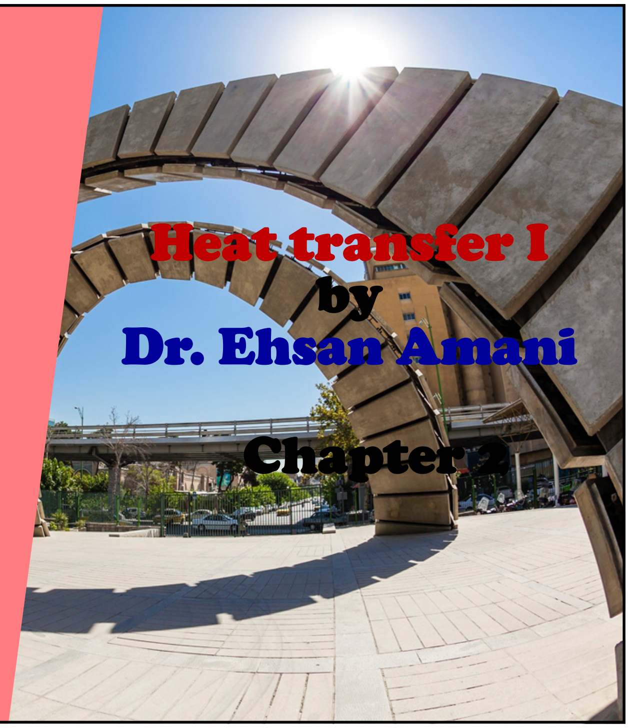
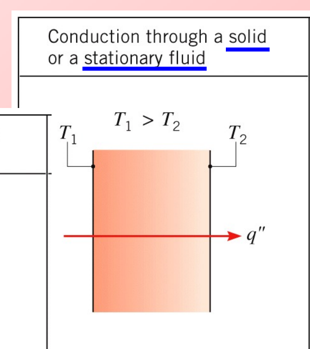


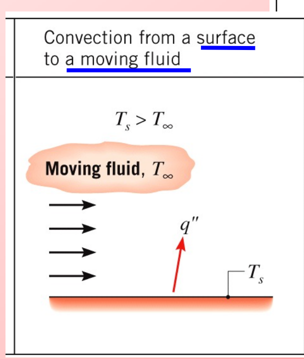
Heat transfer I
by
Dr. Ehsan Amani

Chapter 2

1.2 Heat transfer

- **Definition:**
  - Thermal energy in transit due to a temperature difference
- **Modes:**
  - Through material medium:
    1. Conduction or heat diffusion:
    2. Convection:

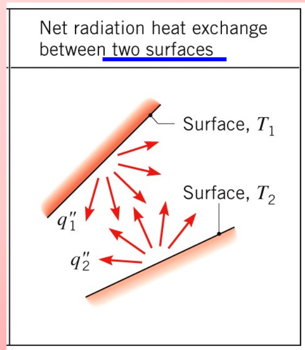




Chapter 2 By E. Amani

1.2 Heat transfer

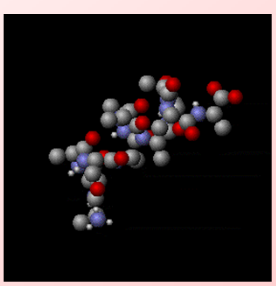
- **Definition:**
  - Thermal energy in transit due to a temperature difference
- **Modes:**
  - Through material medium:
    1. Conduction or heat diffusion:
    2. Convection:
  - Without material medium:
    3. Radiation:



Chapter 2 By E. Amani

2.2 Conduction

- **Physical interpretation:**
  - Heat transfer in a medium due to the random motion of its, molecules, atoms, and/or electrons (heat diffusion)
  - Needs no bulk (macroscopic) mass motion
  - The sole mechanism of heat transfer in solids and stagnant fluids (neglecting volumetric radiation in gasses)



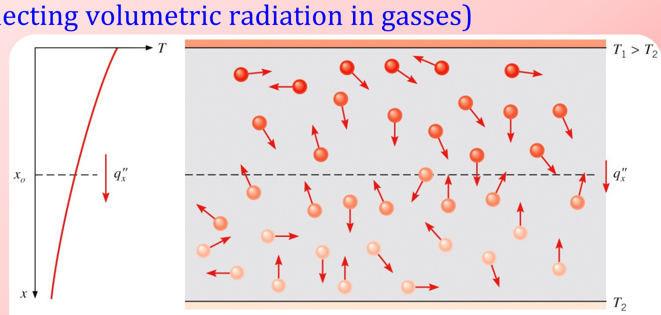


Figure 1.2

Chapter 2 By E. Amani

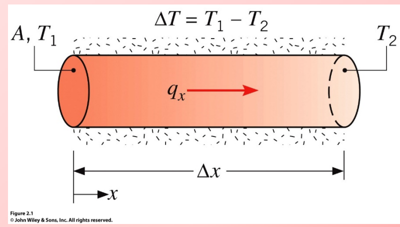
2.2 Conduction

- **Heat transfer rate (macroscopic point of view):**
  - For a 1D, steady problem:

Correct direction

$$q_x \propto A\left[\frac{-\overbrace{(T_2 - T_1)}^{\Delta T}}{\Delta x}\right]$$

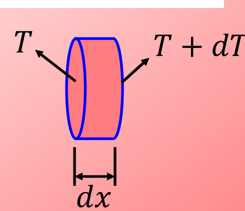
Heat transfer rate in the x-direction (W)



$$q_x'' = \frac{q_x}{A} \propto -\frac{\Delta T}{\Delta x} \qquad (1.2)$$

Heat flux in the x-direction (W/m^2)

$$q_x'' \propto -\frac{dT}{dx}$$



Chapter 2 By E. Amani

2.2 Conduction

- **Heat transfer rate (macroscopic point of view):**
  - For a 1D, steady problem:

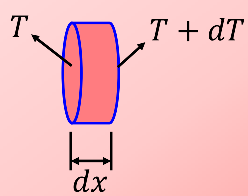
slope of $\mathrm{T-x}$

$$q_x'' = -k\frac{dT}{dx} \qquad (2.2)$$

$\boxed{\text{Fourier law}}$

Thermal conductivity $\left(\frac{W}{m.K}\right)$

$f(\text{material}, T, p)$



Chapter 2 By E. Amani

2.2 Conduction

- **Heat transfer rate (macroscopic point of view):**
  - For a 1D, steady problem:
    - $+$ Pure conduction
    - $+$ Homogeneous material
    - $\Longrightarrow$ Linear temperature profile (to be proved later)

$$q_x''(x) = -k\frac{dT}{dx} = q_x'' = -k\frac{\Delta T}{\Delta x} =$$

$$q_x'' = -k\frac{(T_2 - T_1)}{L} \quad (3.2)$$

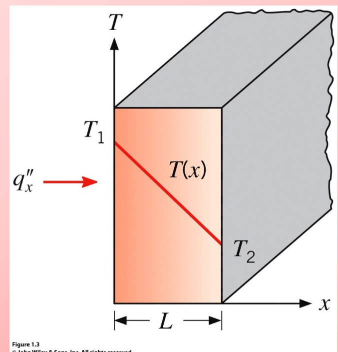


Figure 1.3
© John Wiley & Sons, Inc. All rights reserved.

Chapter 2 By E. Amani

3.2 Convection

- **Physical interpretation:**
  - Convention: from a solid surface to fluid flow over a surface
  - Mechanism: conduction + advection (bulk mass transport)
  - Consider a boundary layer:

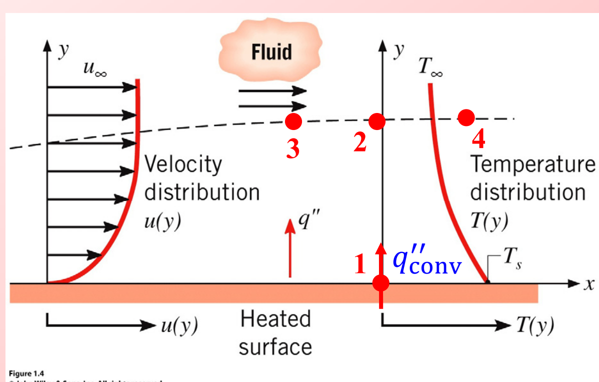


Figure 1.4
© John Wiley & Sons, Inc. All rights reserved.

Chapter 2 By E. Amani

3.2 Convection

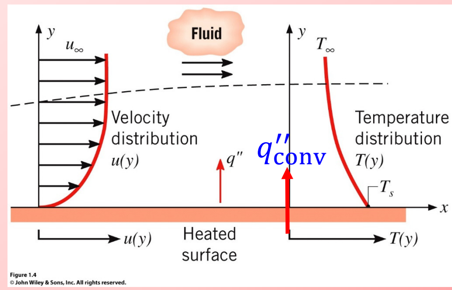
- **Heat transfer rate:**
  - Consider a boundary layer:

$$q''_{\text{conv}} = q''_{\text{cond},y}(y=0) =$$

$$-k_f \left.\frac{dT_f}{dy}\right|_{y=0} = -k_s \left.\frac{dT_s}{dy}\right|_{y=0}$$

Complicated

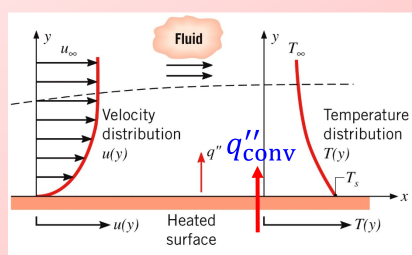
$\boldsymbol{f}$**(fluid and solid material, geometry, flow details,** $\boldsymbol{T}$**, …)**



3.2 Convection

- **Heat transfer rate:**
  - Consider a boundary layer:

$$q''_{\text{conv}} = -k_f \left.\frac{dT_f}{dy}\right|_{y=0} = -k_s \left.\frac{dT_s}{dy}\right|_{y=0} \quad (4.2)$$



  - Newton's law of cooling:

$$q''_{\text{conv}} = h(T_s - T_\infty) \quad (5.2) \xrightarrow{(4.2)} h = -\frac{k_f}{(T_s - T_\infty)} \left.\frac{dT_f}{dy}\right|_{y=0} = -\frac{k_s}{(T_s - T_\infty)} \left.\frac{dT_s}{dy}\right|_{y=0} \quad (6.2)$$

Convection heat transfer coefficient $\left(\frac{W}{m^2.K}\right)$

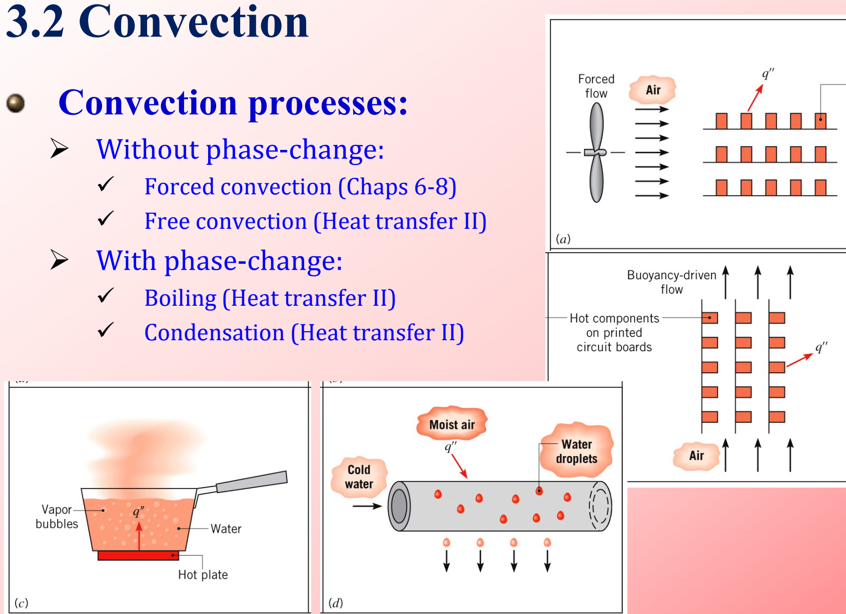
Given in Chaps 2-5

$\boldsymbol{f}$**(fluid and solid material, geometry, flow details,** $\boldsymbol{T}$**, …)**

Calculated in Chaps 6-8

3.2 Convection

- **Convection processes:**
  - Without phase-change:
    - ✓ Forced convection (Chaps 6-8)
    - ✓ Free convection (Heat transfer II)
  - With phase-change:
    - ✓ Boiling (Heat transfer II)
    - ✓ Condensation (Heat transfer II)



Chapter 2 By E. Amani

3.2 Convection

- **Convection processes:**
  - Without phase-change:
    - ✓ Forced convection (Chaps 6-8)
    - ✓ Free convection (Heat transfer II)
  - With phase-change:
    - ✓ Boiling (Heat transfer II)
    - ✓ Condensation (Heat transf

TABLE 1.1 Typical values of the convection heat transfer coefficient

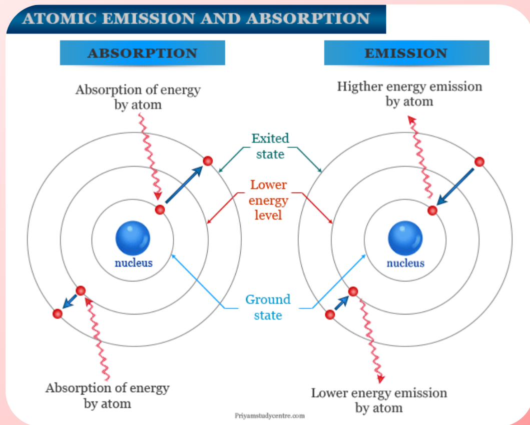
Process	h $(W/m^2 \cdot K)$
Free convection	
Gases	2–25
Liquids	50–1000
Forced convection	
Gases	25–250
Liquids	100–20,000
Convection with phase change	
Boiling or condensation	2500–100,000

Table 1.1

Chapter 2 By E. Amani

4.2 Radiation

- **Physical interpretation:**
  - The change of electron configurations in an atom leads to the emission or absorption of energy



Chapter 2 By E. Amani

4.2 Radiation

- **Physical interpretation:**
  - The change of electron configurations in an atom leads to the emission or absorption of energy
  - The origin needs a material medium but the transfer does not
  - The emissive power depends on the material temperature
  - Modeling (Microscopic):
    - ✓ Wave viewpoint: Electromagnetic waves
    - ✓ Quantum viewpoint: Photons
  - Modeling (Macroscopic):
    - ✓ Radiation between surfaces (opaque solids and liquids): Chaps 9 and 10
    - ✓ Volumetric radiation (gases and semi-transparent liquids and solids): Heat transfer II

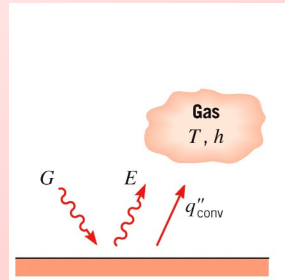
Chapter 2 By E. Amani

4.2 Radiation

- **Heat transfer rate:**

G: irradiation $\left(\frac{W}{m^2}\right)$

E: emissive power $\left(\frac{W}{m^2}\right)$



➢ For a black body (Quantum mechanics):

$$\underbrace{E_b = \sigma T_s^4}_{\sigma:\ \text{Stefan-Boltzmann constant}} \quad (7.2) \qquad \sigma = 5.67 \times 10^{-8}\ \frac{W}{m^2 K^4}$$

Stefan-Boltzmann constant

➢ Generally,

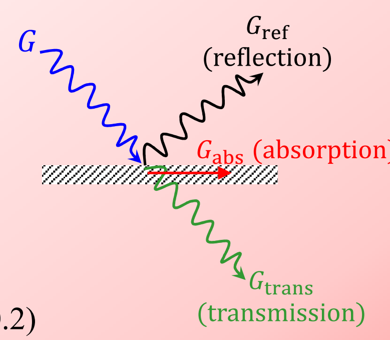
$$E = \varepsilon E_b = \varepsilon \sigma T_s^4 \quad (8.2)$$

Emissivity $(-)$ f(**surface material and finish**) → $\boxed{\textbf{Appendix A}}$

$0 < \varepsilon < 1$

4.2 Radiation

- **Heat transfer rate:**



$$G_{\text{abs}} = \alpha G \qquad (9.2)$$

Absorptivity $(-)$

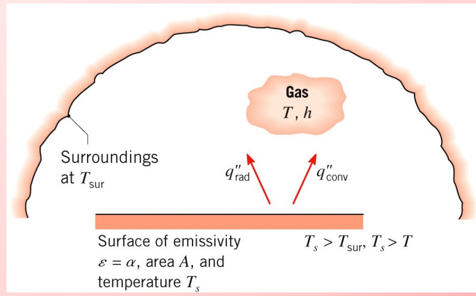
$0 < \alpha < 1$

$$G = \underbrace{G_{\text{abs}}}_{\alpha G} + \underbrace{G_{\text{ref}} + G_{\text{trans}}}_{(1-\alpha)G} \qquad (10.2)$$

➢ General calculation of G is rather complicated (chaps 9 and 10)

4.2 Radiation

- **Heat transfer rate:**
  - For a large surface with temperature T_{sur} surrounding a small surface, G for the small surface is given by (proof: chapter 9):

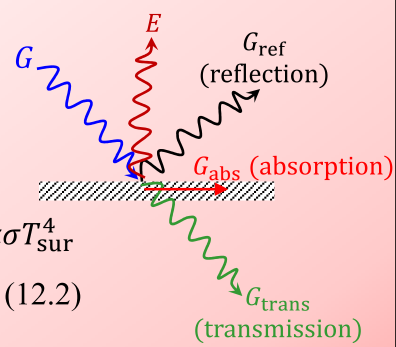


$$G = \sigma T_{sur}^4 \quad (11.2)$$

Chapter 2 By E. Amani

4.2 Radiation

- **Heat transfer rate:**



$q''_{rad} = E - \alpha G =$

Net radiation emission $\quad q''_{rad} = E - \alpha G = \varepsilon\sigma T_s^4 - \alpha\sigma T_{sur}^4 \quad (12.2)$

  - For a gray surface ($\alpha = \varepsilon$):

$$q''_{rad} = \varepsilon\sigma(T_s^4 - T_{sur}^4) \quad (13.2)$$

$$q''_{rad} = h_r(T_s - T_{sur}) \quad (14.2) \qquad h_r = \varepsilon\sigma(T_s + T_{sur})(T_s^2 + T_{sur}^2) \quad (15.2)$$

  - Attention: Use temperatures in the Kelvin unit for problems involving radiation!

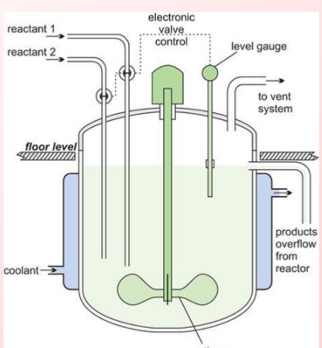
Chapter 2 By E. Amani

5.2 Thermal energy equation

Lecture Notes

6.2 Sample problems

Chemical reactor cooling



6.2 Sample problems

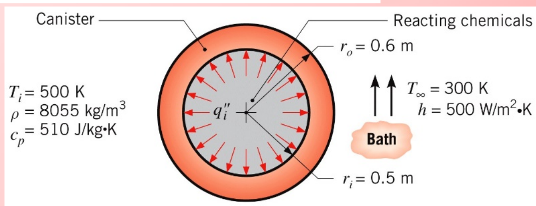
Chemical reactor cooling

1.64 A spherical, stainless steel (AISI 302) canister is used to store reacting chemicals that provide for a uniform heat flux q_i'' to its inner surface. The canister is suddenly submerged in a liquid bath of temperature $T_\infty < T_i$, where T_i is the initial temperature of the canister wall.

(a) Assuming negligible temperature gradients in the canister wall and a constant heat flux q_i'', develop an equation that governs the variation of the wall temperature with time during the transient process. What is the initial rate of change of the wall temperature if $q_i'' = 10^5$ W/m^2?

(b) What is the steady-state temperature of the wall?

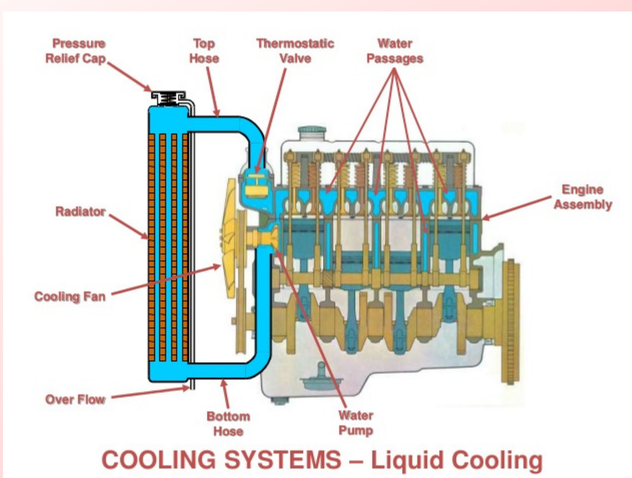
(c) Determine the minimum h to prevent the canister from melting.

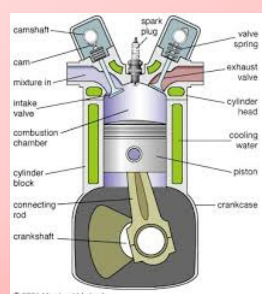


Chapter 2 By E. Amani

6.2 Sample problems

Internal combustion engines cooling system



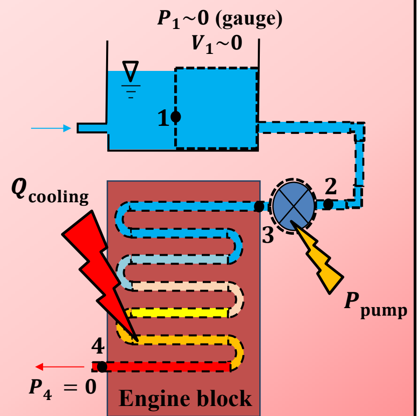


Chapter 2 By E. Amani

6.2 Sample problems

Internal combustion engines cooling system

Ex. A diesel engine cooling system is composed of a large water tank and a pump with the power of $P_{\text{pump}} = 248.5$ W, mechanical efficiency of 50%, and the mass flow rate of $\dot{m} = 2.4$ kg/s. Calculate the heat absorbed by the cooling system from the engine, $\dot{Q}_{\text{cooling}}$, if the water temperature rise across the engine is $\Delta T = T_4 - T_1 = 15$ °C. The system is assumed adiabatic and with negligible head loss between sections 1 and 3. The pipe diameter at sections 2,3, and 4 is 5 cm. $(\rho_w = 997\ kg/m^3,\ c_w = 4179\ J/Kg.K)$



Chapter 2 **By E. Amani**

6.2 Sample problems

Electronic device cooling

Chapter 2 **By E. Amani**

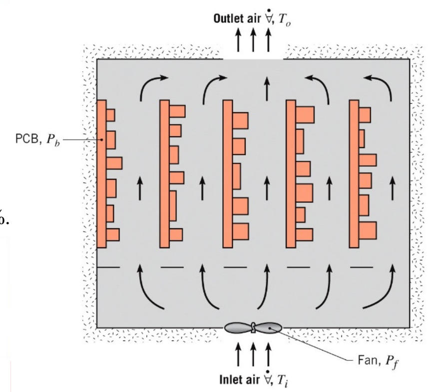
6.2 Sample problems

Electronic device cooling

1.70 A computer consists of an array of five printed circuit boards (PCBs), each dissipating $P_b = 20$ W of power. Cooling of the electronic components on a board is provided by the forced flow of air, equally distributed in passages formed by adjoining boards, and the convection coefficient associated with heat transfer from the components to the air is approximately $h = 200$ W/m$^2 \cdot$K. Air enters the computer console at a temperature of $T_i = 20$°C, and flow is driven by a fan whose power consumption is $P_f = 25$ W. The fan efficiency is 70%.

(a) If the temperature rise of the airflow, $(T_o - T_i)$, is not to exceed 15°C, what is the minimum allowable volumetric flow rate $\dot{\forall}$ of the air? The density and specific heat of the air may be approximated as $\rho = 1.189$ kg/m^3 and $c_p = 1007$ J/kg$\cdot$K, respectively.

(b) The component that is most susceptible to thermal failure dissipates 1 W/cm^2 of surface area. To minimize the potential for thermal failure, where should the component be installed on a PCB? What is its surface temperature at this location?



Problem 1.70

6.2 Sample problems

Cryogenics: Phase change

1.49 Liquid oxygen, which has a boiling point of 90 K and a latent heat of vaporization of 214 kJ/kg, is stored in a spherical container whose outer surface is of 500-mm diameter and at a temperature of −10°C. The container is housed in a laboratory whose air and walls are at 25°C.

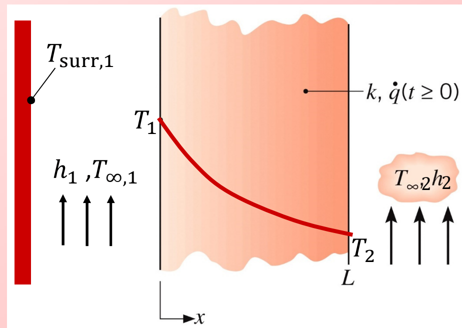
(a) If the surface emissivity is 0.20 and the heat transfer coefficient associated with free convection at the outer surface of the container is 10 W/m$^2 \cdot$K, what is the rate, in kg/s, at which oxygen vapor must be vented from the system?

$\rho_f = 1141\ kg/m^3, \rho_g = 1.429\ kg/m^3$

6.2 Sample problems

Analysis

The temperature distribution along a wall of thickness L is illustrated in the figure. There is no thermal energy generation within the wall. Does the wall absorb or release thermal energy? Why?



The end of chapter 2