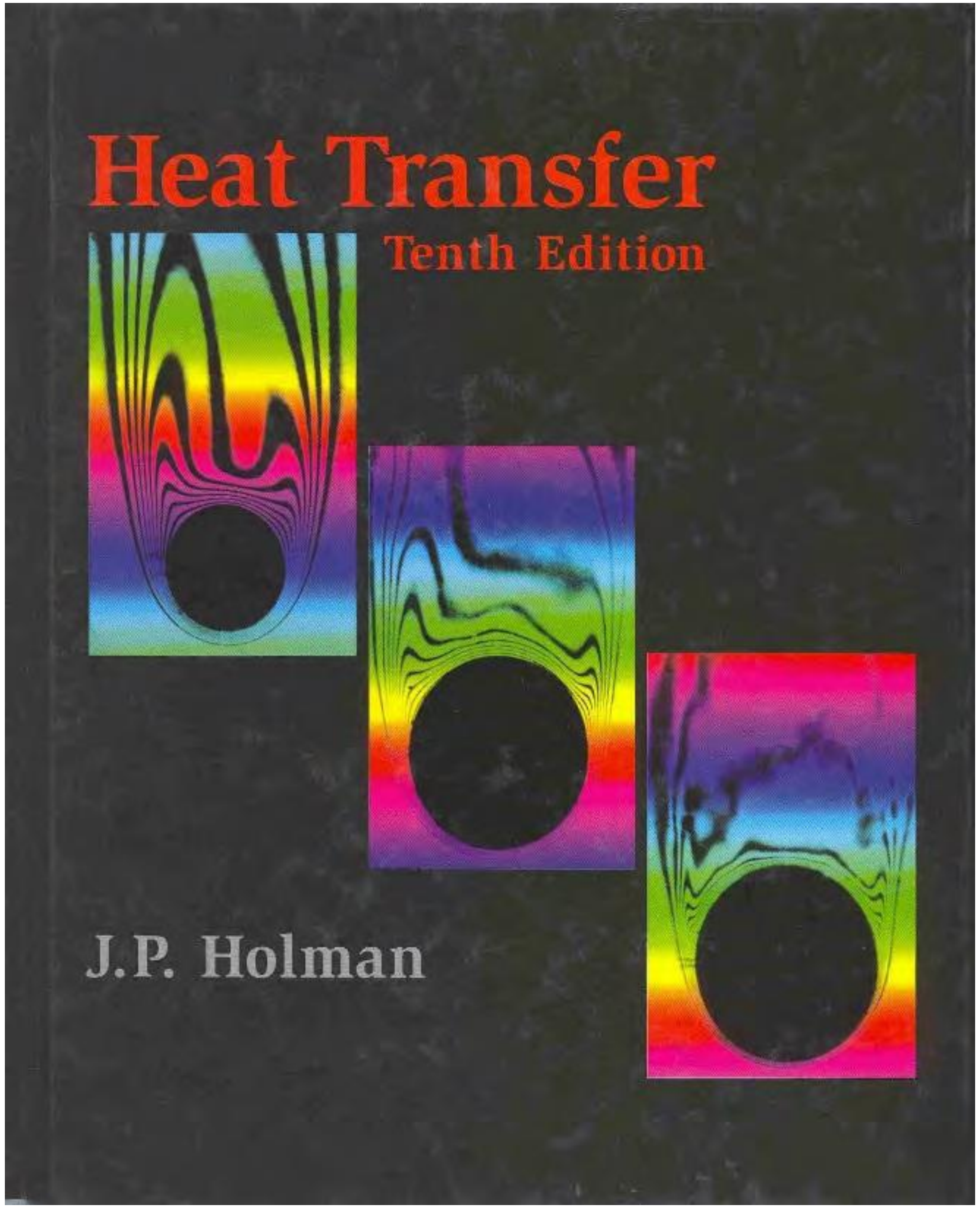


Heat and Mass Transfer

Instructor: Dr. Wisam J. Khudhayer

Textbook

Heat Transfer, Tenth Edition

McGraw Hill

By

J. P. Holman

Chapter One: Introduction

Heat transfer is the science that seeks to predict the energy transfer that may take place between material bodies as a result of a temperature difference.

Difference between heat and temperature

- Temperature is a measure of the amount of energy possessed by the molecules of a substance. It manifests itself as a degree of hotness, and can be used to predict the direction of heat transfer. The usual symbol for temperature is T. The scales for measuring temperature in SI units are the Celsius and Kelvin temperature scales.
- Heat, on the other hand, is energy in transit. Spontaneously, heat flows from a hotter body to a colder one. The usual symbol for heat is Q. In the SI system, common units for measuring heat are the Joule and calorie.

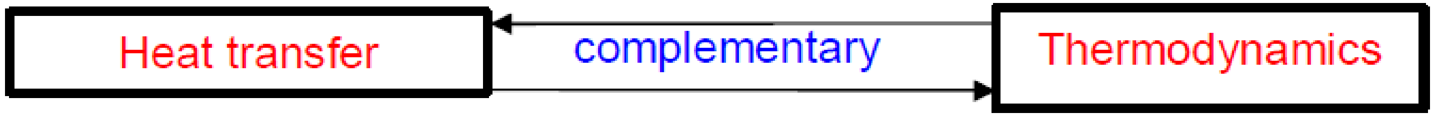
Difference between thermodynamics and heat transfer

Thermodynamics tells us:

- how much heat is transferred (δQ)
- how much work is done (δW)
- final state of the system

Heat transfer tells us:

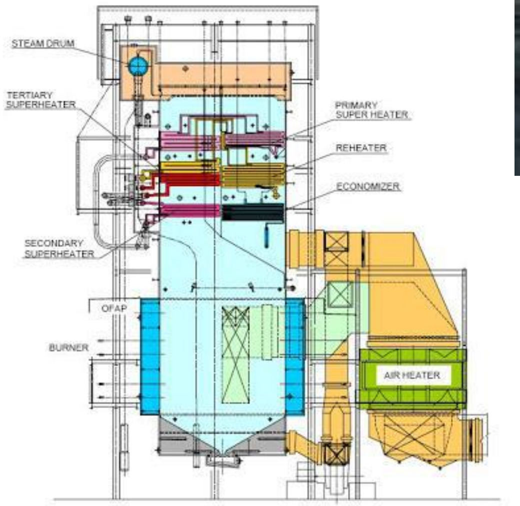
- how (with what modes) δQ is transferred
- at what rate δQ is transferred
- temperature distribution inside the body



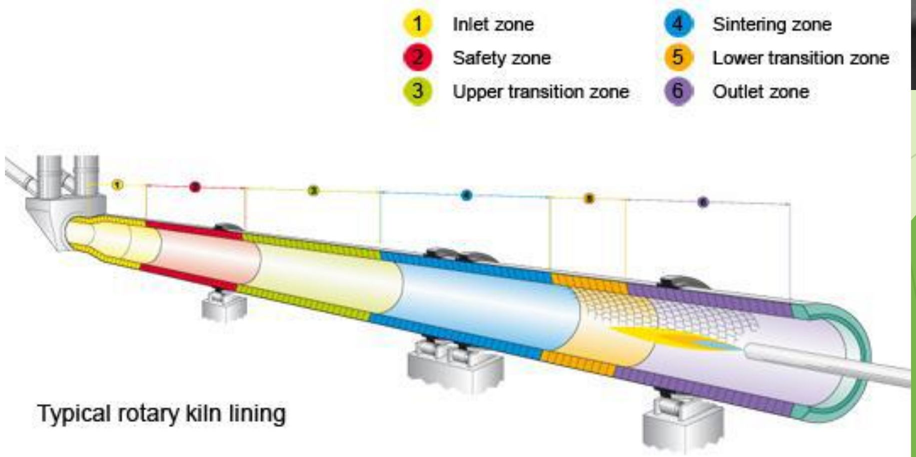
Applications

Power Plants

Al-Musayab
Thermal power plants



Kuffa Cement Factory

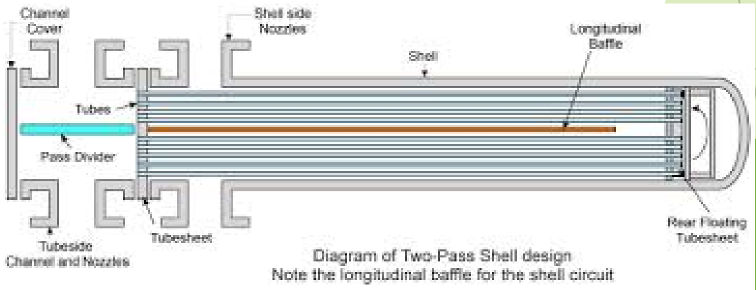


Typical rotary kiln lining

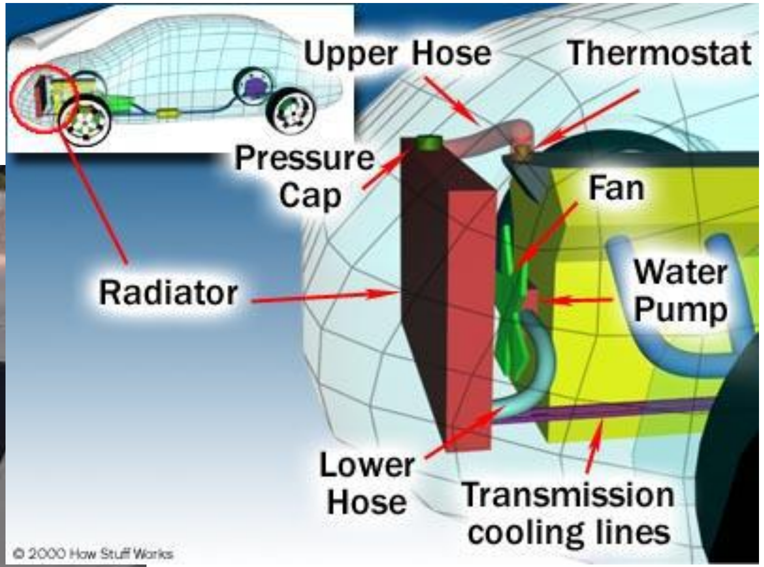
Applications

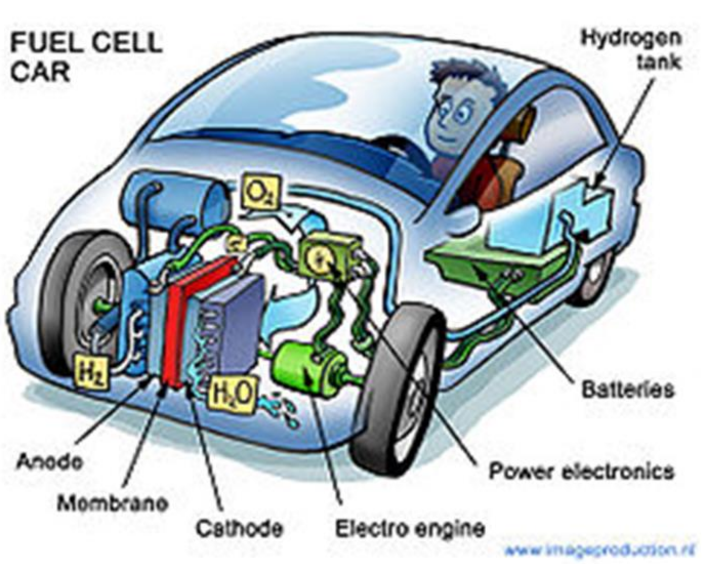
Oil and Gas Industries

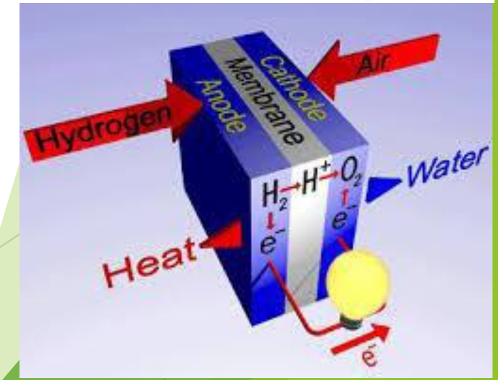
Baiji Oil Refinery



Applications

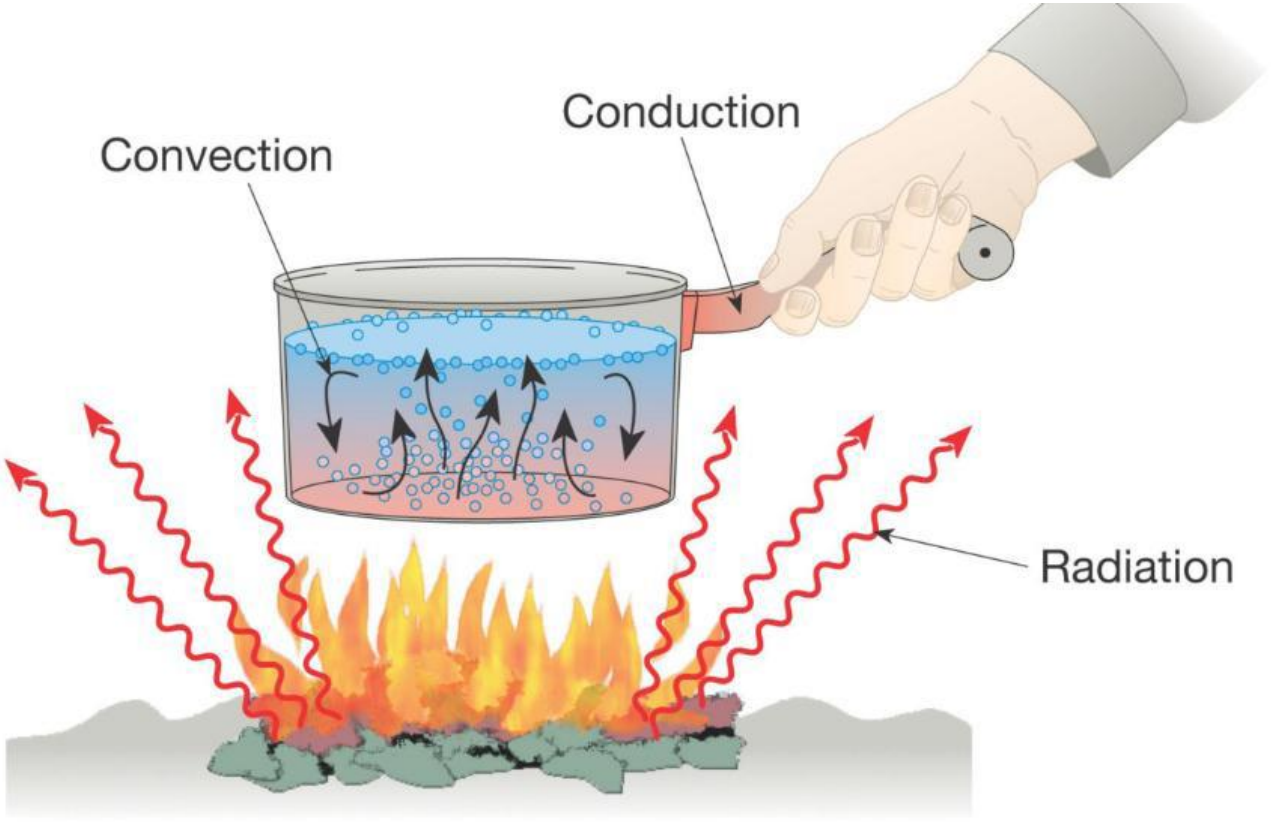






Modes of Heat Transfer

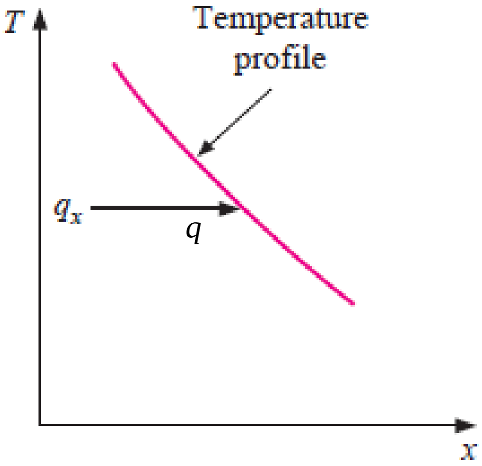
- Conduction
- Convection
- Radiation



Conduction Heat Transfer

An energy transfer across a system boundary due to a temperature difference by the mechanism of intermolecular interactions. Conduction needs matter and does not require any bulk motion of matter.

Figure 1-1 | Sketch showing direction of heat flow.



Fourier's law of conduction

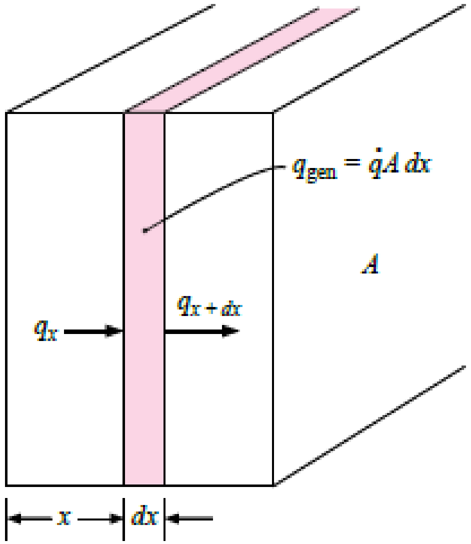
$$\frac{q_x}{A} \sim \frac{\partial T}{\partial x} \qquad q_x = -kA\frac{\partial T}{\partial x}$$

Jean-Baptiste-Joseph Fourier (1768-1830)

where qx is the heat-transfer rate (W), A is the heat transfer area (m2) and $\partial T/\partial x$ is the temperature gradient in the direction of the heat flow (C/m). The positive constant k is called the *thermal conductivity* of the material (W/m C), and the minus sign is inserted so that the second principle of thermodynamics will be satisfied; i.e., heat must flow downhill on the temperature scale, as indicated in the coordinate system of Figure 1-1.

Conduction Heat Transfer

Figure 1-2 | Elemental volume for one-dimensional heat-conduction analysis.



Consider one-dimensional system

Energy Balance

Energy conducted in left face + heat generated within element

= change in internal energy + energy conducted out right face

These energy quantities are given as follows:

$$\text{Energy in left face} = q_x = -kA\frac{\partial T}{\partial x}$$

$$\text{Energy generated within element} = \dot{q}A\,dx$$

$$\text{Change in internal energy} = \rho c A\frac{\partial T}{\partial \tau}dx$$

$$\text{Energy out right face} = q_{x+dx} = -kA\left.\frac{\partial T}{\partial x}\right]_{x+dx}$$

$$= -A\left[k\frac{\partial T}{\partial x} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dx\right]$$

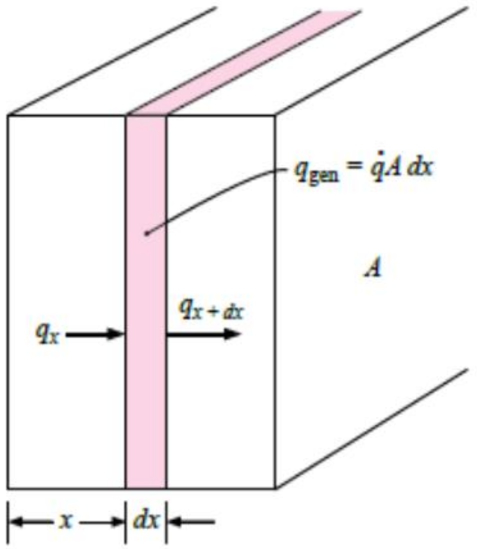


Figure 1-2 | Elemental volume for one-dimensional heat-conduction analysis.

where

$\dot{q}$ = energy generated per unit volume, W/m^3

c = specific heat of material, J/kg · °C

ρ = density, kg/m^3

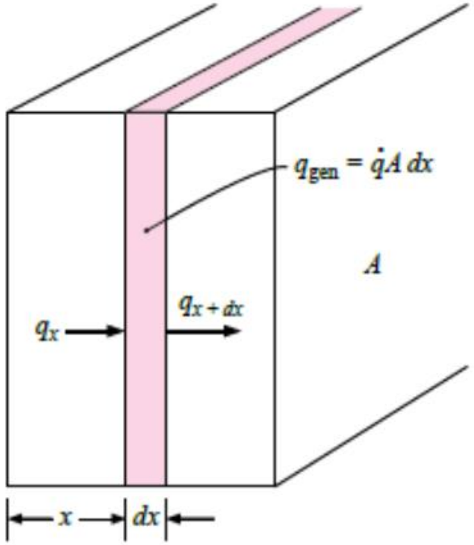
Combining the relations above gives

Heat conduction

$$-kA\frac{\partial T}{\partial x} + \dot{q}A\,dx = \rho cA\frac{\partial T}{\partial t}\,dx - A\left[k\frac{\partial T}{\partial x} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dx\right]$$

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \dot{q} = \rho c\frac{\partial T}{\partial t}$$ (one-dimensional heat-conduction equation)

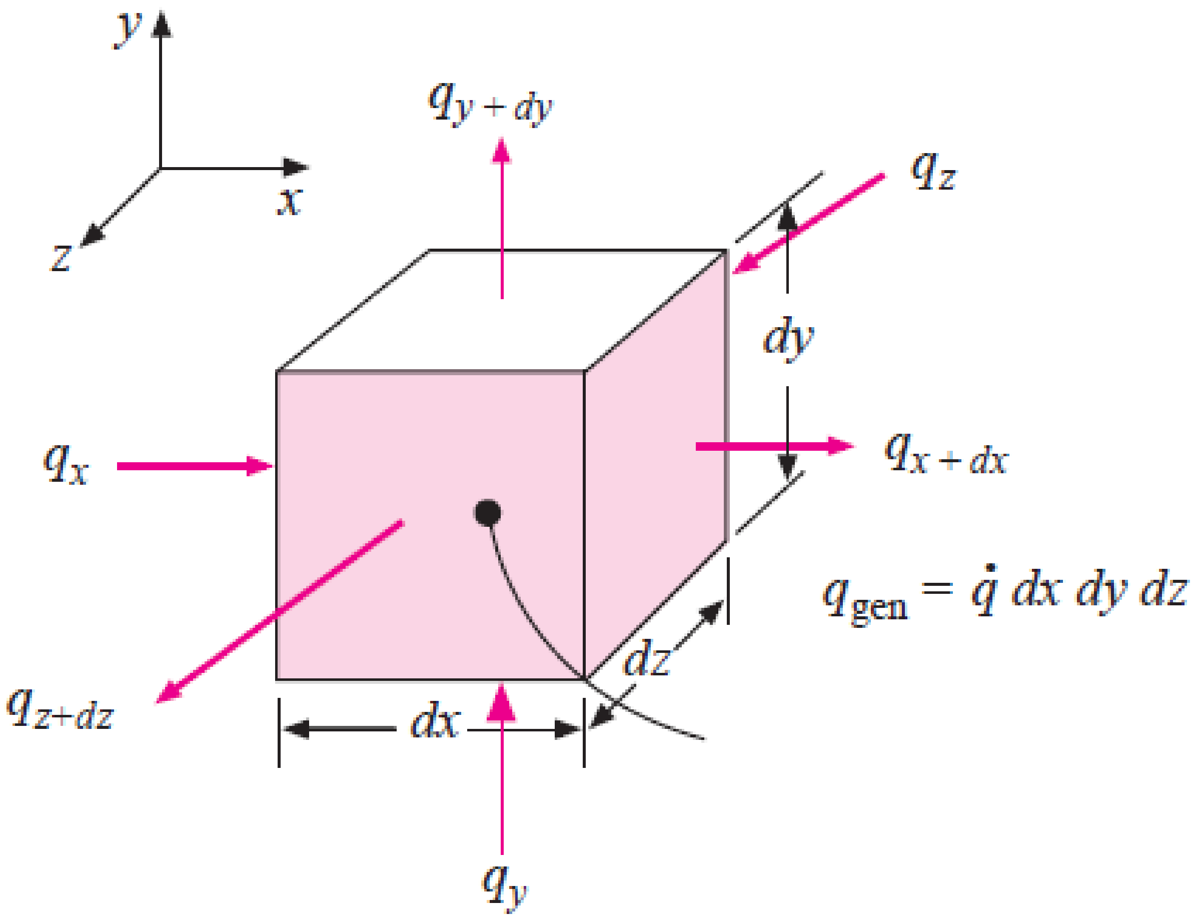
Figure 1-2 | Elemental volume for one-dimensional heat-conduction analysis.



Three-dimensional heat conduction equation

we need consider the heat conducted in and out of a unit volume in all three coordinate directions

$$q_x + q_y + q_z + q_{gen} = q_{x+dx} + q_{y+dy} + q_{z+dz} + \frac{dE}{dt}$$



Heat conduction

$$q_x = -k\,dydz\frac{\partial T}{\partial x}$$

$$q_{x+dx} = -\left[k\frac{\partial T}{\partial x} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dx\right]dydz$$

$$q_y = -k\,dxdz\frac{\partial T}{\partial y}$$

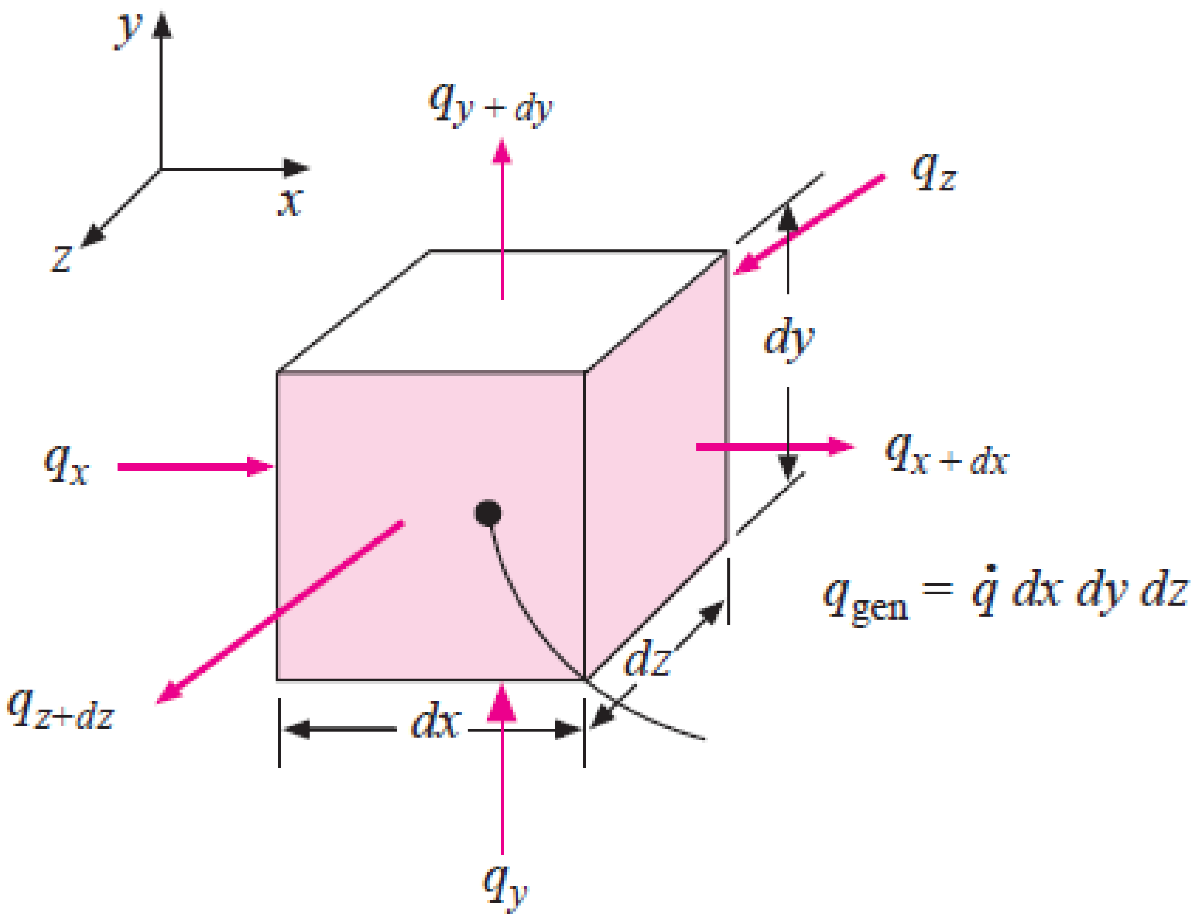
$$q_{y+dy} = -\left[k\frac{\partial T}{\partial y} + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)dy\right]dxdz$$

$$q_z = -k\,dxdy\frac{\partial T}{\partial z}$$

$$q_{z+dz} = -\left[k\frac{\partial T}{\partial z} + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)dz\right]dxdy$$

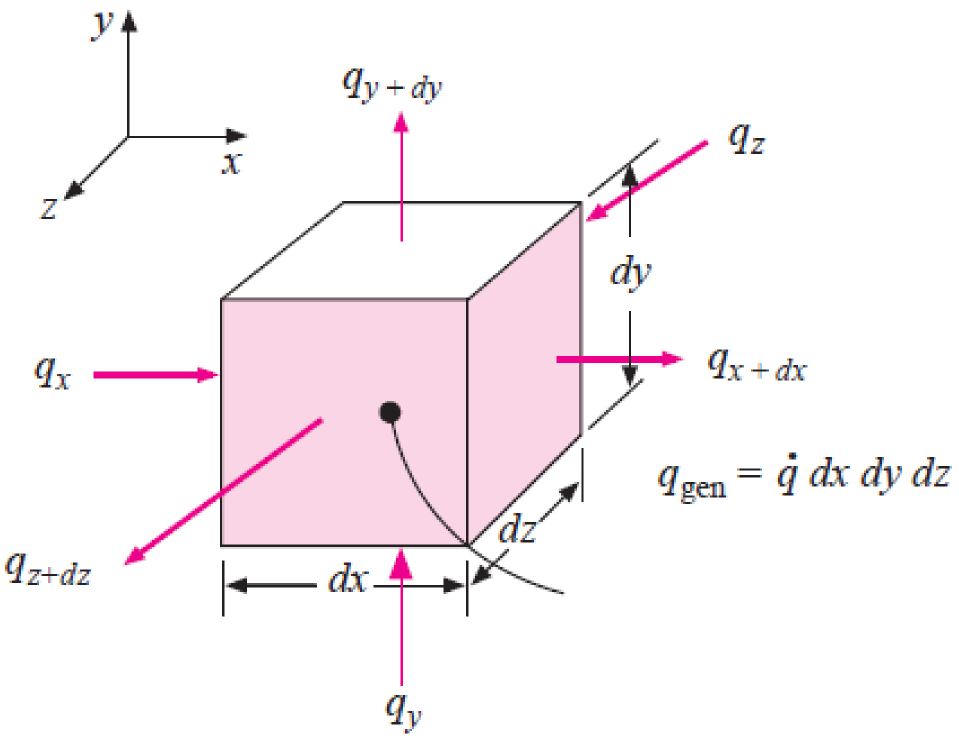
$$q_{gen} = \dot{q}dxdydz$$

$$\frac{dE}{dt} = \rho c\,dxdydz\frac{\partial T}{\partial t}$$



Heat conduction

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c\frac{\partial T}{\partial t} \qquad (1\text{-}3)$$



for constant thermal conductivity Equation (1-3) is written

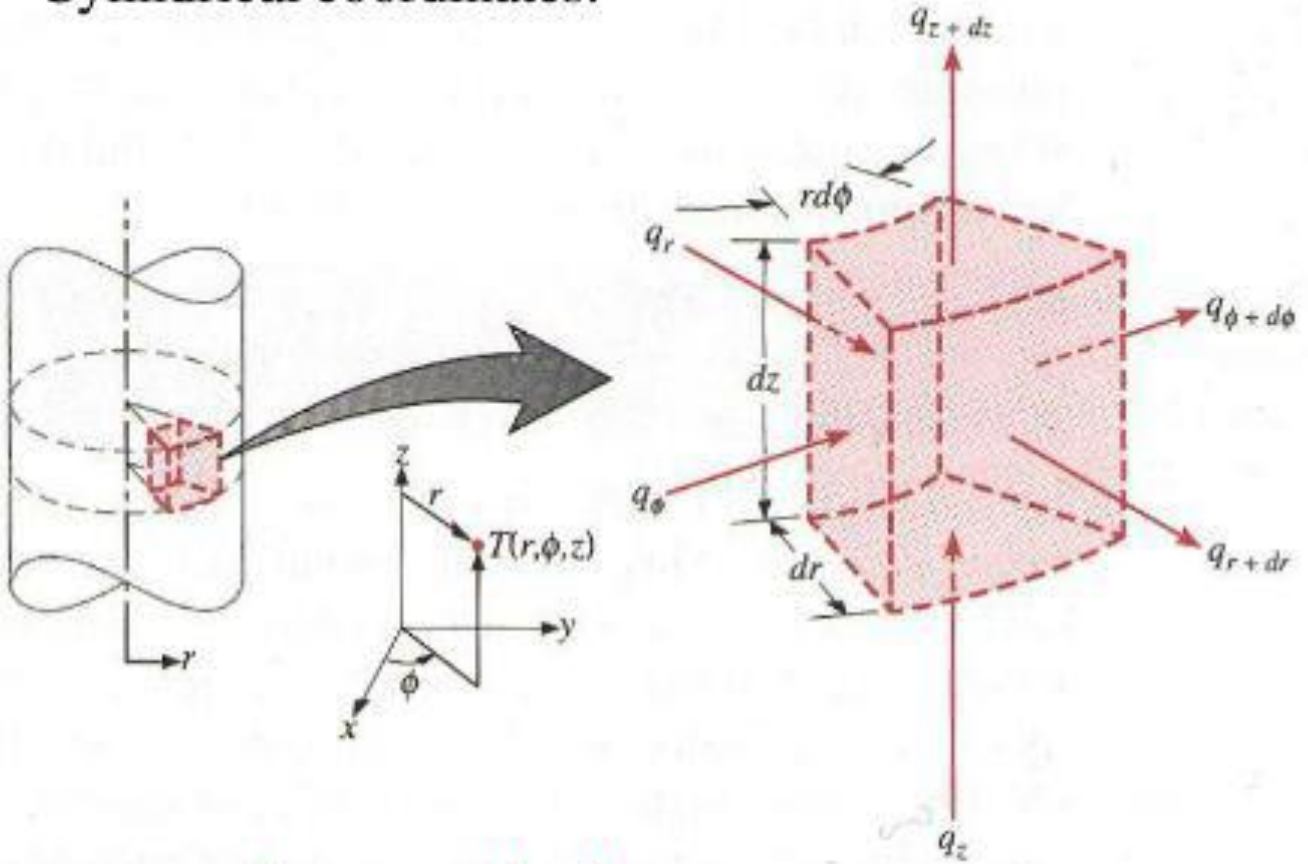
$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{\dot{q}}{k}=\frac{1}{a}\frac{\partial T}{\partial t} \qquad (1\text{-}3a)$$

$$a=\frac{k}{\rho c} \qquad m^2/s$$

thermal diffusivity of the material, the larger the value of a, the faster heat will diffuse through the material. a has units of square meters per second.

Heat conduction

- Cylindrical coordinates:

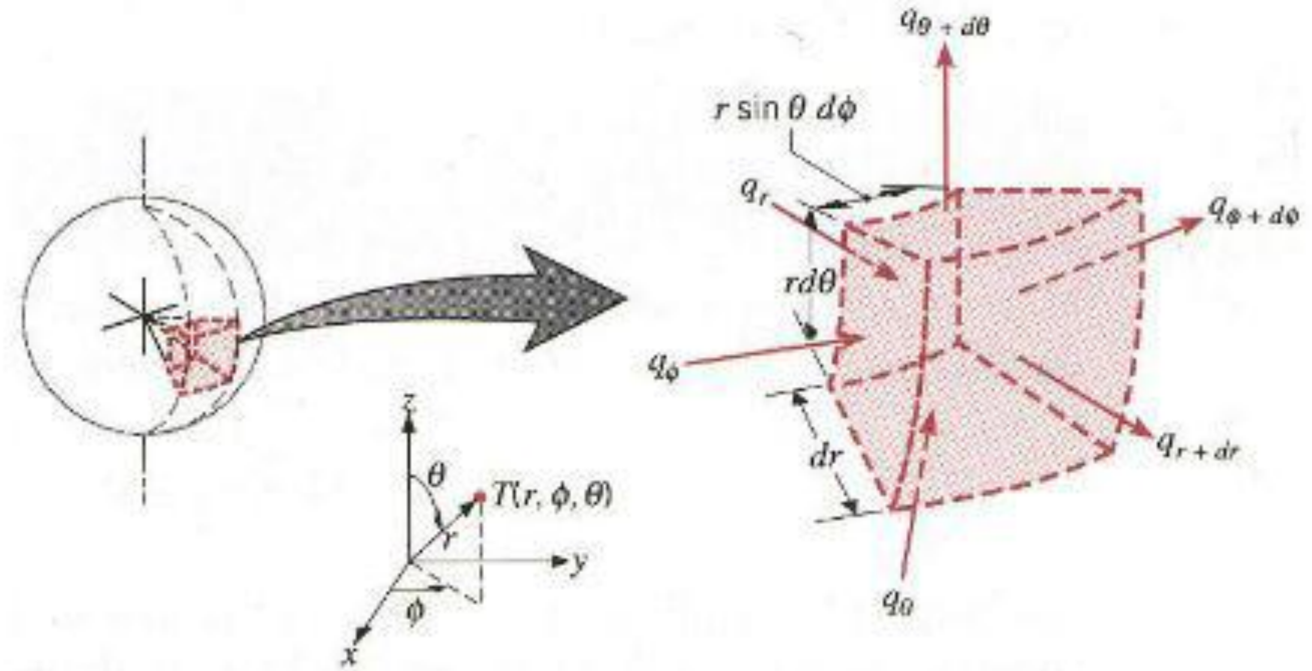


$x = r\cos\phi;\ \ y = r\sin\phi;\ \ z = z$

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{a}\frac{\partial T}{\partial t} \qquad (1\text{-}3b)$$

Heat conduction

- Spherical coordinates:



$$x = r\sin\theta\cdot\cos\phi;\quad y = r\sin\theta\cdot\sin\phi;\quad z = r\cos\theta$$

$$\frac{1}{r}\frac{\partial^2}{\partial r}(rT)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial T}{\partial\theta}\right)+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 T}{\partial\phi^2}+\frac{\dot q}{k}=\frac{1}{a}\frac{\partial T}{\partial t} \qquad (1\text{-}3c)$$

Reduced Form of The General Equations For Several Cases of Practical Interest.

Steady-state one-dimensional heat flow (no heat generation):

$$\frac{d^2T}{dx^2} = 0 \qquad [1\text{-}4]$$

Note that this equation is the same as Equation (1-1) when $q =$ constant.

Steady-state one-dimensional heat flow in cylindrical coordinates (no heat generation):

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} = 0 \qquad [1\text{-}5]$$

Steady-state one-dimensional heat flow with heat sources:

$$\frac{d^2T}{dx^2} + \frac{\dot{q}}{k} = 0 \qquad [1\text{-}6]$$

Two-dimensional steady-state conduction without heat sources:

$$\frac{\partial^2T}{\partial x^2} + \frac{\partial^2T}{\partial y^2} = 0 \qquad [1\text{-}7]$$

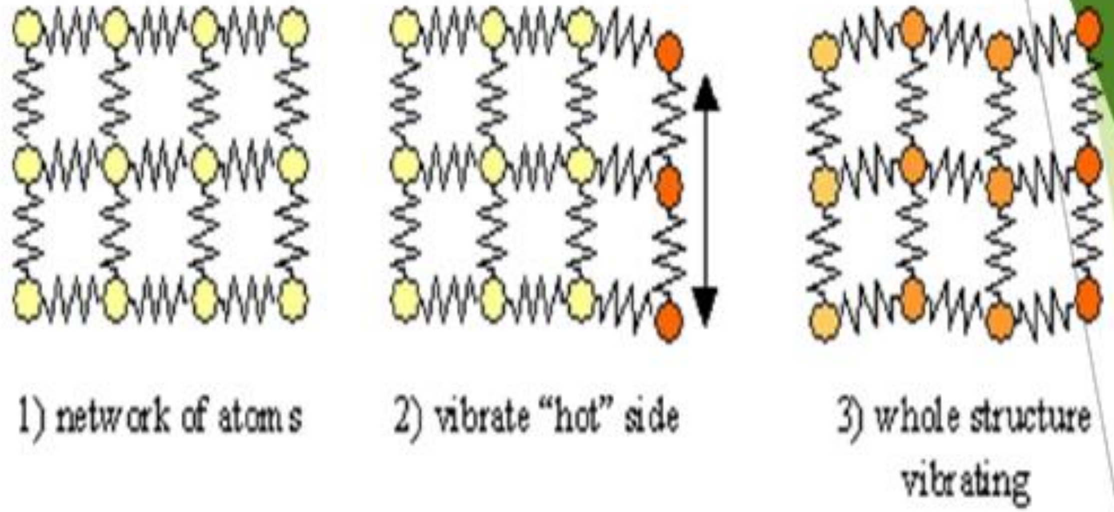
Heat Conduction

Thermal Conductivity

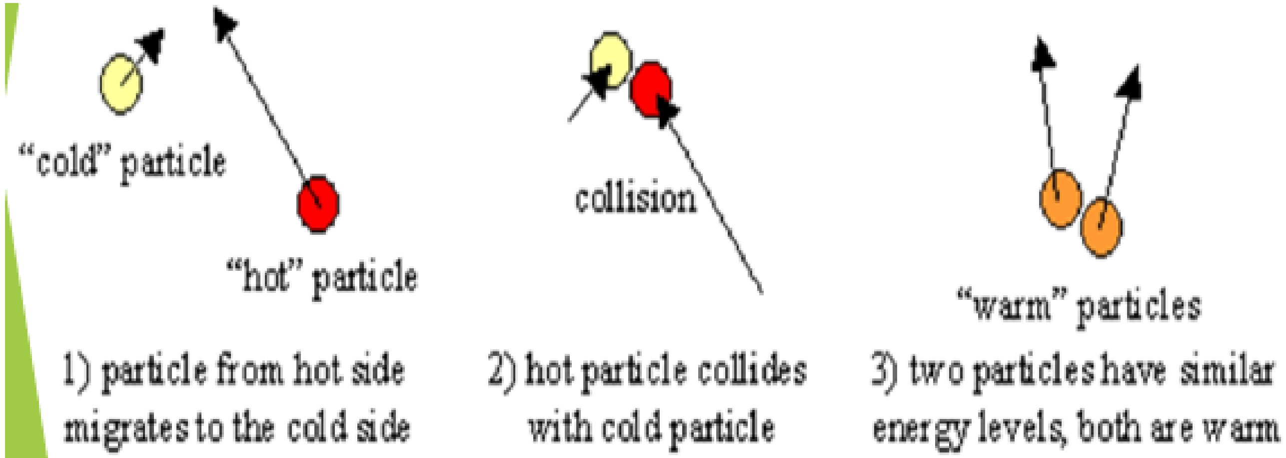
- Equation (1-1) can be used to determine the thermal conductivity experimentally for different materials.
- For gases at moderately low temperatures, analytical treatments in the kinetic theory of gases may be used to predict accurately.
- In some cases, theories are available for the prediction of thermal conductivities in liquids and solids
- In general, many open questions and concepts still need clarification.

Heat Conduction

Thermal Conductivity



Conduction by lattice vibration



Conduction by particle collision

Thermal Conductivity

Figure 1-4 | Thermal conductivities of some typical gases [1 W/m · °C = 0.5779 Btu/h · ft · °F].

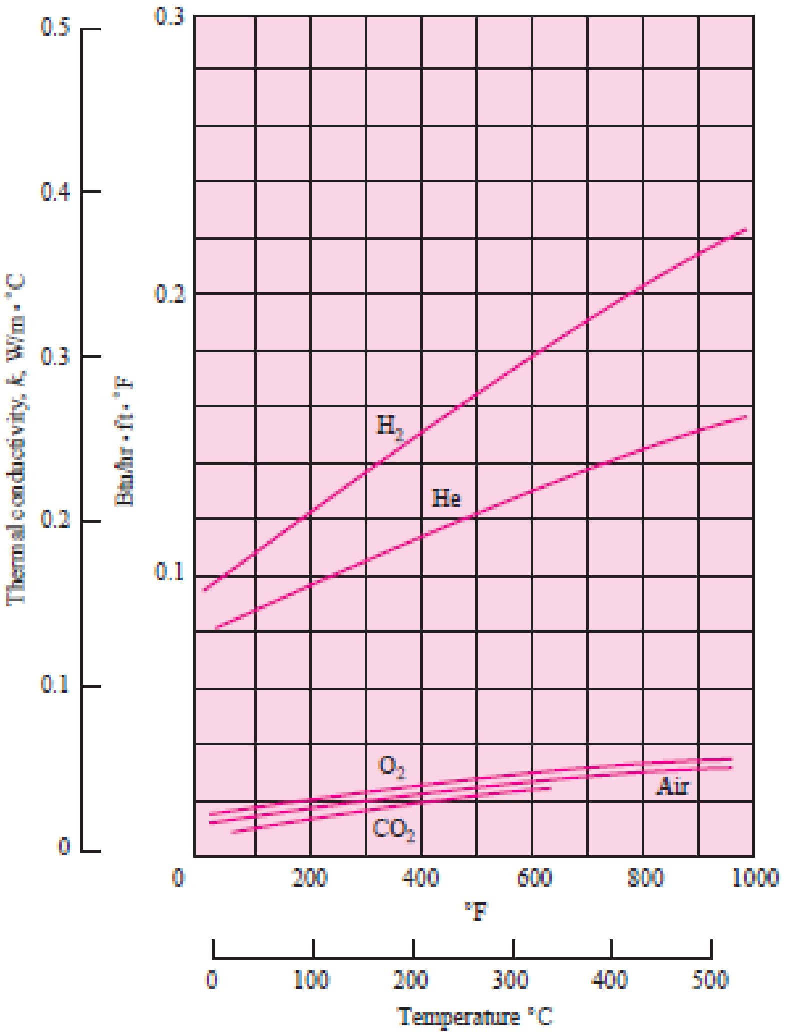


Figure 1-5 | Thermal conductivities of some typical liquids.

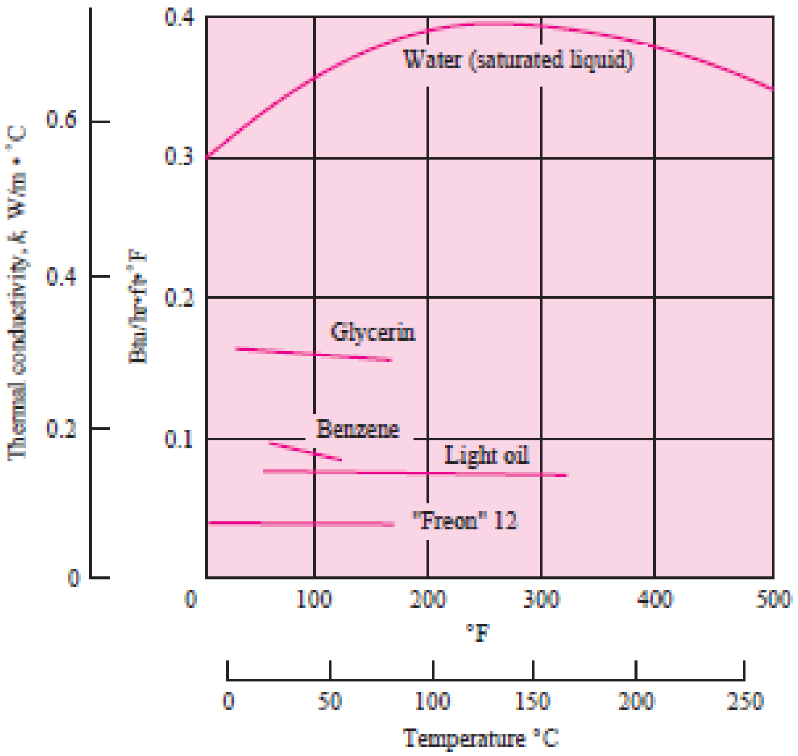
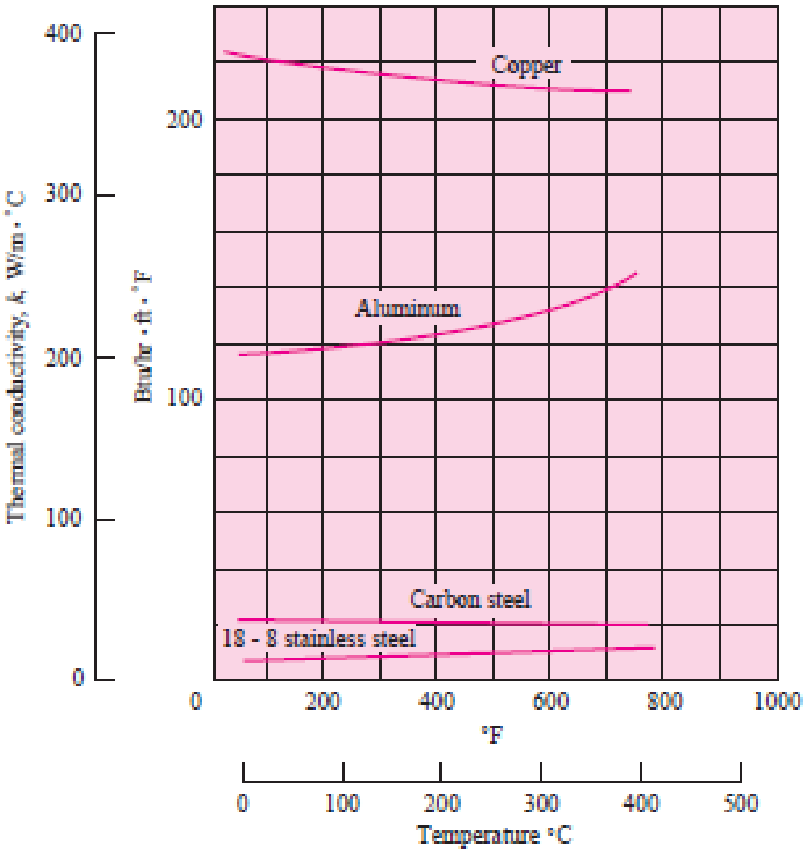


Figure 1-6 | Thermal conductivities of some typical solids.



Heat Conduction

EXAMPLE 1-1 Conduction Through Copper Plate

One face of a copper plate 3 cm thick is maintained at 400°C, and the other face is maintained at 100°C. How much heat is transferred through the plate?

Solution

From Appendix A, the thermal conductivity for copper is 370 W/m · °C at 250°C. From Fourier's law

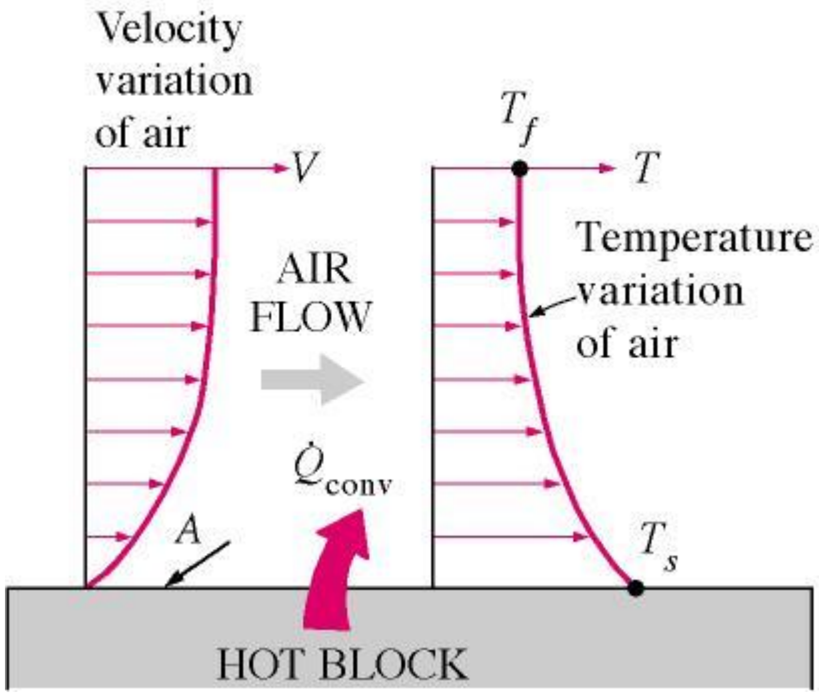
$$\frac{q}{A} = -k\frac{dT}{dx}$$

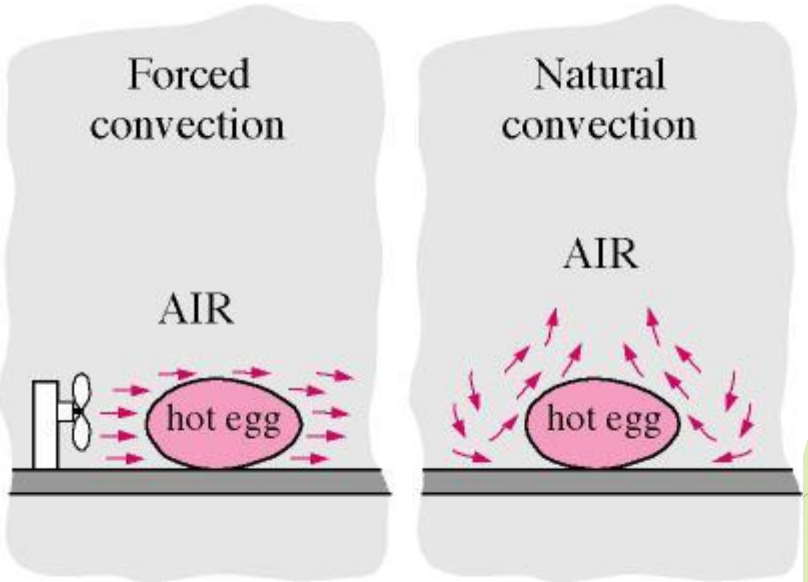
Integrating gives

$$\frac{q}{A} = -k\frac{\Delta T}{\Delta x} = \frac{-(370)(100-400)}{3\times 10^{-2}} = 3.7\ \mathrm{MW/m^2} \quad [1.173\times 10^{6}\ \mathrm{Btu/h\cdot ft^2}]$$

Convection Heat Transfer

Convection: An energy transfer across a system boundary due to a temperature difference by the combined mechanisms of intermolecular interactions and bulk transport. Convection needs fluid matter.





Convection Heat Transfer

Newton's law of cooling

$$q = hA(T_s - T_f)$$

Isaac Newton: (1642-1727)

Where *h* is convective heat transfer coefficient [W/oC.m2] depends on velocity and thermal properties of the fluid, A is the heat transfer area (m2), Ts is the surface temperature (K), and Tf is the bulk fluid temperature away from the surface (K).

Convection Heat Transfer Coefficient

Table 1-3 | Approximate values of convection heat-transfer coefficients.

Mode	h W/m^2 · °C	h Btu/h · ft^2 · °F
Across 2.5-cm air gap evacuated to a pressure of 10^{-6} atm and subjected to $\Delta T = 100°C - 30°C$	0.087	0.015
Free convection, $\Delta T = 30°C$		
Vertical plate 0.3 m [1 ft] high in air	4.5	0.79
Horizontal cylinder, 5-cm diameter, in air	6.5	1.14
Horizontal cylinder, 2-cm diameter, in water	890	157
Heat transfer across 1.5-cm vertical air gap with $\Delta T = 60°C$	2.64	0.46
Fine wire in air, $d = 0.02$ mm, $\Delta T = 55°C$	490	86
Forced convection		
Airflow at 2 m/s over 0.2-m square plate	12	2.1
Airflow at 35 m/s over 0.75-m square plate	75	13.2
Airflow at Mach number = 3, $p = 1/20$ atm, $T_\infty = -40°C$, across 0.2-m square plate	56	9.9
Air at 2 atm flowing in 2.5-cm-diameter tube at 10 m/s	65	11.4
Water at 0.5 kg/s flowing in 2.5-cm-diameter tube	3500	616
Airflow *across* 5-cm-diameter cylinder with velocity of 50 m/s	180	32
Liquid bismuth at 4.5 kg/s and 420°C in 5.0-cm-diameter tube	3410	600
Airflow at 50 m/s across fine wire, $d = 0.04$ mm	3850	678
Boiling water		
In a pool or container	2500–35,000	440–6200
Flowing in a tube	5000–100,000	880–17,600
Condensation of water vapor, 1 atm		
Vertical surfaces	4000–11,300	700–2000
Outside horizontal tubes	9500–25,000	1700–4400
Dropwise condensation	170,000–290,000	30,000–50,000

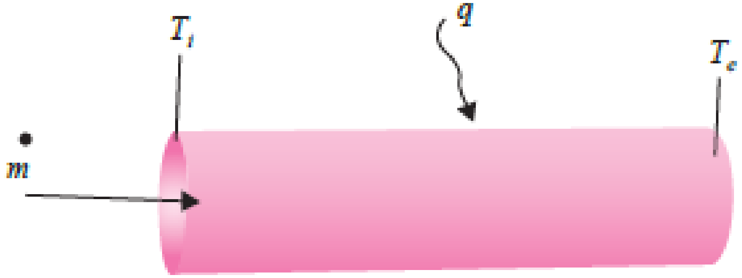
Convection Energy Balance on a Flow Channel

$$q = \dot{m}(i_e - i_i)$$

$$q = \dot{m}c_p(T_e - T_i)$$

$$q = \dot{m}c_p(T_e - T_i) = hA(T_{w,\text{avg}} - T_{\text{fluid, avg}}) \qquad (1\text{-}8a)$$

Figure 1-8 | Convection in a channel.



- *i* is the enthalpy, *m* is the fluid mass flow rate, and *A* is the surface area of the flow channel in contact with the fluid.

We must be careful to distinguish between the surface area for convection that is employed in convection Equation (1-8) and the cross-sectional area that is used to calculate the flow rate from

$$\dot{m} = \rho u_{\text{mean}} A_c$$

where $A_c = \pi d^2/4$ for flow in a circular tube. The surface area for convection in this case would be πdL, where L is the tube length. The surface area for convection is always the area of the heated surface in contact with the fluid.

Convection Heat Transfer

Convection Calculation

EXAMPLE 1-2

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/m^2 · °C. Calculate the heat transfer.

Solution

From Newton's law of cooling

$$q = hA\,(T_w - T_\infty)$$

$$= (25)(0.50)(0.75)(250 - 20)$$

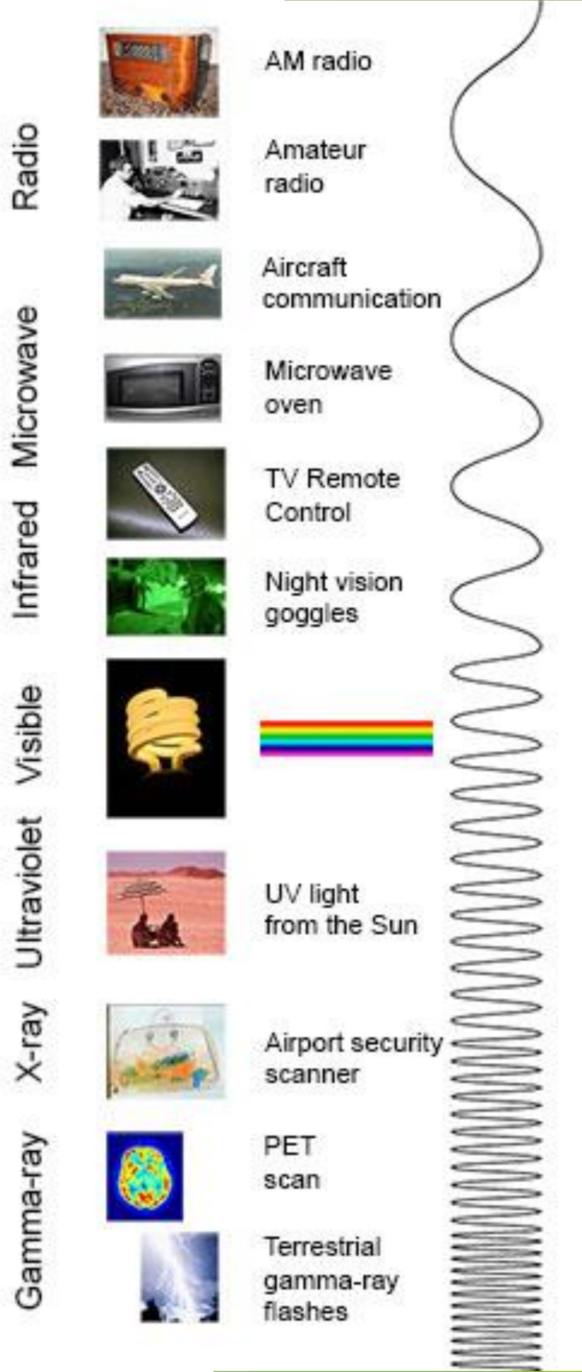
$$= 2.156 \text{ kW} \quad [7356 \text{ Btu/h}]$$

Radiation Heat Transfer

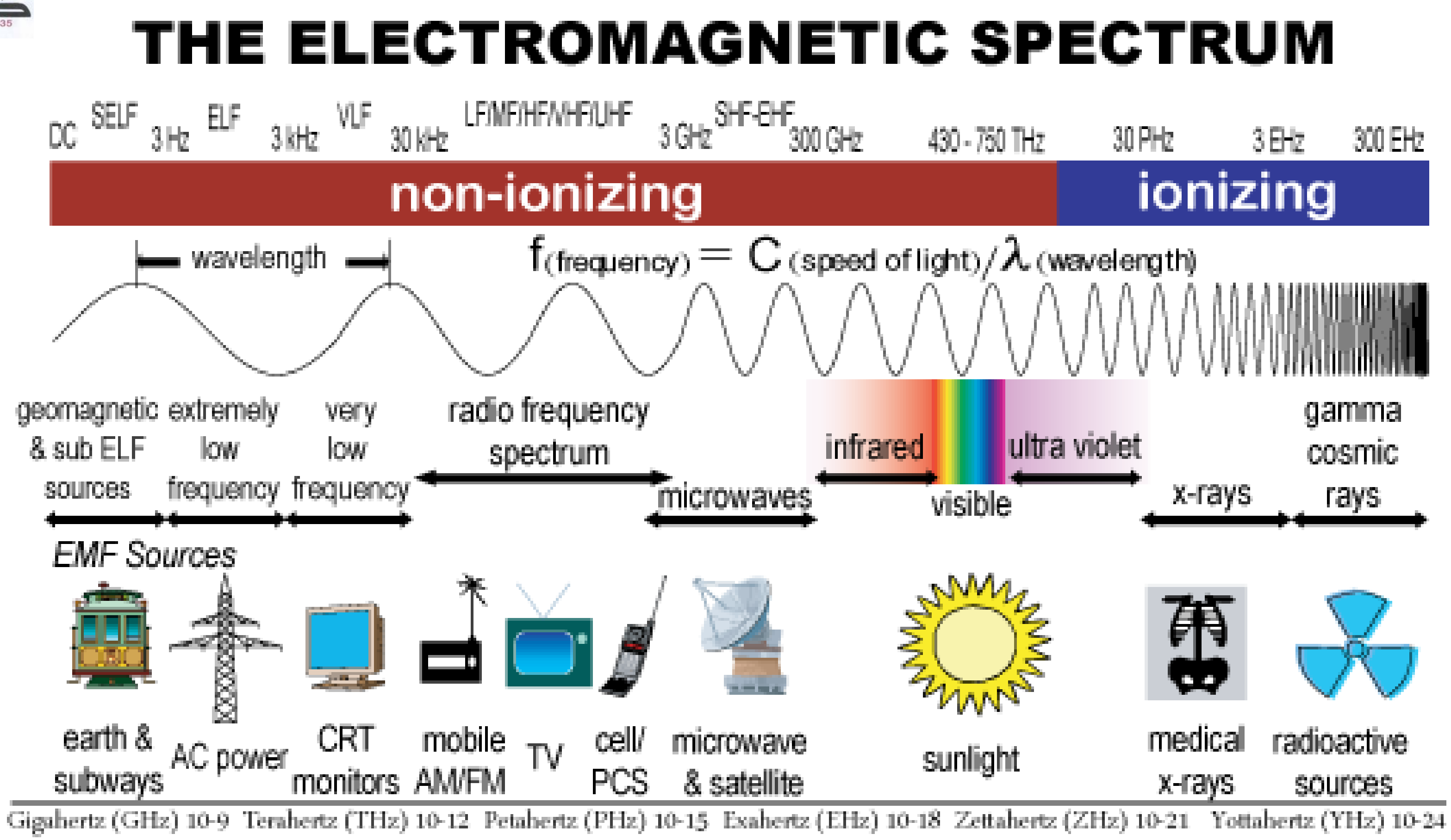
Radiation heat transfer involves the transfer of heat by electromagnetic radiation that arises due to the temperature of the body. Radiation does not need matter.

The electromagnetic (EM) spectrum is the range of all types of EM radiation. Radiation is energy that travels and spreads out as it goes – the visible light that comes from a lamp in your house and the radio waves that come from a radio station are two types of electromagnetic radiation. The other types of EM radiation that make up the electromagnetic spectrum are microwaves, infrared light, ultraviolet light, X-rays and gamma-rays.

The electromagnetic spectrum from lowest energy/longest (at wavelength the top) to highest energy/shortest wavelength (at the bottom). (Credit: NASA's Imagine the Universe)

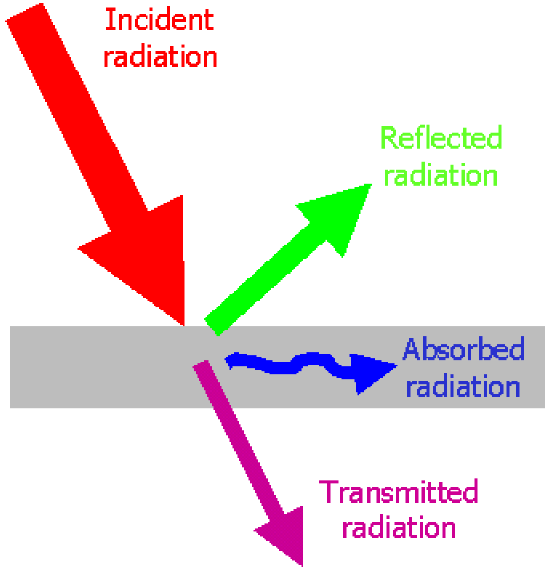


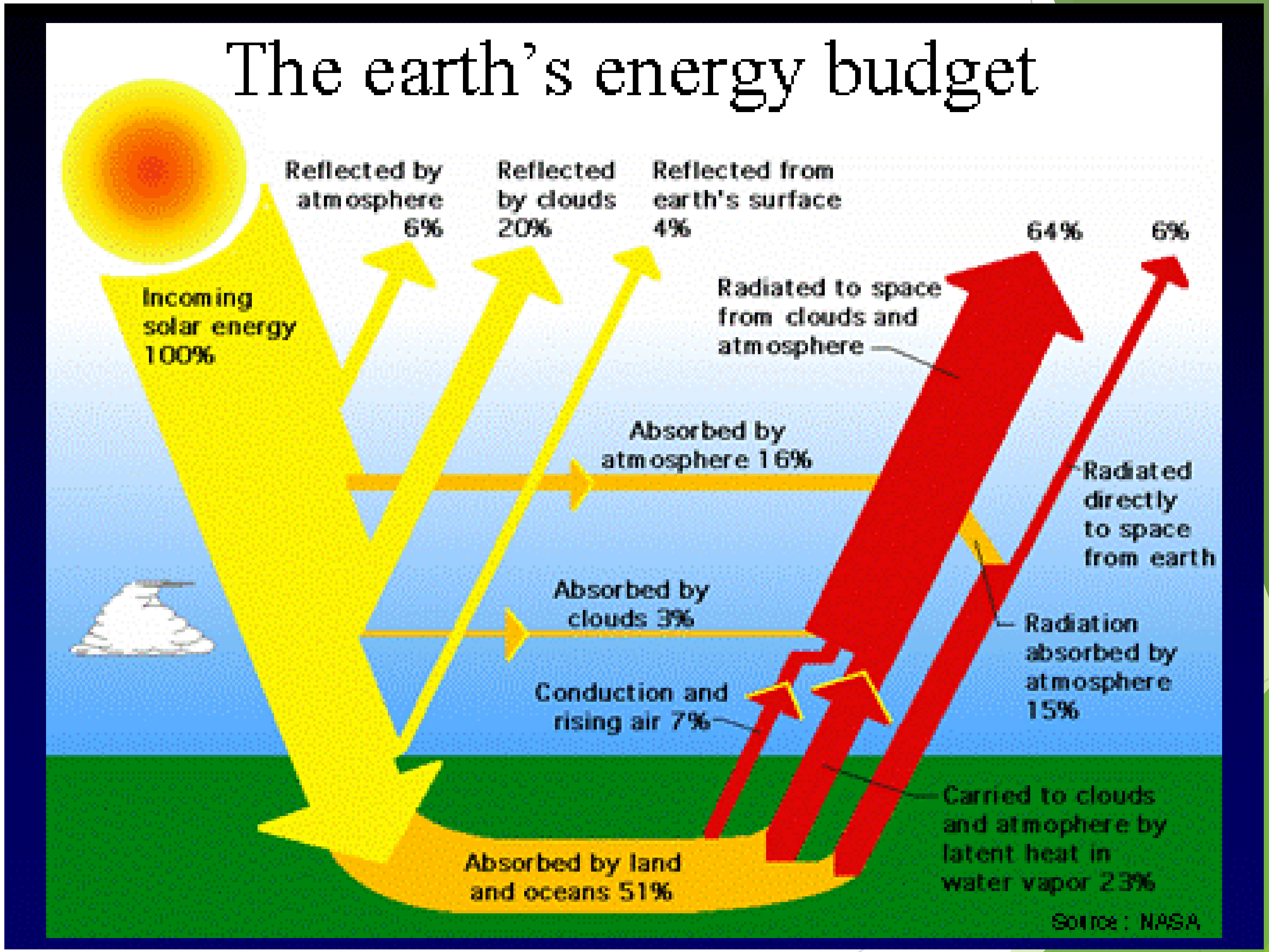
Radiation Heat Transfer



Electromagnetic radiation can be described in terms of a stream of mass-less particles, called photons, each traveling in a wave-like pattern at the speed of light. Each photon contains a certain amount of energy. The different types of radiation are defined by the amount of energy found in the photons.

Radiation Heat Transfer





Radiation Heat Transfer

Stefan-Boltzmann Law of Thermal Radiation

Thermodynamic considerations show that an ideal thermal radiator, or blackbody, will emit energy according to:

$$q_{emitted} = \sigma A T^4 \quad [1\text{-}9]$$

σ is Stefan-Boltzmann constant =5.669×10 E−8 W/m2K4.

Jožef Stefan (1835–1893)

Radiation Heat Transfer

The net radiant exchange between two surfaces:

$$\frac{q_{\text{net exchange}}}{A} \propto \sigma(T_1^4 - T_2^4) \qquad [1\text{-}10]$$

For real bodies:

$$q = F_\epsilon F_G \sigma A\,(T_1^4 - T_2^4) \qquad [1\text{-}11]$$

where $F\epsilon$ is the emissivity function, and FG is the geometric “view factor” function

Radiation in an Enclosure

$$q = \epsilon_1 \sigma A_1\,(T_1^4 - T_2^4) \qquad [1\text{-}12]$$

Radiation Heat Transfer

EXAMPLE 1-5 Radiation Heat Transfer

Two infinite black plates at 800°C and 300°C exchange heat by radiation. Calculate the heat transfer per unit area.

Solution

Equation (1-10) may be employed for this problem, so we find immediately

$$q/A = \sigma(T_1^4 - T_2^4)$$
$$= (5.669 \times 10^{-8})(1073^4 - 573^4)$$
$$= 69.03 \text{ kW/m}^2 \quad [21{,}884 \text{ Btu/h} \cdot \text{ft}^2]$$

Multimode Heat Transfer

EXAMPLE 1-3

Assuming that the plate in Example 1-2 is made of carbon steel (1%) 2 cm thick and that 300 W is lost from the plate surface by radiation, calculate the inside plate temperature.

Solution

The heat conducted through the plate must be equal to the sum of convection and radiation heat losses:

$$q_{\text{cond}} = q_{\text{conv}} + q_{\text{rad}}$$

$$-kA\frac{\Delta T}{\Delta x} = 2.156 + 0.3 = 2.456 \text{ kW}$$

$$\Delta T = \frac{(-2456)(0.02)}{(0.5)(0.75)(43)} = -3.05°\text{C} \quad [-5.49°\text{F}]$$

where the value of k is taken from Table 1-1. The inside plate temperature is therefore

$$T_i = 250 + 3.05 = 253.05°\text{C}$$

Heat Source and Convection

EXAMPLE 1-4

An electric current is passed through a wire 1 mm in diameter and 10 cm long. The wire is submerged in liquid water at atmospheric pressure, and the current is increased until the water boils. For this situation $h = 5000\ \text{W/m}^2 \cdot {}^\circ\text{C}$, and the water temperature will be 100°C. How much electric power must be supplied to the wire to maintain the wire surface at 114°C?

Solution

The total convection loss is given by Equation (1-8):

$$q = hA\,(T_w - T_\infty)$$

For this problem the surface area of the wire is

$$A = \pi dL = \pi(1 \times 10^{-3})(10 \times 10^{-2}) = 3.142 \times 10^{-4}\ \text{m}^2$$

The heat transfer is therefore

$$q = (5000\ \text{W/m}^2 \cdot {}^\circ\text{C})(3.142 \times 10^{-4}\ \text{m}^2)(114 - 100) = 21.99\ \text{W} \quad [75.03\ \text{Btu/h}]$$

and this is equal to the electric power that must be applied.

EXAMPLE 1-6 Total Heat Loss by Convection and Radiation

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°C. The surface emissivity of the steel may be taken as 0.8. Using the data of Table 1-3, calculate the total heat lost by the pipe per unit length.

Solution

The total heat loss is the sum of convection and radiation. From Table 1-3 we see that an estimate for the heat-transfer coefficient for *free* convection with this geometry and air is $h = 6.5\ \mathrm{W/m^2 \cdot °C}$. The surface area is πdL, so the convection loss per unit length is

$$q/L]_{\text{conv}} = h(\pi d)(T_w - T_\infty)$$
$$= (6.5)(\pi)(0.05)(50 - 20) = 30.63\ \mathrm{W/m}$$

The pipe is a body surrounded by a large enclosure so the radiation heat transfer can be calculated from Equation (1-12). With $T_1 = 50°\mathrm{C} = 323°\mathrm{K}$ and $T_2 = 20°\mathrm{C} = 293°\mathrm{K}$, we have

$$q/L]_{\text{rad}} = \epsilon_1(\pi d_1)\sigma(T_1^4 - T_2^4)$$
$$= (0.8)(\pi)(0.05)(5.669 \times 10^{-8})(323^4 - 293^4)$$
$$= 25.04\ \mathrm{W/m}$$

The total heat loss is therefore

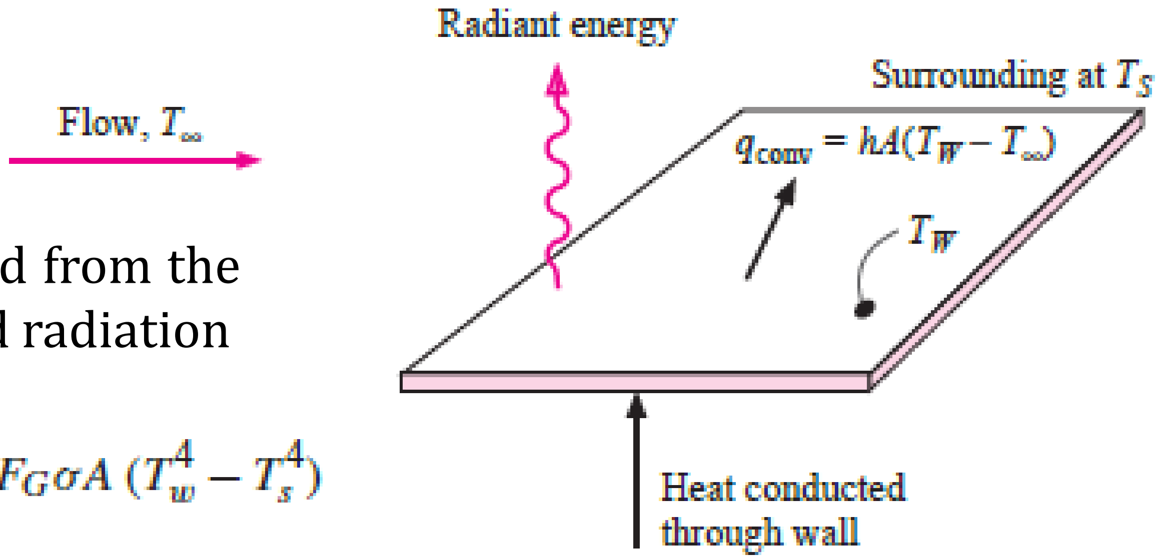
$$q/L]_{\text{tot}} = q/L]_{\text{conv}} + q/L]_{\text{rad}}$$
$$= 30.63 + 25.04 = 55.67\ \mathrm{W/m}$$

In this example we see that the convection and radiation are about the same. To neglect either would be a serious mistake.

Summary

Three modes: conduction, convection, and radiation

Figure 1-9 | Combination of conduction, convection, and radiation heat transfer.



The heat conducted through the plate is removed from the plate surface by a combination of convection and radiation

$$-kA\left.\frac{dT}{dy}\right]_{wall} = hA\,(T_w - T_\infty) + F_\epsilon F_G \sigma A\,(T_w^4 - T_s^4)$$

where

T_s = temperature of surroundings

T_w = surface temperature

T_∞ = fluid temperature