Class: 3rd
Subject: Heat transfer
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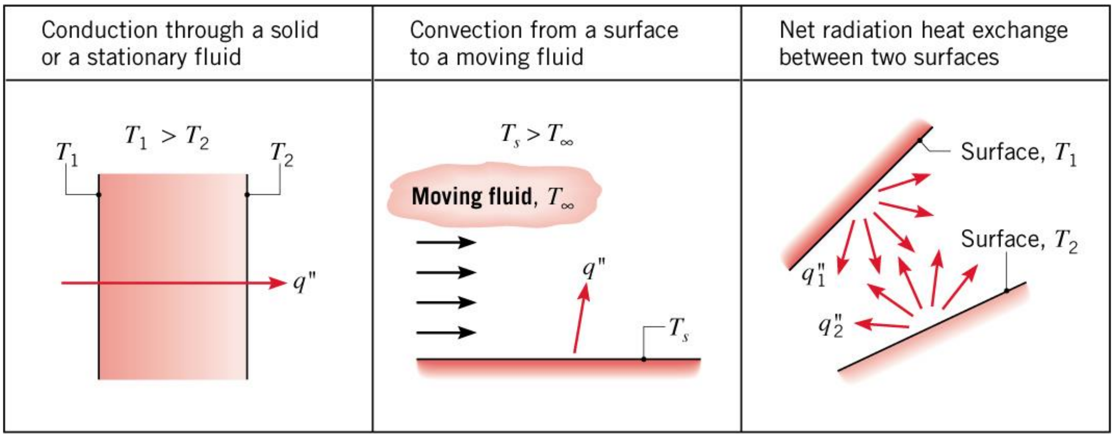
What is heat transfer ?

It is that science which seeks to predict the energy transfer that may take place between atoms and molecules that comprise matter as a result of a temperature difference

Modes of Heat Transfer



Conduction: Heat transfer in a solid or a stationary fluid (gas or liquid) due to the random motion of its constituent atoms, and /or electrons. (e.g., gas: molecular collision, crystal: phonon or lattice vibration, metals: free electron flow)

Convection: Heat transfer due to the combined influence of bulk and random motion for fluid (particle) flow over a surface.

Radiation: Energy that is emitted by matter due to changes in the electron configurations of its atoms or molecules and is transported as electromagnetic waves (or photons).

- Conduction and convection require the presence of temperature variations in a material medium.
- Although radiation originates from matter, its transport does not require a material medium and occurs most efficiently in vacuum

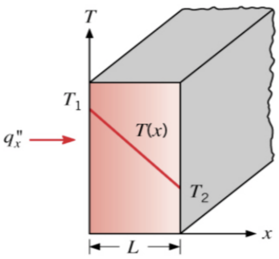
Conduction

Fourier's Law:

$$q'' = -k\nabla T$$

Heat flux (W/m^2); Thermal conductivity ($W/m \cdot K$); Temperature gradient (°C/m or K/m)

1-D, steady conduction across a plane wall of constant k



Heat flux (W/m^2):

$$q''_x = -k\frac{dT}{dx} = -k\frac{T_2 - T_1}{L} = k\frac{T_1 - T_2}{L}$$

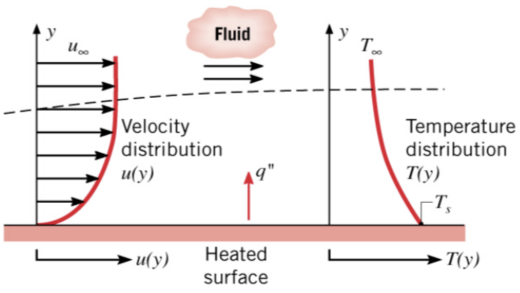
Heat transfer rate (W):

$$q_x = q''_x \cdot A$$

Thermal conductivities [W/m-K]	
Cu = 401	Aerogel = 0.023
Al = 237	Air = 0.0267
SS 302 = 15	Water (l) = 0.58
Diamond = 2300	Water (v) = 0.0181

Convection

Relation of convection to flow over a surface and development of velocity and thermal boundary layers:



Newton's law of cooling:

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

h: Convection heat transfer coefficient ($W/m^2 - K$)

Order of magnitude of h [W/m²-K]			
Water		Air	
Natural Convection	< 1,000	Natural Convection	< 25
Forced Convection	< 10,000	Forced Convection	< 200
Boiling	< 100,000		

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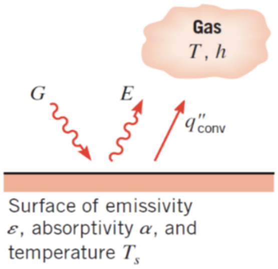
Radiation

Heat transfer at a gas/surface interface involves radiation Emission (E) from the surface and may also involve the absorption of radiation incident from the surroundings (irradiation, G), as well as convection (if $T_s \neq T_\infty$).



Energy outflow due to emission (E):

$$E = \varepsilon E_b, \qquad E_b = \sigma T_s^4 \text{ (Stefan Boltzmann Law)} \tag{1.5}$$

E : Emissive power $\left(\text{W/m}^2\right)$

ε : Surface emissivity $\left(0 \le \varepsilon \le 1\right)$

E_b : Emissive power of a blackbody (the perfect emitter)

σ : Stefan-Boltzmann constant $\left(5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4\right)$

Energy absorption due to irradiation (G):

$$G_{abs} = \alpha G \tag{1.6}$$

G_{abs} :Absorbed incident radiation (W/m^2)

α : Surface absorptivity $\left(0 \le \alpha \le 1\right)$

G : Irradiation $\left(\text{W/m}^2\right)$

Alternatively,

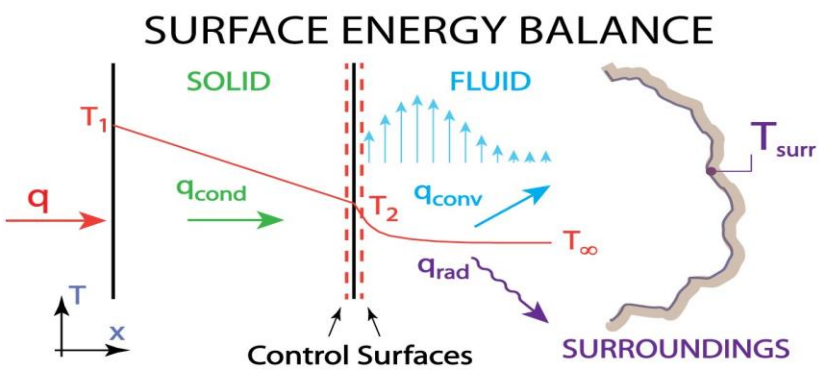
$$q''_{rad} = h_r\left(T_s - T_{sur}\right) \tag{1.8}$$

h_r: Radiation heat transfer coefficient $\left(\text{W/m}^2\cdot\text{K}\right)$

$$h_r = \varepsilon\sigma\left(T_s + T_{sur}\right)\left(T_s^2 + T_{sur}^2\right) \tag{1.9}$$

For combined convection and radiation,

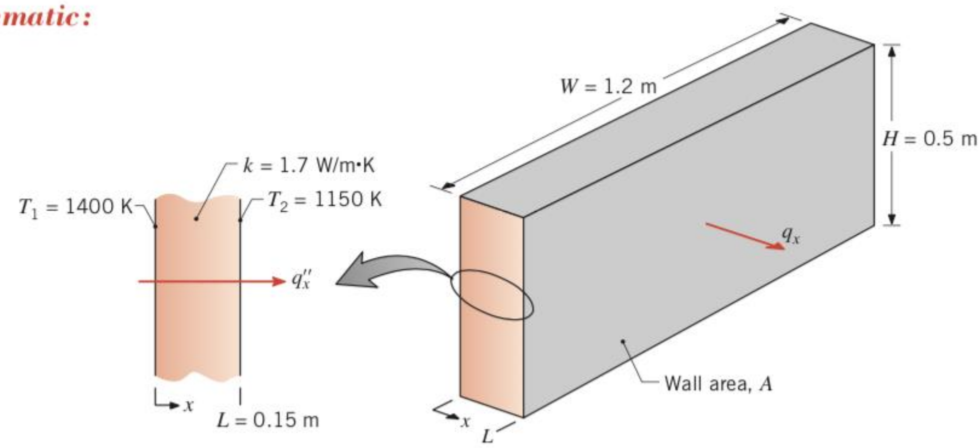
$$q'' = q''_{conv} + q''_{rad} = h\left(T_s - T_\infty\right) + h_r\left(T_s - T_{sur}\right) \tag{1.10}$$



Example: 1

The wall of an industrial furnace is constructed from 0.15-m-thick fireclay brick having a thermal conductivity of 1.7 W/m . K. Measurements made during steady-state operation reveal temperatures of 1400 and 1150 K at the inner and outer surfaces, respectively. What is the rate of heat loss through a wall that is 0.5 m X1.2 m on a side

Schematic:



Assumptions:

1. Steady-state conditions.
2. One-dimensional conduction through the wall.
3. Constant thermal conductivity.

Analysis: Since heat transfer through the wall is by conduction, the heat flux may be determined from Fourier's law. Using Equation 1.2, we have

$$q''_x = k\,\frac{\Delta T}{L} = 1.7\ \text{W/m}\cdot\text{K} \times \frac{250\ \text{K}}{0.15\ \text{m}} = 2833\ \text{W/m}^2$$

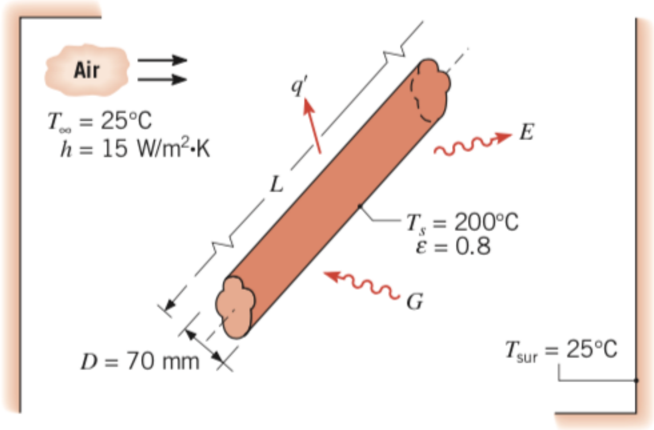
The heat flux represents the rate of heat transfer through a section of unit area, and it is uniform (invariant) across the surface of the wall. The heat loss through the wall of area $A = H \times W$ is then

$$q_x = (HW)\,q''_x = (0.5\ \text{m} \times 1.2\ \text{m})\,2833\ \text{W/m}^2 = 1700\ \text{W} \qquad \triangleleft$$

Example: 2

An uninsulated steam pipe passes through a room in which the air and 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 and irradiation? If the coefficient associated with free convection heat transfer from the surface to the air is 15 W/m^2. K, what is the rate of heat loss from the surface per unit length of pipe

Schematic:



Assumptions:

1. Steady-state conditions.
2. Radiation exchange between the pipe and the room is between a small surface and a much larger enclosure.
3. The surface emissivity and absorptivity are equal.

Analysis:

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

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

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

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

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

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

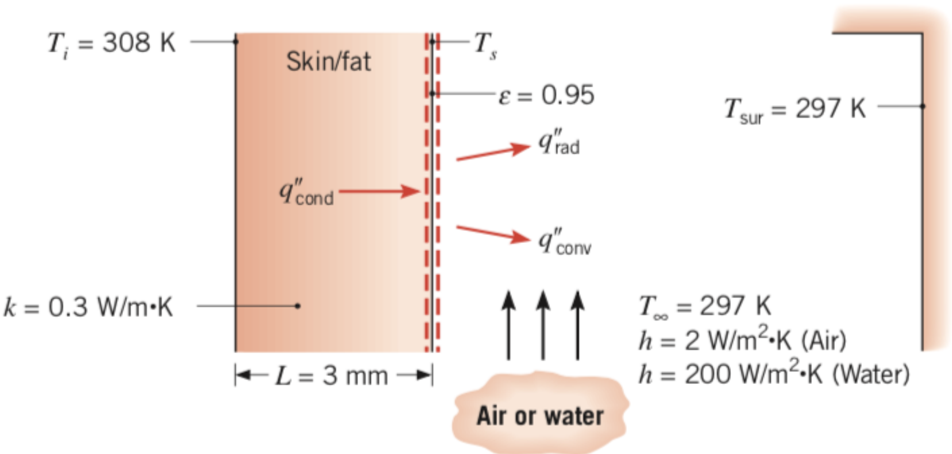
$$q' = 577\ \text{W/m} + 421\ \text{W/m} = 998\ \text{W/m} \quad \triangleleft$$

Example 3:

Humans are able to control their heat production rate and heat loss rate to maintain a nearly constant core temperature of Tc = 37 °C under a wide range of environmental conditions. This process is called *thermoregulation*. From the perspective of calculating heat transfer between a human body and its surroundings, we focus on a layer of skin and fat, with its outer surface exposed to the environment and its inner surface at a temperature slightly less than the core temperature, Ti =35 °C = 308 K. Consider a person with a skin/fat layer of thickness L = 3mm and effective thermal conductivity k= 0.3W/m.K. The person has a surface area A =1.8 m^2 and is dressed in a bathing suit. The radiation heta transfer coefficient is h_r= 5.9 W/m^2.k.

Find out that:

When the person is in still air at $T\infty$ = 297 K, what is the skin surface temperature and rate of heat loss to the environment? Convection heat transfer to the air is characterized by a free convection coefficient of h = 2 W/m^2 . K



Solution:

Energy balance at the skin surface

$$\dot{E}_{in} - \dot{E}_{out} = 0 \qquad q''_{cond} - q''_{conv} - q''_{rad} = 0$$

$$k\frac{T_i - T_s}{L} = h(T_s - T_\infty) + \varepsilon\sigma(T_s^4 - T_{sur}^4)$$

$$k\frac{T_i - T_s}{L} = h(T_s - T_\infty) + \varepsilon\sigma(T_s^4 - T_{sur}^4)$$

Solving for T_s, with $T_{sur} = T_\infty$, we have

$$T_s = \frac{\frac{kT_i}{L} + (h + h_r)T_\infty}{\frac{k}{L} + (h + h_r)}$$

$$T_s = \frac{\dfrac{0.3\ \text{W/m}\cdot\text{K} \times 308\ \text{K}}{3 \times 10^{-3}\,\text{m}} + (2 + 5.9)\ \text{W/m}^2\cdot\text{K} \times 297\ \text{K}}{\dfrac{0.3\ \text{W/m}\cdot\text{K}}{3 \times 10^{-3}\,\text{m}} + (2 + 5.9)\ \text{W/m}^2\cdot\text{K}} = 307.2\ \text{K}$$

The rate of heat loss can be found by evaluating the conduction through the skin/fat layer

$$q_s = kA\frac{T_i - T_s}{L} = 0.3\ \text{W/m}\cdot\text{K} \times 1.8\ \text{m}^2 \times \frac{(308 - 307.2)\ \text{K}}{3 \times 10^{-3}\,\text{m}} = 146\ \text{W}$$

Table 1.2 SI base and supplementary units

Quantity and Symbol	Unit and Symbol
Length (L)	meter (m)
Mass (M)	kilogram (kg)
Amount of substance	mole (mol)
Time (t)	second (s)
Electric current (I)	ampere (A)
Thermodynamic temperature (T)	kelvin (K)
Plane angle[a] (θ)	radian (rad)
Solid angle[a] (ω)	steradian (sr)

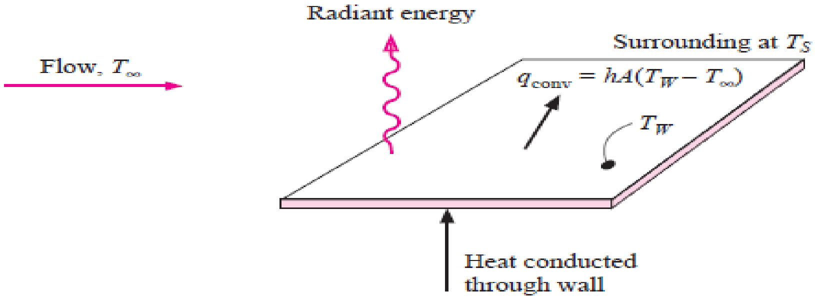
[a]Supplementary unit.

Table 1.3 SI derived units for selected quantities

Quantity	Name and Symbol	Formula	Expression in SI Base Units
Force	newton (N)	$\text{m}\cdot\text{kg/s}^2$	$\text{m}\cdot\text{kg/s}^2$
Pressure and stress	pascal (Pa)	N/m^2	$\text{kg/m}\cdot\text{s}^2$
Energy	joule (J)	$\text{N}\cdot\text{m}$	$\text{m}^2\cdot\text{kg/s}^2$
Power	watt (W)	J/s	$\text{m}^2\cdot\text{kg/s}^3$

Combination of Conduction, Convection and Radiation Heat Transfer

Example (4): Air at 20 ºC blows over a hot plate (50 by 75 cm) through wall is made of carbon steel (2 cm) thick maintained at (250 ºC) and that (300 W) is lost from the plate surface by radiation. Calculate the inside plate temperature The Convection heat transfer coefficient is (25 W/m2. K) and (k = 43 W/m. ºC)



Solution:

$$Q = Q_{conv} + Q_{rad}$$

$$-KA\frac{\Delta T}{\Delta x} = hA(T_s - T_\infty) + Q_{rad}$$

$$\frac{\Delta T}{\Delta x} = \frac{hA(T_s - T_\infty) + Q_{rad}}{-KA}$$

$$\frac{\Delta T}{\Delta x} = \frac{25 * 0.5 * 0.75\ (250 - 20)\ + 300}{-43 * 0.5 * 0.75}$$

$$\frac{\Delta T}{0.2} = -152.5 \Rightarrow \Delta T = -3.05$$

$$\Delta T = T_s - T_i \Rightarrow -3.05 = 250 - T_i$$

$$T_i = 253.05\ ℃$$

Home Work (1):

1- The thermal conductivity of a sheet of rigid, extruded insulation is reported to be (0.029 W/m. K). The measured temperature difference across a (20 mm) thick sheet of the material is ($T1 - T2 = 10$ ºC).

(a) What is the heat flux through a (2 m x 2 m) sheet of the insulation?

(b) What is the rate of heat transfer through the sheet of insulation?

2- One face of a copper plate 3 cm thick is maintained at (400 °C), and the other face is maintained at (100 ºC) and the thermal conductivity for copper is (370 W/m•°C). How much heat is transferred through the plate?

3- Air at (20 °C) blows over a hot plate (50 by 75 cm) maintained at (250 °C). The convection heat-transfer coefficient is (25 W/m2. °C). Calculate the heat transfer.

4- A horizontal steel pipe having a diameter of (5 cm) is maintained at a temperature of 50◦C in a large room where the air and wall temperature are at (20 ºC). The surface emissivity of the steel may be taken as (0.8). If the heat transfer coefficient for free convection with this geometry and air is (6.5 W/m2.°C), calculate the total heat lost by the pipe per unit length.

5- If (3 kW) is conducted through a section of insulating material 0.6 m2 in cross section and (2.5 cm) thick and the thermal conductivity may be taken as (0.2 W/m.°C), compute the temperature difference across the material.

6- A certain insulation has a thermal conductivity of (0.01 W/m.°C). What thickness is necessary to effect a temperature drop of 500 °C for a heat flow of (400 W/m2. K).

7- Two very large parallel planes having surface conditions that very nearly approximate those of a blackbody are maintained at (1100 °C) and (425 °C), respectively. Calculate the heat transfer by radiation between the planes per unit surface area.

8- Boiling water at 1 atm may require a surface heat flux of (170340 W/m2) for a surface temperature of (120 °C). What is the value of the heat transfer coefficient?

9- A flat wall is exposed to an environmental temperature of (38 °C). The wall is covered with a layer of insulation (2.5 cm) thick whose thermal conductivity is (1.4 W/m. °C), and the temperature of the wall on the inside of the insulation is (315 °C). The wall loses heat to the environment by convection. Compute the value of the convection heat-transfer coefficient that must be maintained on the outer surface of the insulation to ensure that the outer-surface temperature does not exceed (41 °C).

10- One side of a plane wall is maintained at (100 °C), while the other side is exposed to a convection environment having (T = 10 °C) and (h = 10 W/m2.°C). The wall has (k = 1.6 W/m.°C) and is (40 cm) thick. Calculate the heat-transfer rate through the wall.

11- A vertical square plate, (30 cm) on a side, is maintained at (50 °C) and exposed to room air at (20 °C). The surface emissivity is (0.8) and the convection heat transfear coefficient is (4.5 W/m2.°C). Calculate the total heat lost by both sides of the plate.

12- A glass window of width (W=1 m) and height (H =2 m) is (5 mm) thick and has a thermal conductivity of (kg= 1.4 W/m.K). If the inner and outer surface temperatures of the glass are (15 °C) and (-20 °C), respectively, on a cold winter day, what is the rate of heat loss through the glass? To reduce heat loss through windows, it is customary to use a double pane construction in which adjoining panes are separated by an air space. If the spacing is (10 mm) and the glass surfaces in contact with the air have temperatures of (10 °C) and (-15 °C), what is the rate of heat loss from a (1 m × 2 m) window? The thermal conductivity of air is (ka= 0.024 W/m.K).