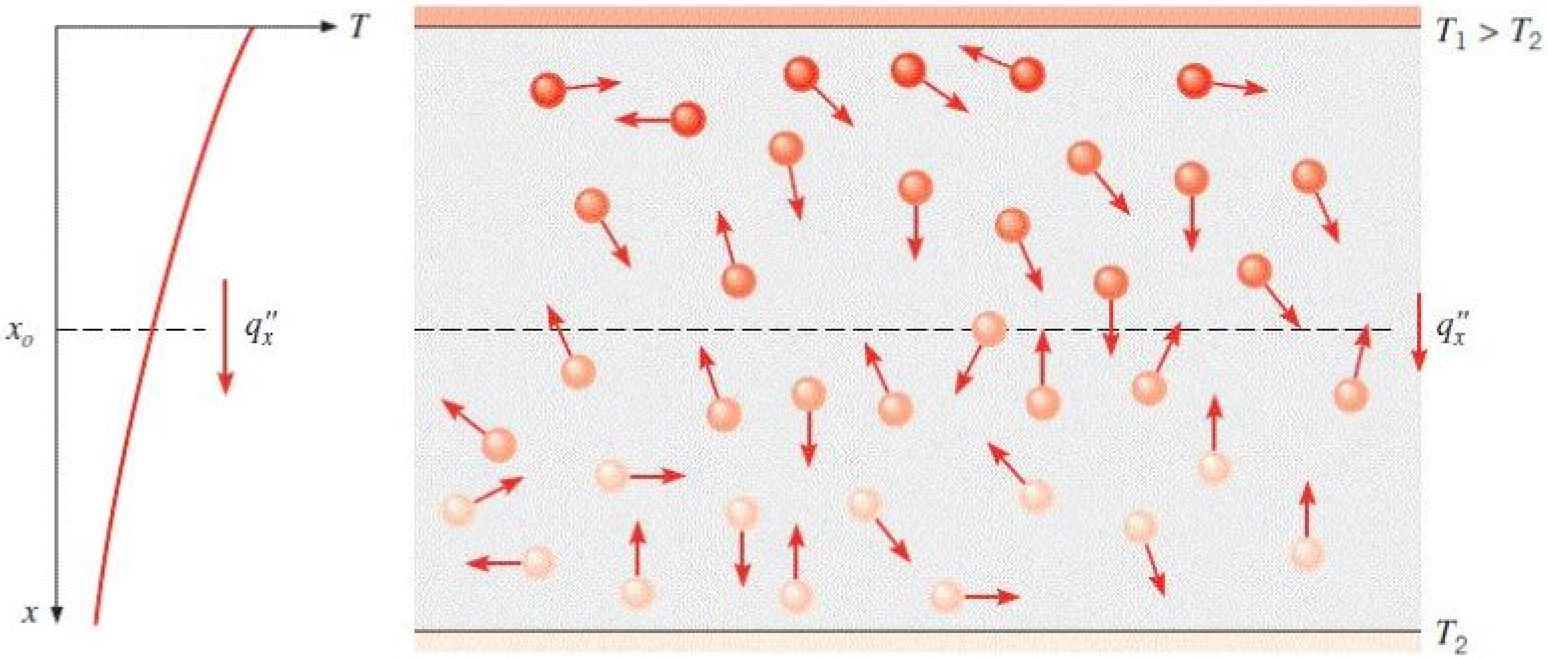


Introduction

- Heat Conduction
  - Conduction may be viewed as the transfer of energy from more energetic to the less energetic particles of a substance due to interaction between the particles.
  - Conduction heat transfer occurs only when there is physical contact between bodies (systems) at different temperatures by molecular motion.
  - Heat transfer through solid bodies is by conduction alone, whereas the heat may transfer from a solid surface to a fluid partly by conduction and partly by convection.

Introduction

- Heat Conduction
  - Mechanism: gas

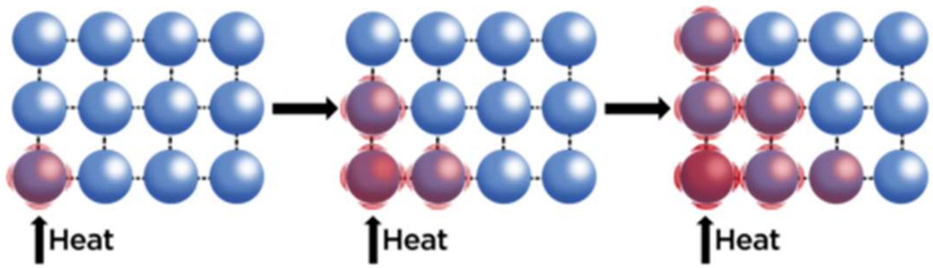


Introduction

- Heat Conduction
  - Mechanism: gas
    - ✓ The gas molecules with higher temperature have higher kinetic energy, and thus higher moving speed.
    - ✓ When the molecular with higher temperature collides with that with lower temperature, a transfer of energy from the more energetic to the less energetic molecules occurs.
    - ✓ In the presence of a temperature gradient, energy transfer by conduction must then occur in the direction of decreasing temperature.

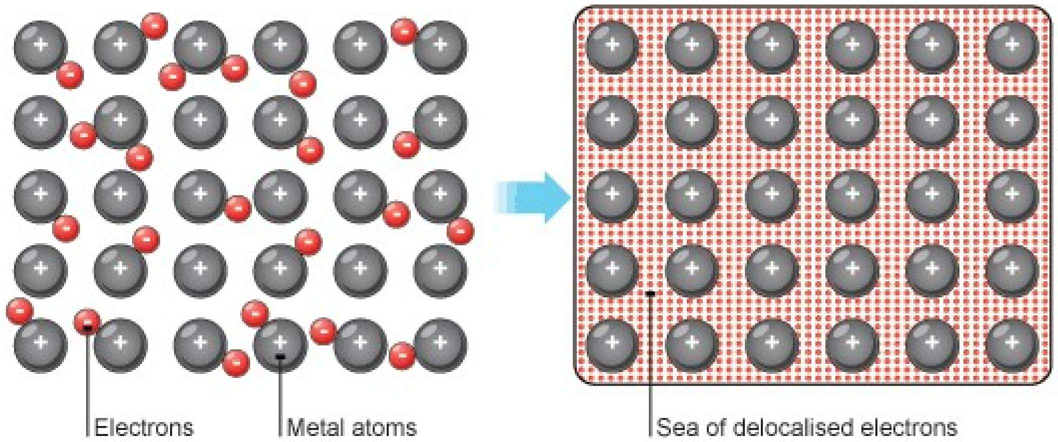
Introduction

- Heat Conduction
  - Mechanism: solid → electrical insulator
    - ✓ In insulators, the heat flux is carried almost entirely by phonon (lattice) vibrations



Introduction

- Heat Conduction
  - Mechanism: solid → electrical conductor
    - ✓ The electron fluid of a conductive metallic solid conducts most of the heat flux through the solid.
    - ✓ Phonon flux is still present, but carries less of the energy.

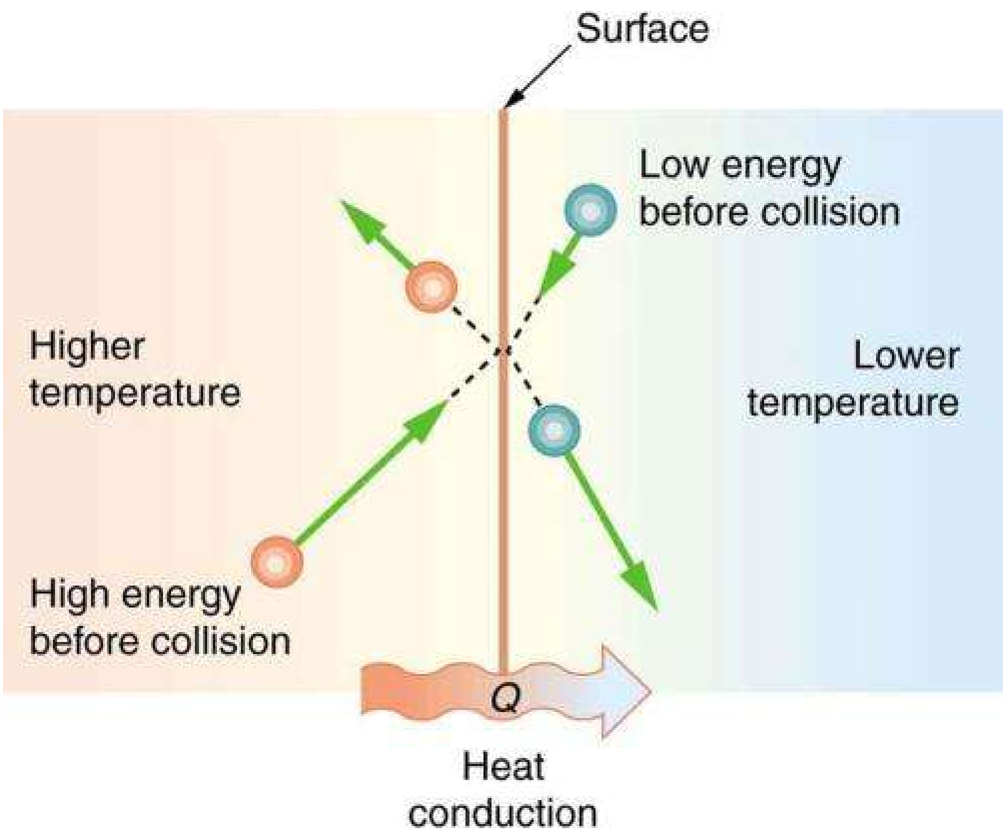


Introduction

- Heat Conduction
  - Mechanism: liquid
    - ✓ Some people think the mechanism for heat conduction in liquid is similar to that for gas.
    - ✓ Some people think the mechanism for heat conduction in liquid is similar to that for insulator.

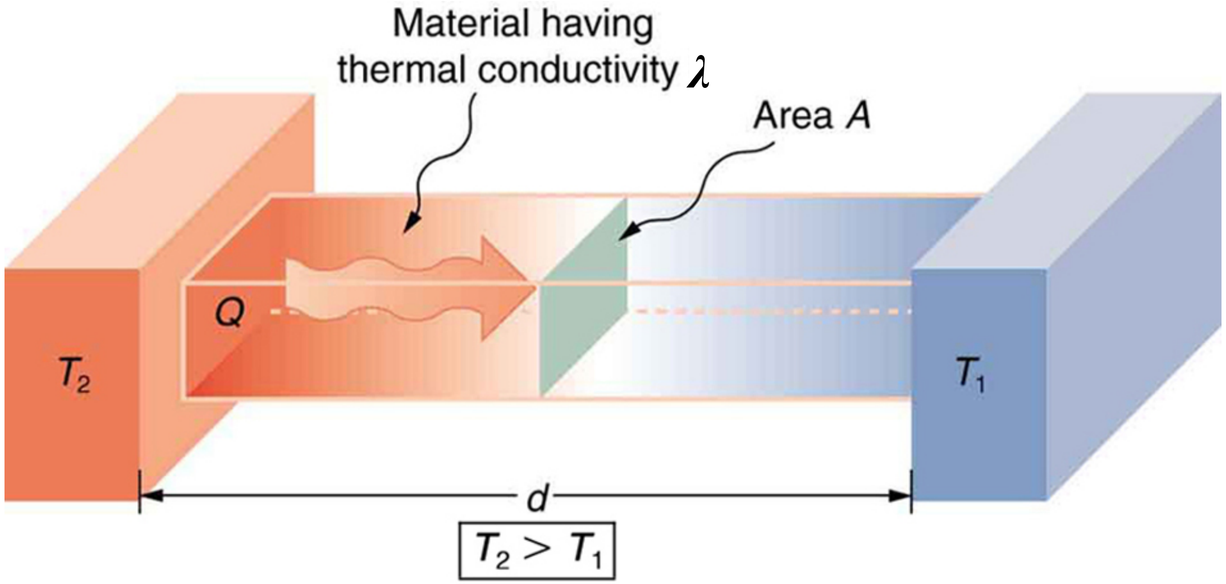
Introduction

- Heat Conduction
  - Mechanism: interface



Introduction

- Heat Conduction
  - Fourier's Law



$$\Phi = -\lambda A \frac{dT}{dx} \qquad \text{or} \qquad q = \frac{\Phi}{A} = -\lambda \frac{dT}{dx}$$

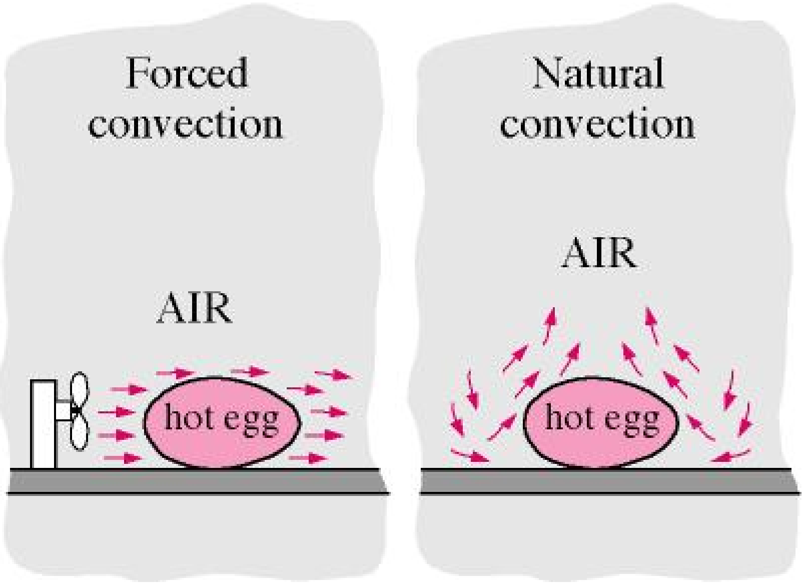
✓ Φ is heat transfer rate, q is heat flux; λ is thermal conductivity; T is temperature; A is cross-section area; x is Cartesian coordinate.

Introduction

- Heat Convection
  - Convection is the process of heat transfer from one location to the next by the movement of fluids.
  - Convection heat transfer includes both forced convection and natural convection
    - ✓ Natural convection → the driving force of the circulation of fluid is natural - differences in density between two locations as the result of fluid being heated. (think about the concept of buoyant forces).
    - ✓ Forced convection involves fluid being forced from one location to another by fans, pumps and other devices
  - Heat transfer processes that involve change of phase of a fluid are also being considered to be convection.

Introduction

- Heat Convection
  - Forced and natural convection: an example



Introduction

- Heat Convection
  - Newton's law of cooling.

Fluid is heated up: $q = h\left(T_w - T_f\right)$

Fluid is cooled down: $q = h\left(T_f - T_w\right)$

✓ T_w and T_f are wall temperature and fluid temperature, respectively; q is heat flux; h is the convective heat transfer coefficient.

✓ If ΔT denotes the temperature different and is always positive, the formula of the Newton's law of cooling can be written as

$$q = h\Delta T$$

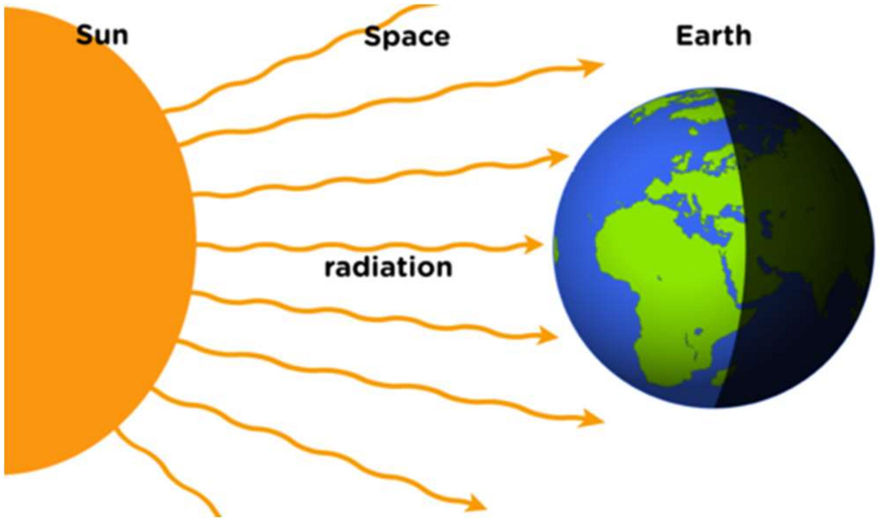
$$\Phi = hA\Delta T$$

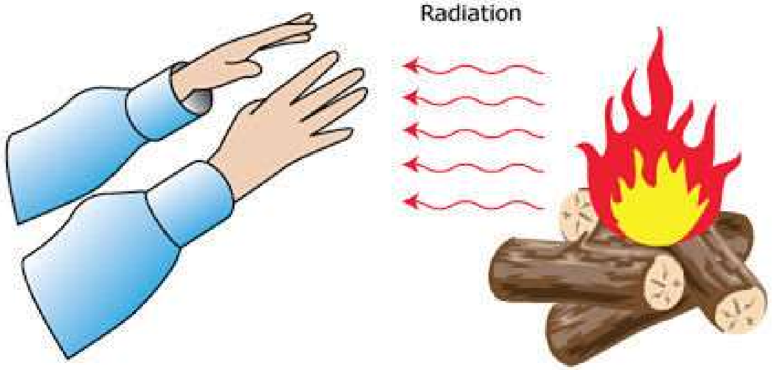
Introduction

- Heat Radiation
  - Thermal radiation is the energy radiated from hot surfaces as electromagnetic waves.
  - Thermal radiation can occur through matter or through a region of space that is void of matter (i.e., a vacuum).
  - Heat transfer by radiation occur between solid surfaces, although radiation from gases is also possible.
  - Solids radiate over a wide range of wavelengths, while some gases emit and absorb radiation on certain wavelengths only.
  - In many situation, radiation is very small compared with convection and conduction.

Introduction

- Heat Radiation





Introduction

- Heat Radiation
  - Stefan-Boltzmann Law

The maximum flux, E_b (W/m^2), at which radiation may be emitted from a blackbody surface is given by:

$$E_b = \sigma T^4$$

E_b is the emissive power

σ is the Stefan- Boltzmann constant (5.67×10^{-8} Wm^{-2}K^{-4})

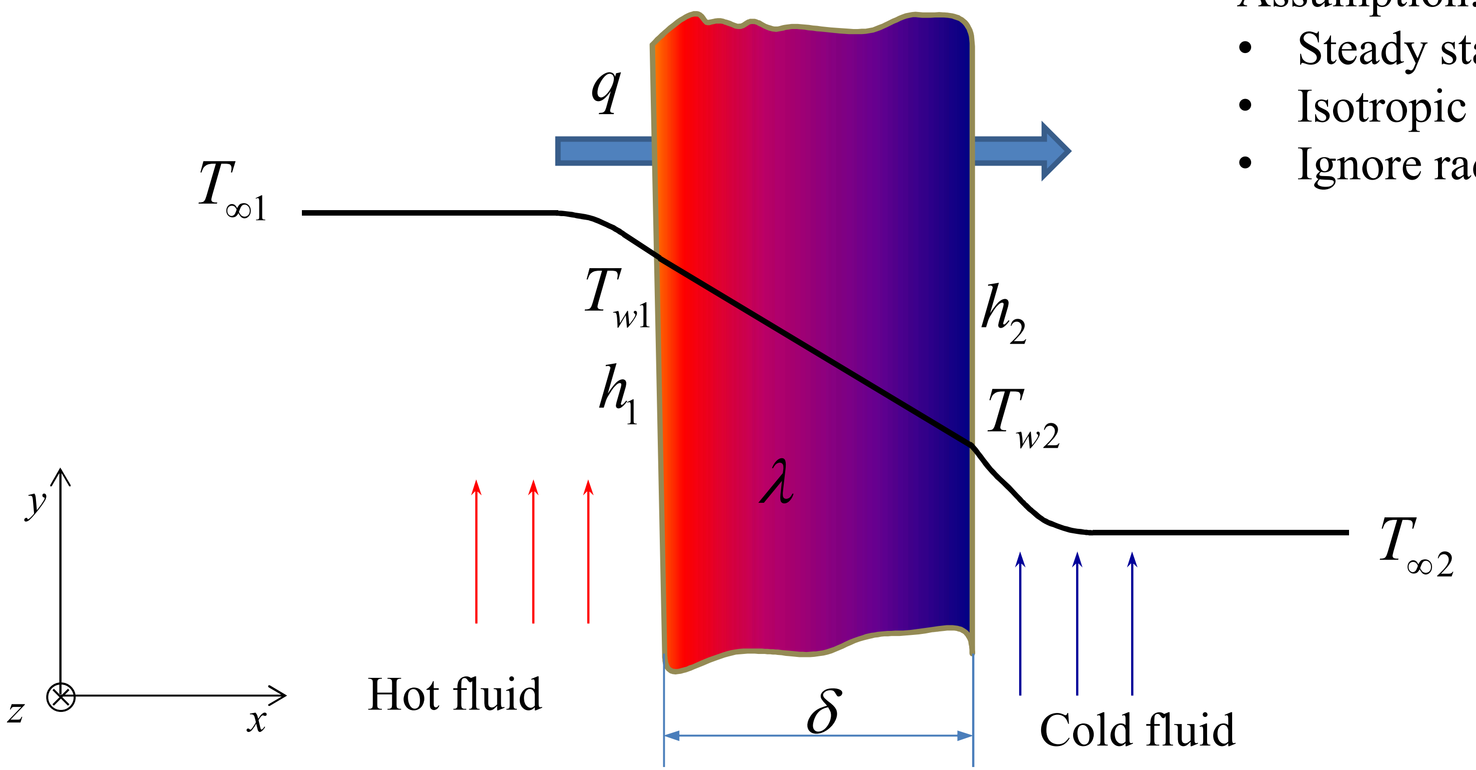
T is the absolute temperature

Heat transfer rate:

$$\Phi = \varepsilon_1 A_1 \sigma \left(T_1^4 - T_2^4 \right)$$

Introduction

- Heat Transfer Process
  - A plane wall subjected to convective heat transfer

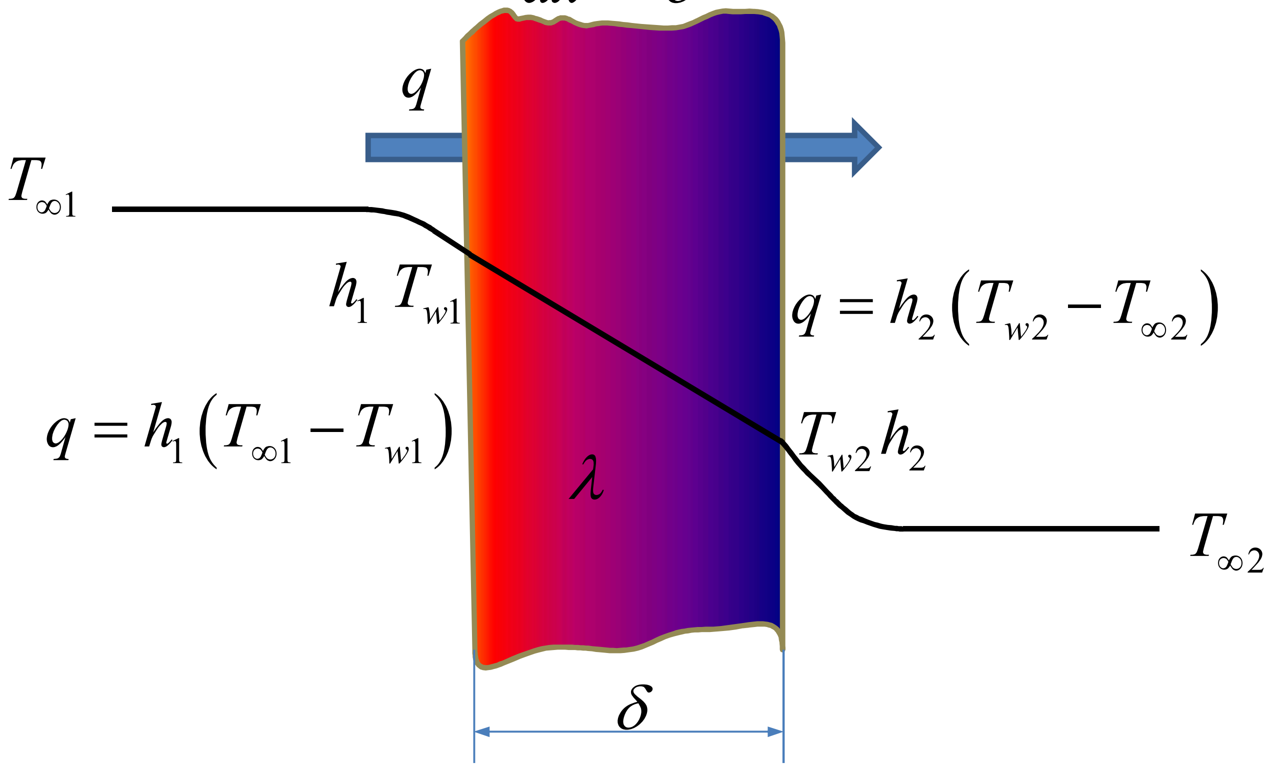


Assumption:
- Steady state
- Isotropic
- Ignore radiation

Introduction

- Heat Transfer Process

$$q = -\lambda \frac{dT}{dx} = \frac{\lambda}{\delta}\left(T_{w1} - T_{w2}\right)$$



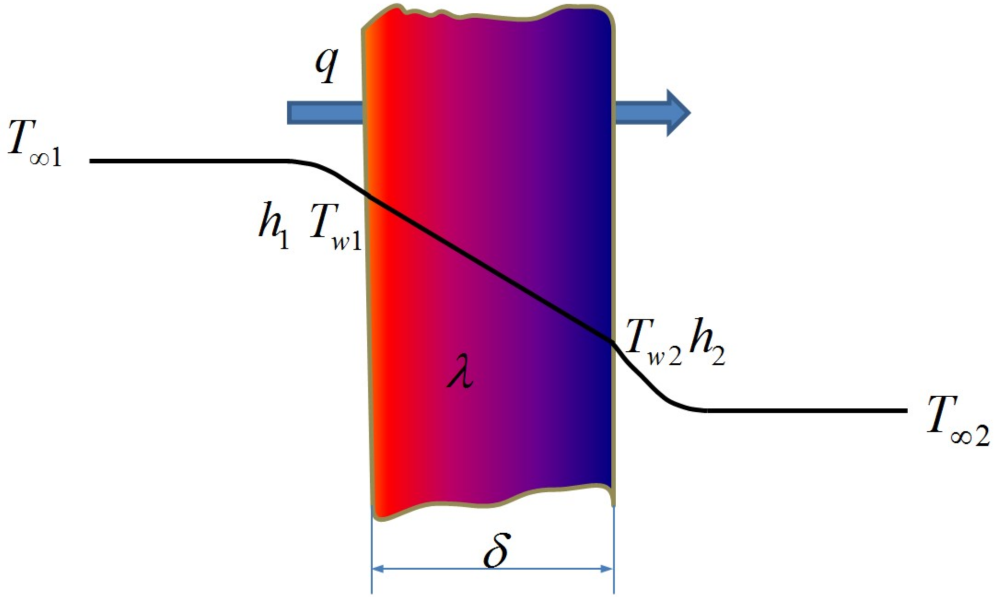
Introduction

- Heat Transfer Process

$$T_{\infty 1} - T_{w1} = \frac{q}{h_1}$$

$$T_{w1} - T_{w2} = \frac{q}{\lambda/\delta}$$

$$T_{w2} - T_{\infty 2} = \frac{q}{h_2}$$



Remove T_{w1} and T_{w2}

$$q = \frac{T_{\infty 1} - T_{\infty 2}}{\frac{1}{h_1} + \frac{\delta}{\lambda} + \frac{1}{h_2}}$$

Define an overall heat transfer coefficient k:

$$k = \frac{1}{\frac{1}{h_1} + \frac{\delta}{\lambda} + \frac{1}{h_2}}$$

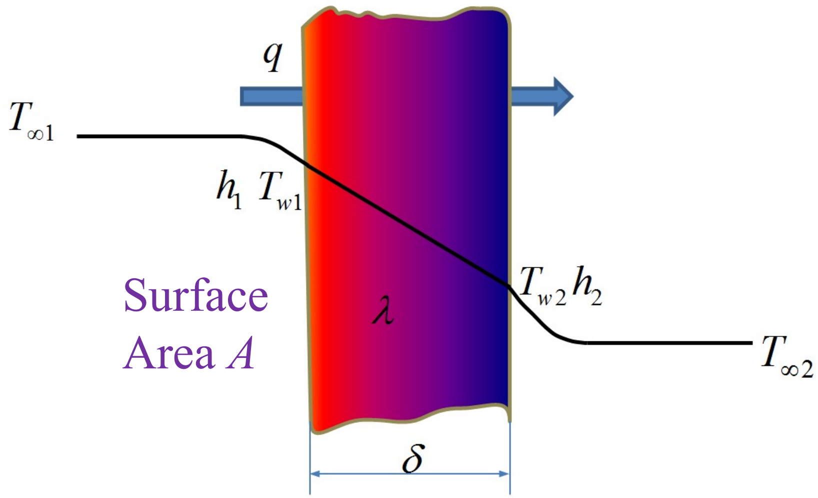
$$q = k\left(T_{\infty 1} - T_{\infty 2}\right)$$

Introduction

- Thermal Resistance
  - Consider the wall area A with constant flux q

$$\Phi = qA = kA\left(T_{\infty 1} - T_{\infty 2}\right) = \frac{\Delta T}{1/kA}$$

$$\frac{1}{kA} = \frac{1}{h_1 A} + \frac{\delta}{\lambda A} + \frac{1}{h_2 A}$$



  - Recall Ohm's Law

$$I = \frac{V}{R}$$

I is the current through the conductor, V is the voltage measured across the conductor, and R is the resistance of the conductor.

Introduction

- Thermal Resistance
  - We can thus define the thermal resistance in the similar way

$$R_{thermal} = \frac{1}{kA}$$

where $R_{thermal}$ is the thermal resistance (across the length of the material) (K/W)

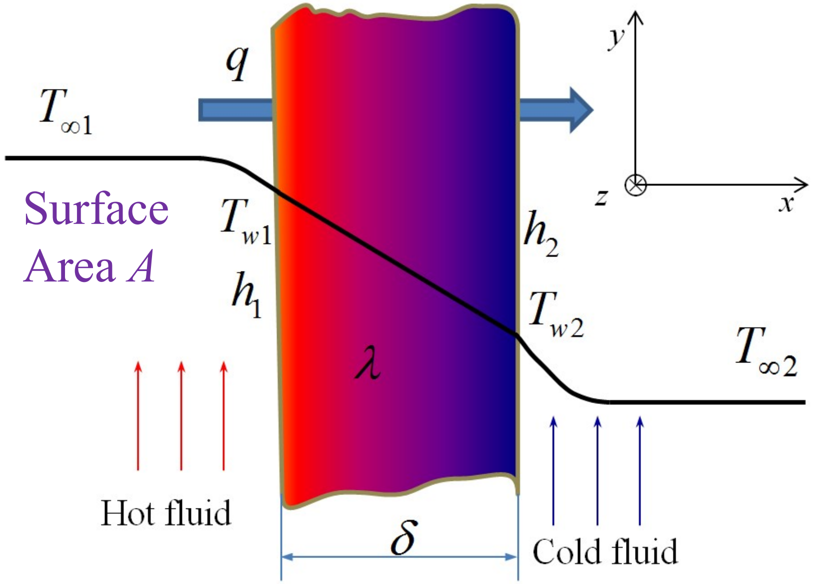
  - Thermal resistance is the temperature difference across a structure when a unit of heat energy flows through it in unit time.
  - Thermal resistance can be regarded as a property of a particular component. For example, a characteristic of a heat sink.

Introduction

- Heat Transfer Circuit (传热回路)
  - Series Circuit
    - ✓ A plane wall subjected to convective heat transfer

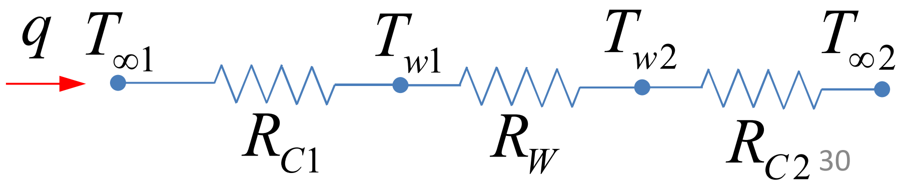
Electric Circuits
电路

$$R_{C1} = \frac{1}{h_1 A} \qquad R_W = \frac{\delta}{\lambda A} \qquad R_{C2} = \frac{1}{h_2 A}$$



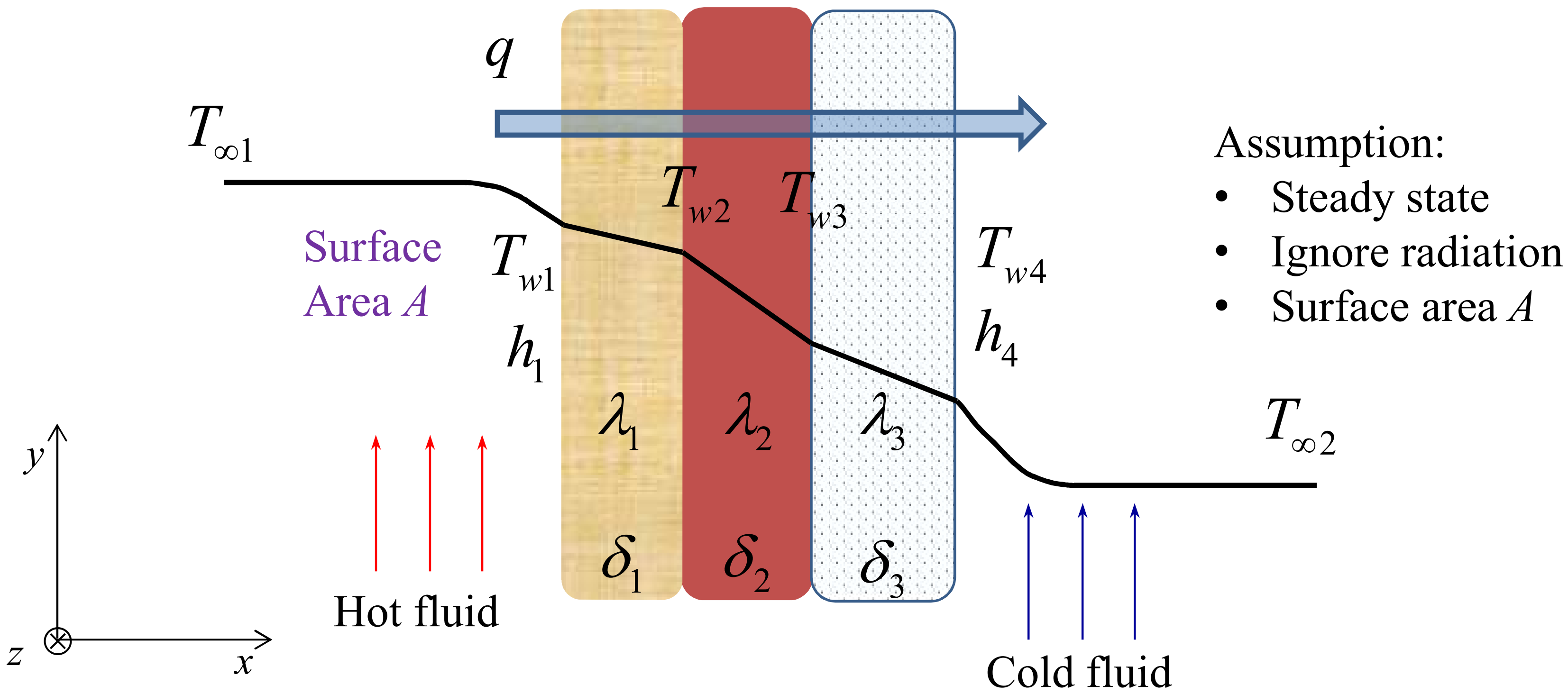
$$R_{thermal} = R_{C1} + R_W + R_{C2}$$
$$= \frac{1}{h_1 A} + \frac{\delta}{\lambda A} + \frac{1}{h_2 A}$$

$$\Phi = \frac{T_{\infty 1} - T_{\infty 2}}{R_{thermal}} = \frac{T_{\infty 1} - T_{\infty 2}}{\frac{1}{h_1 A} + \frac{\delta}{\lambda A} + \frac{1}{h_2 A}}$$



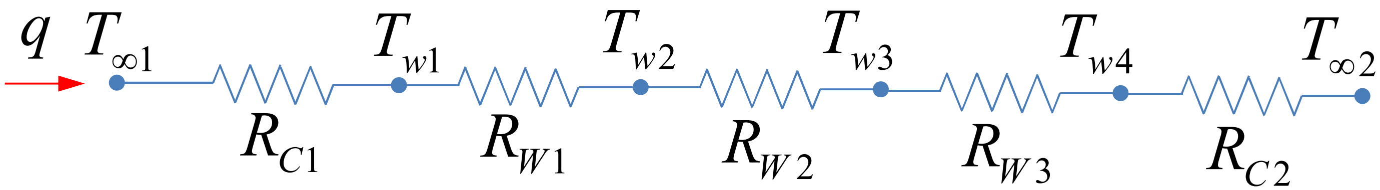
Introduction

- Heat Transfer Circuit
  - Series Circuit
    - ✓ A composite wall subjected to convective heat transfer



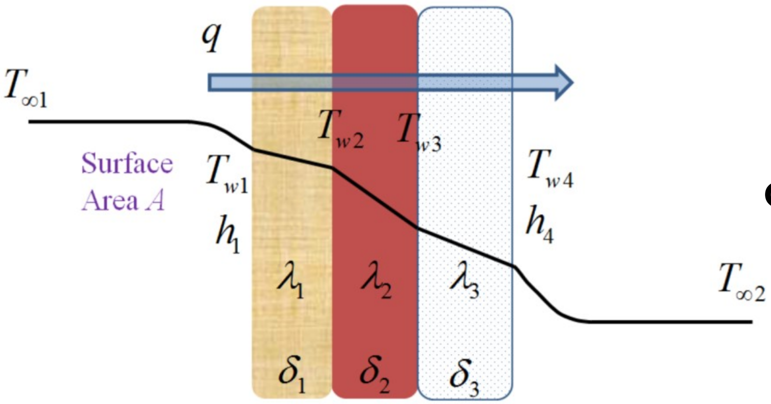
Introduction

- Heat Transfer Circuit
  - Series Circuit
    - ✓ A composite wall subjected to convective heat transfer



$$R_{thermal} = R_{C1} + R_{W1} + R_{W2} + R_{W3} + R_{C2}$$

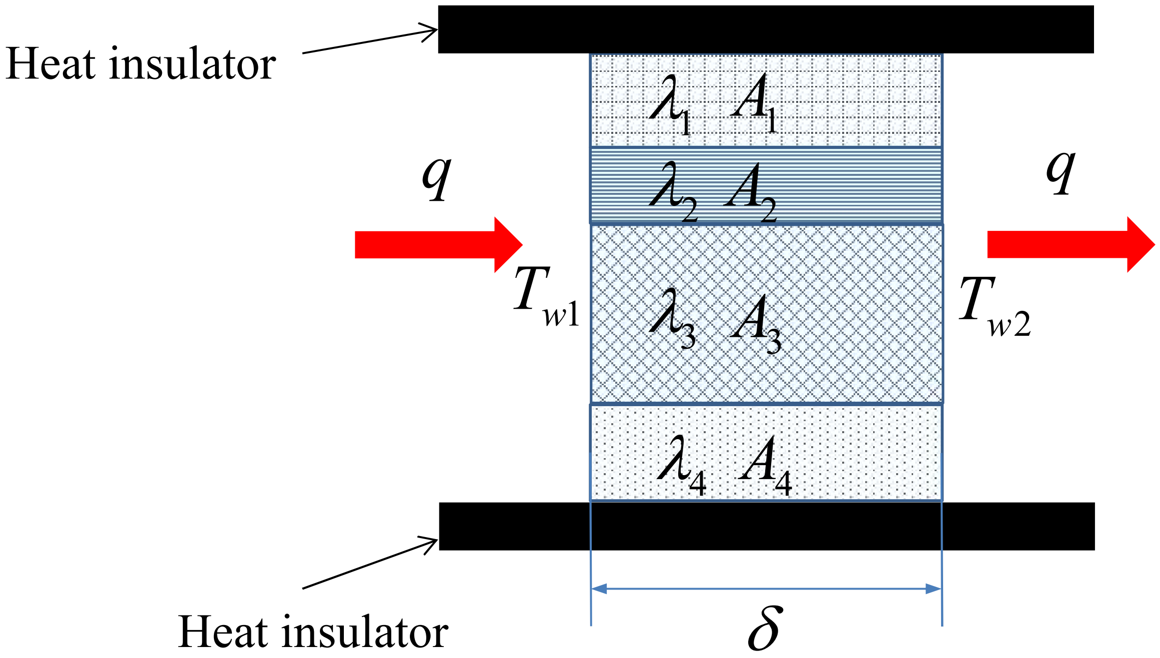
$$= \frac{1}{h_1 A} + \frac{\delta_1}{\lambda_1 A} + \frac{\delta_2}{\lambda_2 A} + \frac{\delta_3}{\lambda_3 A} + \frac{1}{h_2 A}$$



$$\Phi = \frac{T_{\infty 1} - T_{\infty 2}}{R_{thermal}} = \frac{T_{\infty 1} - T_{\infty 2}}{\frac{1}{h_1 A} + \frac{\delta_1}{\lambda_1 A} + \frac{\delta_2}{\lambda_2 A} + \frac{\delta_3}{\lambda_3 A} + \frac{1}{h_2 A}}$$

Introduction

- Heat Transfer Circuit
  - Parallel Circuit
    - A wall with dissimilar materials



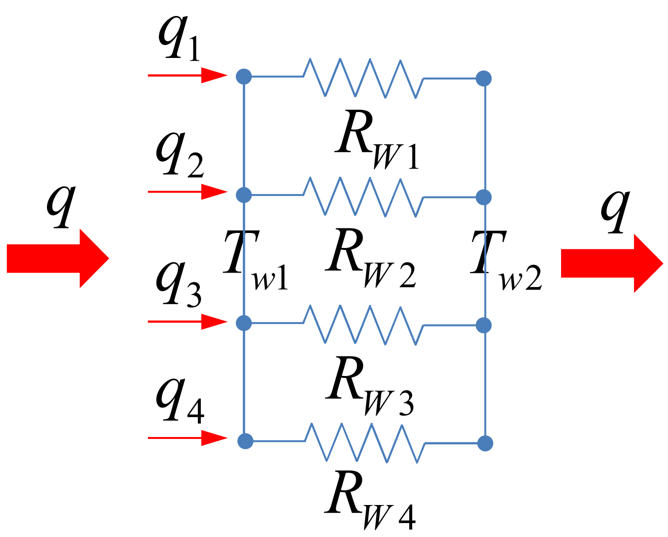
Assumption:
- Steady state
- Ignore radiation
- No heat convection

Introduction

- Heat Transfer Circuit
  - Parallel Circuit
    - A wall with dissimilar materials

$$\frac{1}{R_{thermal}} = \frac{1}{R_{W1}} + \frac{1}{R_{W2}} + \frac{1}{R_{W3}} + \frac{1}{R_{W4}}$$

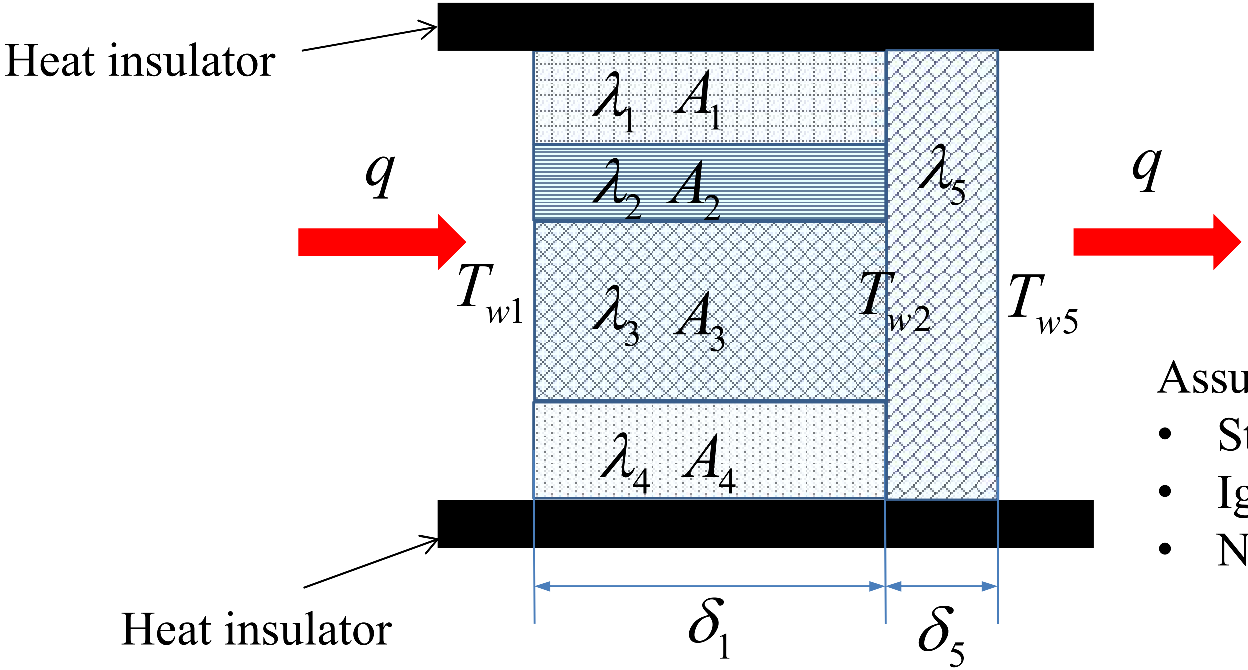
$$= \frac{\lambda_1 A_1}{\delta} + \frac{\lambda_2 A_2}{\delta} + \frac{\lambda_3 A_3}{\delta} + \frac{\lambda_4 A_4}{\delta}$$



$$\Phi = \frac{T_{w1} - T_{w2}}{R_{thermal}} = \frac{T_{\infty 1} - T_{\infty 2}}{\delta}\left(\lambda_1 A_1 + \lambda_2 A_2 + \lambda_3 A_3 + \lambda_4 A_4\right)$$

Introduction

- Heat Transfer Circuit
  - Serial and Parallel Circuit
    - A complex wall structure with dissimilar materials



Assumption:
- Steady state
- Ignore radiation
- No heat convection

Review

- Heat is the energy associated with the random motion of atoms and molecules.
- Heat transfer is energy transfer due to a temperature difference in a medium or between two or more media
- Heat transfer deals with how fast the energy transfers while thermodynamics deals with how much the energy is transferred.
- There are three modes of heat transfer: conduction, convection and radiation.

Review

- Conduction heat transfer is due to a temperature gradient in a stationary medium or media
  - In gases conduction is due to the collisions and diffusion of the molecules during their random motion.
  - In solids, it is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.
  - In liquids, the situation is more complicated.
  - Fourier's Law: the rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer

$$\Phi = -\lambda A \frac{dT}{dx} \qquad \text{or} \qquad q = \frac{\Phi}{A} = -\lambda \frac{dT}{dx}$$

Review

- Convection is heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it.
- Forced convection: The fluid is forced to flow over the surface by external means such as a fan, pump, or the wind.
- Natural (or free) convection: The fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid.
- The rate of convection transfer is given by Newton's Law of Cooling.

$$q = h\Delta T$$

$$\Phi = hA\Delta T$$

Review

- Radiation: the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules.
- All bodies at a temperature above absolute zero emit thermal radiation.
- The maximum flux, E_b (W/m^2), at which radiation may be emitted from a blackbody surface is given by Stefan-Boltzmann Law.

$$E_b = \sigma T^4$$

- The heat transfer rate:

$$\Phi = \varepsilon_1 A_1 \sigma \left(T_1^4 - T_2^4 \right)$$

Review

- Thermal resistance

$$R_{thermal} = \frac{1}{kA} \qquad \Phi = \frac{\Delta T}{R_{thermal}}$$

- Heat transfer circuit:
  - Series Circuit

$$R_{thermal} = R_1 + R_2 + R_3 + \ldots + R_n$$

  - Parallel Circuit

$$\frac{1}{R_{thermal}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$$


Thank You for Your Attention!
Any Questions?