Chapter 1

Introduction to Heat Transfer

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Outline

- Introduction
- Applications
- Definitions
- Conduction
- Convection
- Radiation
- Conservation of Energy Principles

Introduction

Difference between the science of Heat Transfer & Thermodynamics

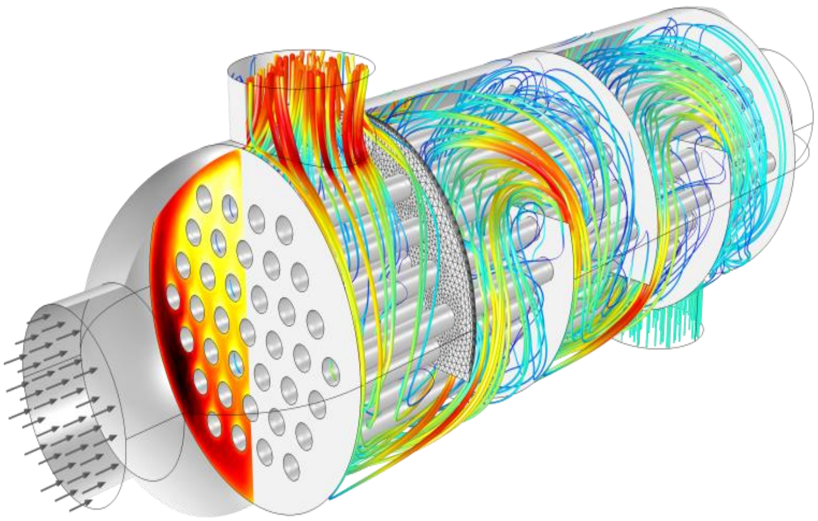
Thermodynamics:

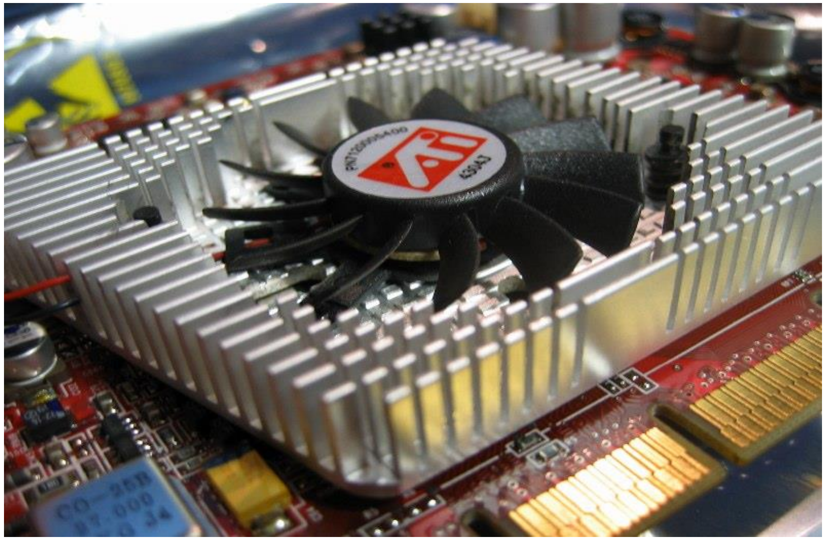
- Energy can be transferred between a system and its surroundings.
- A system interacts with its surroundings by exchanging work and heat
- Deals with equilibrium states
- Does not give information about:
  - *Rates at which energy is transferred*
  - *Mechanisms through with energy is transferred*

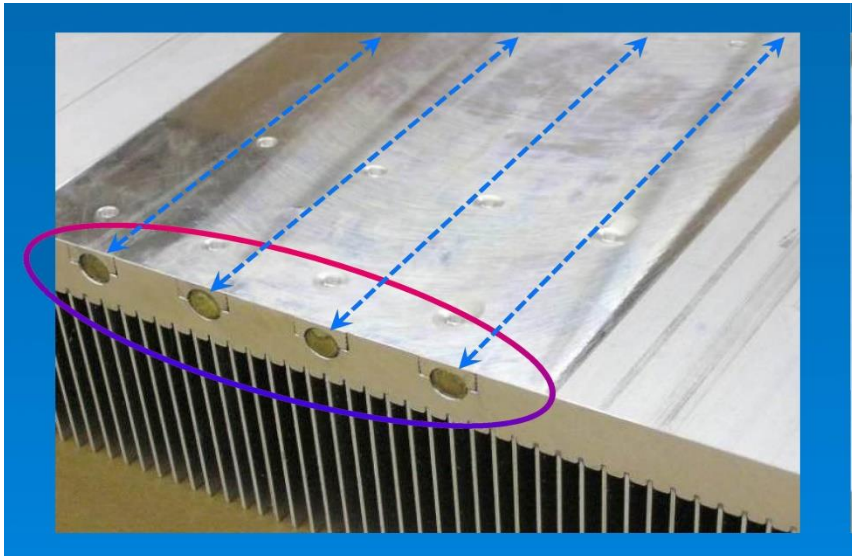
In this chapter we will learn

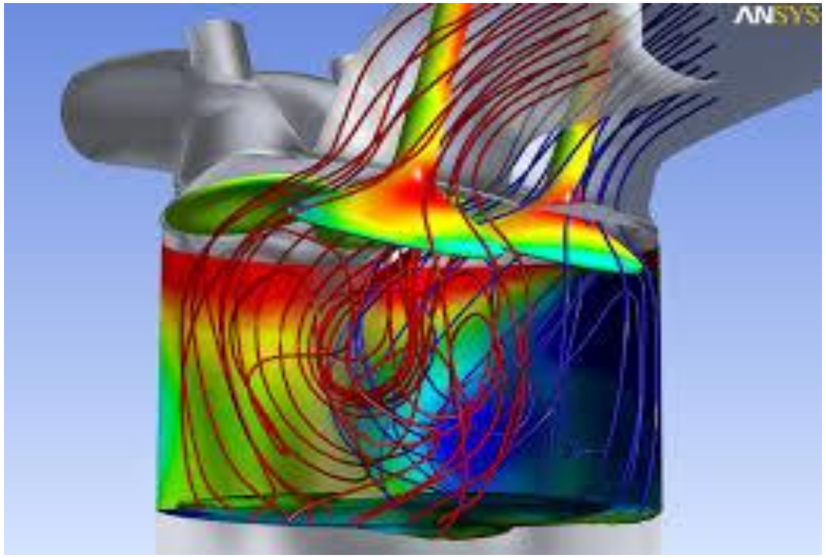
- What is heat transfer
- How is heat transferred
- Relevance and importance

Applications









Definitions

- Heat transfer is thermal energy transfer that is induced by a temperature difference (or *gradient*)
- Predict the energy transfer which may takes place b\n material bodies as a result of a temp. difference.

Modes of heat transfer

- Conduction heat transfer: Occurs when a temperature gradient exists through a solid or a stationary fluid (liquid or gas).

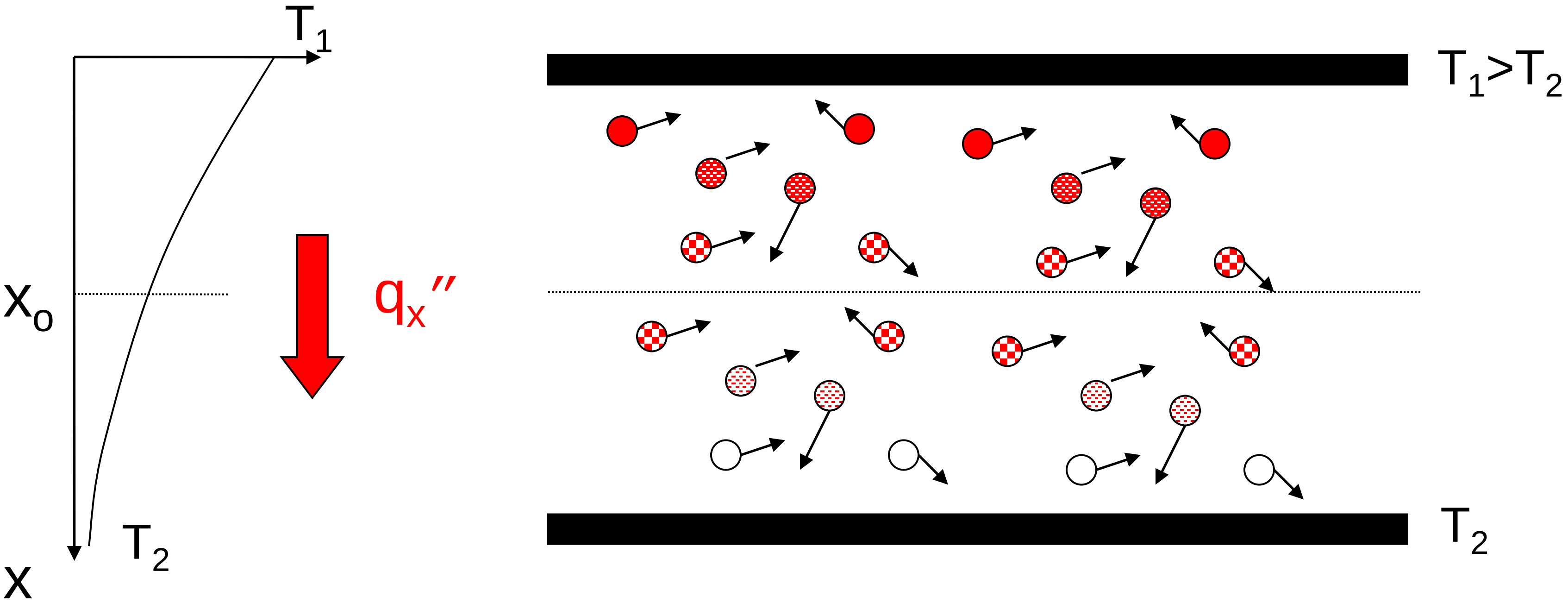
- Convection heat transfer: Occurs within a moving fluid, or between a solid surface and a moving fluid, when they are at different temperatures

- Thermal radiation: Heat transfer between two surfaces (that are not in contact), often in the absence of an intervening medium.

1. Conduction

Transfer of energy from the more energetic to less energetic particles of a substance by collisions between atoms and/or molecules.

- Atomic and molecular activity – random molecular motion (diffusion)



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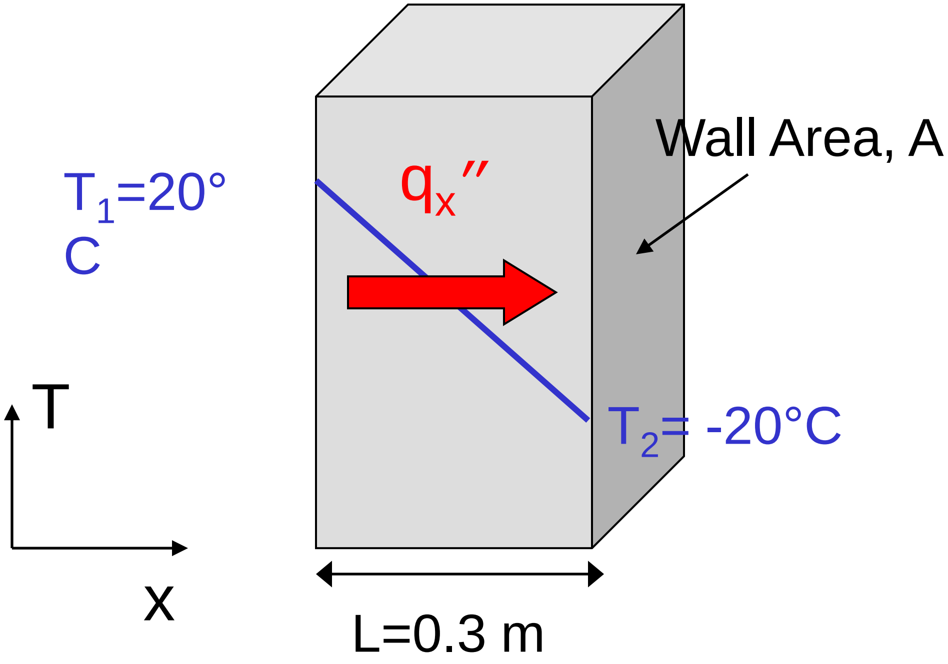
Consider a brick wall, of thickness L=0.3 m which in a cold winter day is exposed to a constant inside temperature, T_1=20°C and a constant outside temperature, T_2=-20°C.



- Under steady-state conditions the temperature varies linearly as a function of x.
- The rate of conductive heat transfer in the x-direction depends on

$$q_x'' \propto \frac{T_1 - T_2}{L}$$

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- The proportionality constant is a transport property, known as thermal conductivity k (units W/m.K)

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

- For the brick wall, k=0.72 W/m.K (assumed constant), therefore q_x''= 96 W/m^2
  - ? *How would this value change if instead of the brick wall we had a piece of polyurethane insulating foam of the same dimensions? (k=0.026 W/m.K)*

- q_x'' is the *heat flux* (units W/m^2 or (J/s)/m^2), which is the heat transfer rate in the x-direction per unit area perpendicular to the direction of transfer.
- The *heat rate*, q_x (units W=J/s) through a plane wall of area A is the product of the flux and the area of heat transfer: $q_x = q_x''$. A

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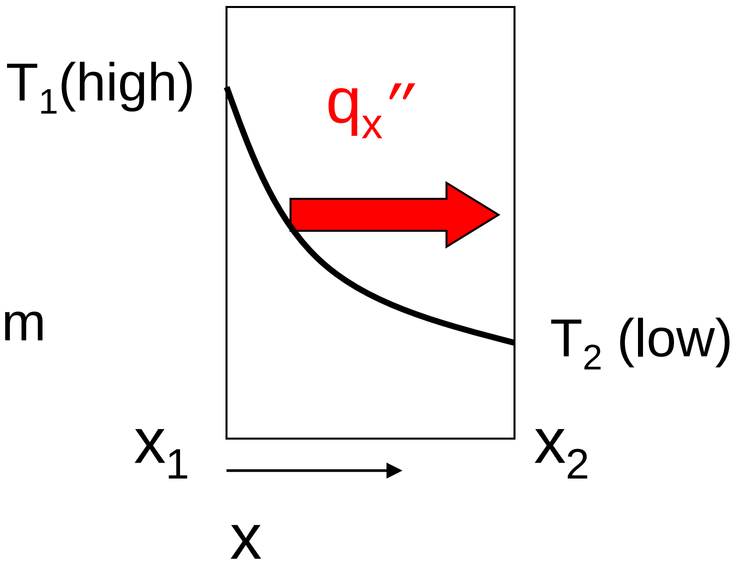
- In the general case ***the rate of heat transfer*** in the x-direction is expressed in terms of the Fourier law:

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



- Minus sign because heat flows from high to low T
  - For a linear profile

$$\frac{dT}{dx} = \frac{(T_2 - T_1)}{(x_2 - x_1)} < 0$$

2. Convection

Energy transfer by random molecular motion (as in conduction) plus bulk (macroscopic) motion of the fluid.

- Convection: transport by random motion of molecules and by bulk motion of fluid.
- Advection: transport due solely to bulk fluid motion.

There are two types of Convection:-

- Forced convection: Caused by external means
- Natural (free) convection: flow induced by buoyancy forces, arising from density differences arising from temperature variations in the fluid

The above cases involve sensible heat (internal energy) of the fluid

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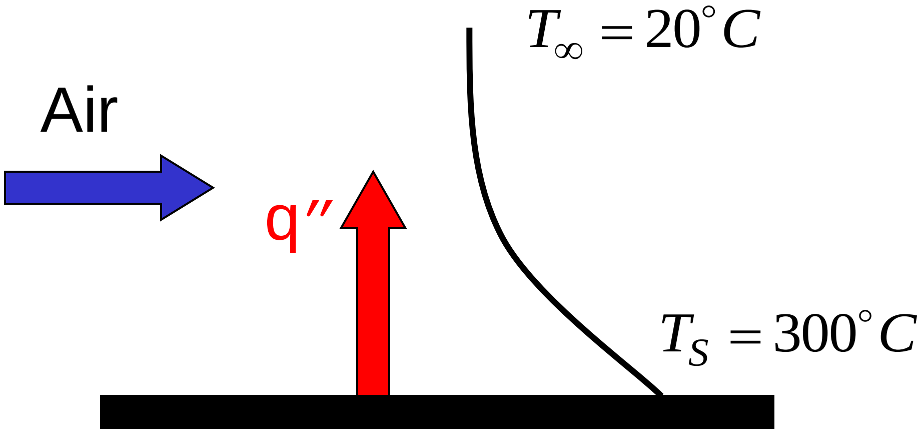
Air at 20°C blows over a hot plate, which is maintained at a temperature T_s=300°C and has dimensions 20x40 cm.



The convective heat flux is proportional to

$$q_x'' \propto T_S - T_\infty$$

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- The proportionality constant is the *convection heat transfer coefficient*, h (W/m^2.K)

$$q_x'' = h(T_S - T_\infty)$$

Newton's law of Cooling

- For air h=25 W/m^2.K, therefore the heat flux is $q_x''= 7{,}000$ W/m^2
  - ? *How would this value change if instead of blowing air we had still air (h=5 W/m^2.K) or flowing water (h=50 W/m^2.K)*
- The *heat rate*, is $q_x = q_x''.\ A = q_x''.\ (0.2 \times 0.4) = 560$ W.
- The heat transfer coefficient depends on surface geometry, nature of the fluid motion, as well as fluid properties. For typical ranges of values, see Table 1.1 textbook.
- In this solution we assumed that heat flux is positive when heat is transferred from the surface to the fluid

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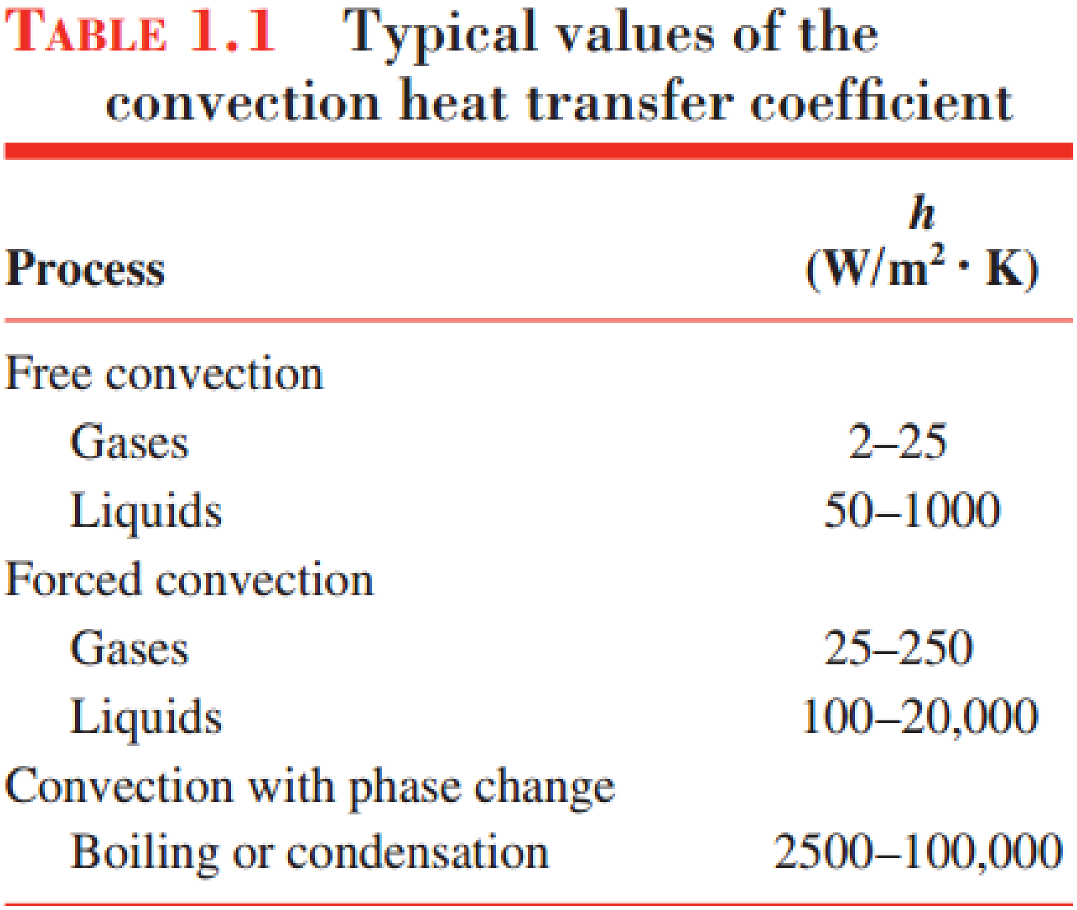
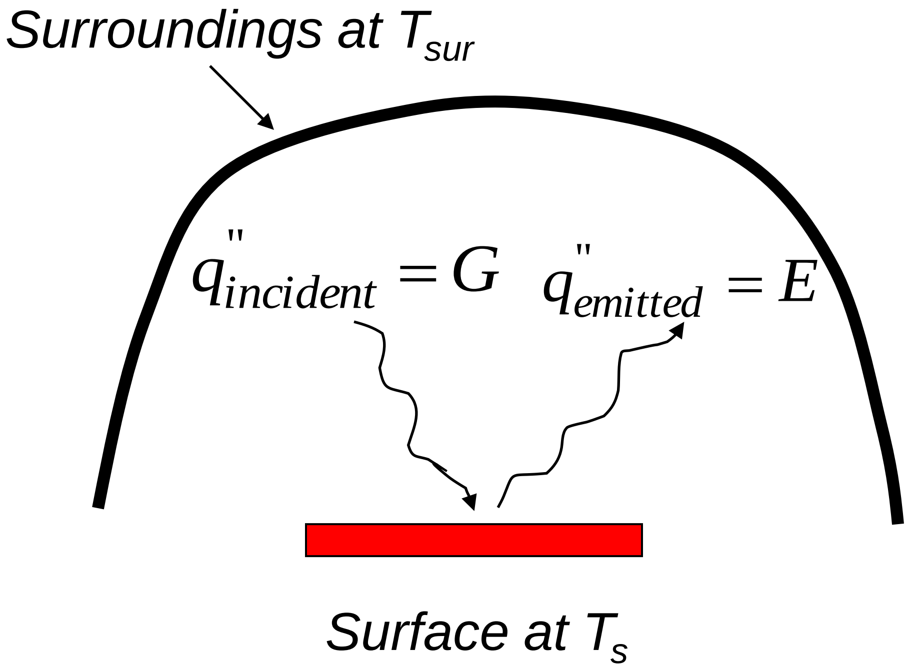


TABLE 1.1 Typical values of the convection heat transfer coefficient

Process	h $(\mathrm{W/m^2 \cdot K})$
Free convection	
Gases	2–25
Liquids	50–1000
Forced convection	
Gases	25–250
Liquids	100–20,000
Convection with phase change	
Boiling or condensation	2500–100,000

3. Radiation

- Thermal radiation is energy emitted by matter
- Energy is transported by electromagnetic waves (or photons).
- Can occur from solid surfaces, liquids and gases.
- Does not require presence of a medium



- ➢ Emissive power E is the rate at which energy is released per unit area (W/m^2) (radiation emitted *from* the surface)
- ➢ Irradiation G is the rate of incident radiation per unit area (W/m^2) of the surface (radiation absorbed *by* the surface), originating from its surroundings

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- For an ideal radiator, or blackbody:

$$q''_{emitted} = E_b = \sigma T_s^4$$ Stefan-Boltzmann law

Where T_s is the absolute temperature of the surface (K) and σ is the Stefan-Boltzmann constant, (σ = 5.67x10^{-8} W/m^2.K^4)

- For a real (non-ideal) surface:

$$q''_{emitted} = E = \varepsilon\sigma T_s^4$$ ε is the emissivity $$0 \le \varepsilon \le 1$$

- The irradiation G, originating from the surroundings is:

$$q''_{incident} = G = \alpha\sigma T_{sur}^4$$

α is the absorptivity $$0 \le a \le 1$$

For a "grey" surface, α=ε

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- Assuming $\alpha = \varepsilon$, the net radiation heat transfer from the surface, per unit area is

$$q''_{rad} = \varepsilon\sigma(T_s^4 - T_{sur}^4)$$

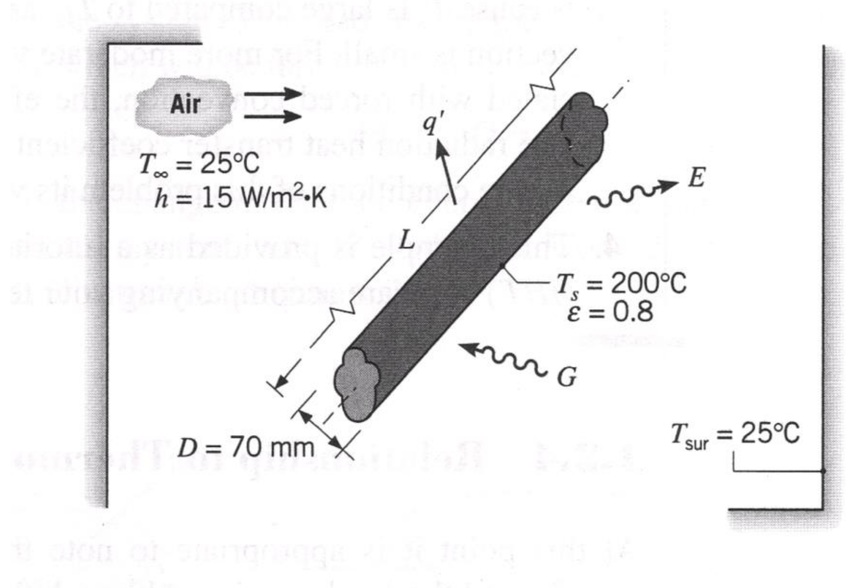
- The net radiation heat exchange can be also expressed in the form:

$$q_{rad} = h_r A(T_s - T_{sur})$$ where $$h_r = \varepsilon\sigma(T_s + T_{sur})(T_s^2 + T_{sur}^2)$$

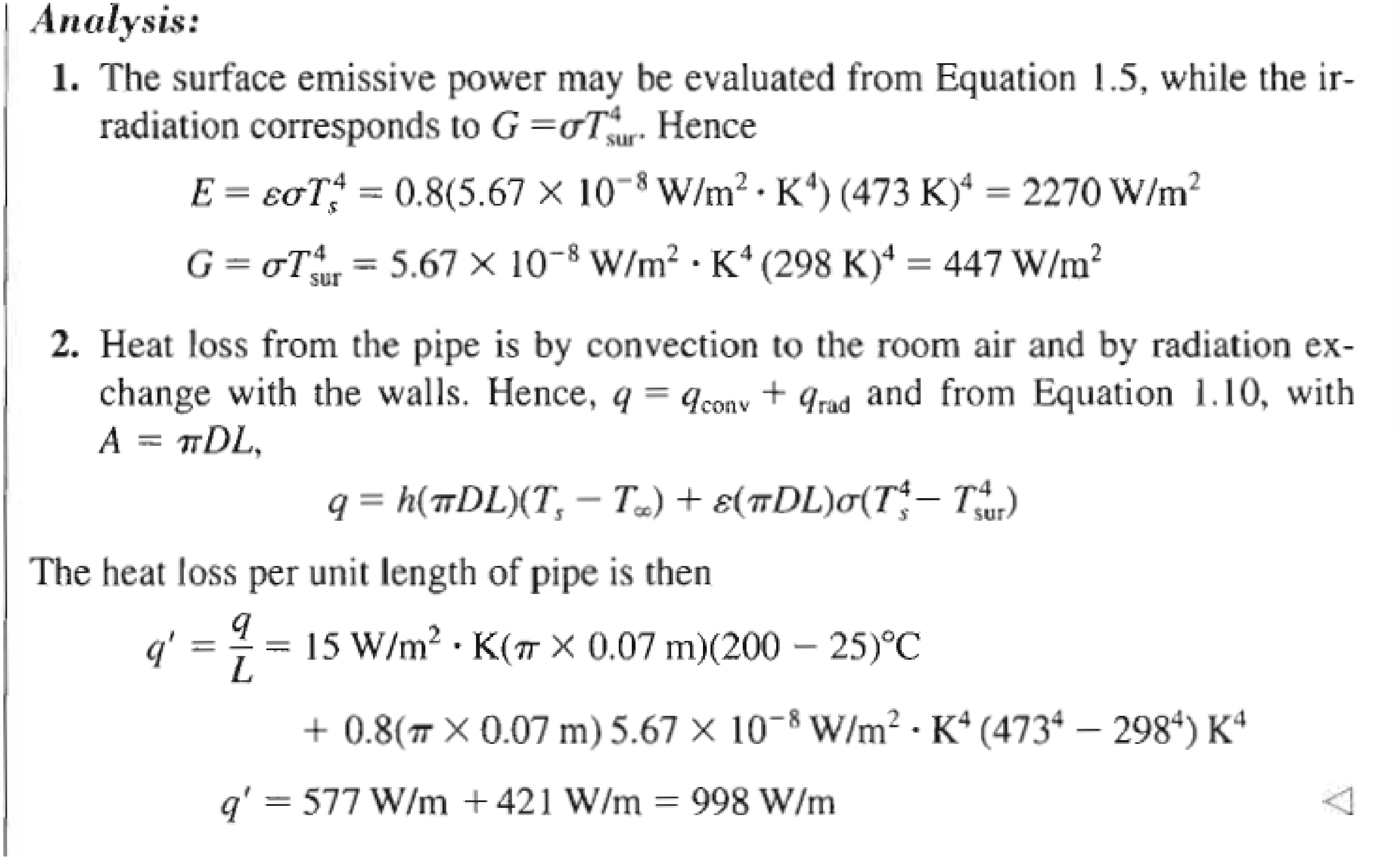
Example 2 (1.2 Textbook)

An uninsulated steam pipe passes through a room in which the air and the walls are at 25°C. The outside diameter of the pipe is 70 mm, and its surface temperature and emissivity are 200°C and 0.8 respectively. What are the surface emissive power (E), and irradiation (G)?

If the coefficient associated with free convection heat transfer from the surface to the air is h=15 W/m^2.K, what is the rate of heat loss from the surface per unit length of pipe, q'?



Solution



Analysis:

1. The surface emissive power may be evaluated from Equation 1.5, while the irradiation corresponds to $G = \sigma T_{sur}^4$. Hence

$$E = \varepsilon\sigma T_s^4 = 0.8(5.67 \times 10^{-8}\ \text{W/m}^2\cdot\text{K}^4)\,(473\ \text{K})^4 = 2270\ \text{W/m}^2$$

$$G = \sigma T_{sur}^4 = 5.67 \times 10^{-8}\ \text{W/m}^2\cdot\text{K}^4\,(298\ \text{K})^4 = 447\ \text{W/m}^2$$

2. Heat loss from the pipe is by convection to the room air and by radiation exchange with the walls. Hence, $q = q_{conv} + q_{rad}$ and from Equation 1.10, with $A = \pi DL$,

$$q = h(\pi DL)(T_s - T_\infty) + \varepsilon(\pi DL)\sigma(T_s^4 - T_{sur}^4)$$

The heat loss per unit length of pipe is then

$$q' = \frac{q}{L} = 15\ \text{W/m}^2\cdot\text{K}(\pi \times 0.07\ \text{m})(200 - 25)°\text{C}$$

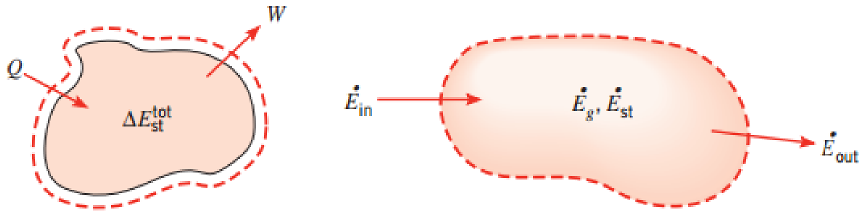
$$+\ 0.8(\pi \times 0.07\ \text{m})\,5.67 \times 10^{-8}\ \text{W/m}^2\cdot\text{K}^4\,(473^4 - 298^4)\ \text{K}^4$$

$$q' = 577\ \text{W/m} + 421\ \text{W/m} = 998\ \text{W/m} \qquad \triangleleft$$

Conservation of Energy Principles

- According to first low of Thermodynamics, for a closed system (a region of fixed mass), there are only two ways of energy transfer: heat transfer through the boundaries and work done on or by the system. This leads to the following statement of the first law for a closed system:

$$\Delta E_{st}^{tot} = Q - W$$



(a) (b)

FIGURE 1.7 Conservation of energy: (*a*) for a closed system over a time interval and (*b*) for a control volume at an instant.

$$\Delta E_{st} = E_{in} - E_{out} + E_g$$

$$\dot{E}_{st} \equiv \frac{dE_{st}}{dt} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_g$$

The rate of increase of thermal and mechanical energy stored in the control volume must equal the rate at which thermal and mechanical energy enters the control volume, minus the rate at which thermal and mechanical energy leaves the control volume, plus the rate at which thermal and mechanical energy is generated within the control volume.