



Thermodynamics and Heat Transfer

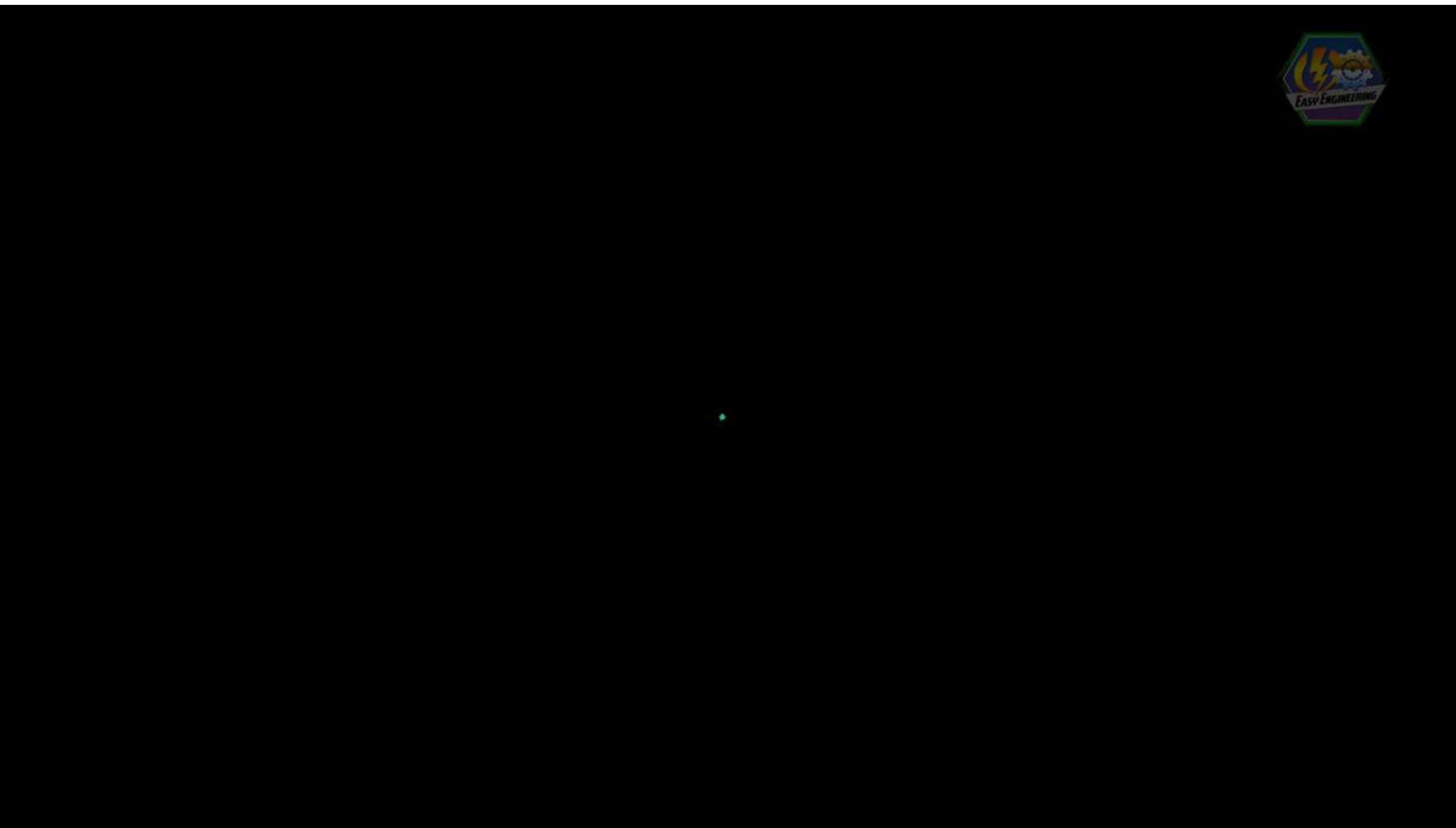
Lecture 11: Heat Transfer

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Learning Outcomes

- Understand the basic mechanisms 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.
- Examples with EES and Matlab
- Example with SAM



Conduction

Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles. Conduction can take place in solids, liquids, or gases. In gases and liquids, 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.

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. That is,

$$\text{Rate of heat conduction} \propto \frac{\text{(Area)(Temperature difference)}}{\text{Thickness}}$$

or,

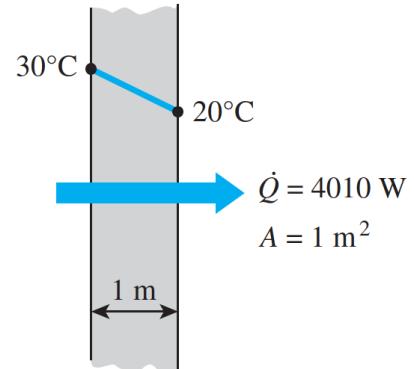
$$\dot{Q}_{\text{cond}} = kA \frac{T_1 - T_2}{\Delta x} = -kA \frac{\Delta T}{\Delta x} \quad (\text{W}) \quad (1-21)$$

thermal conductivity

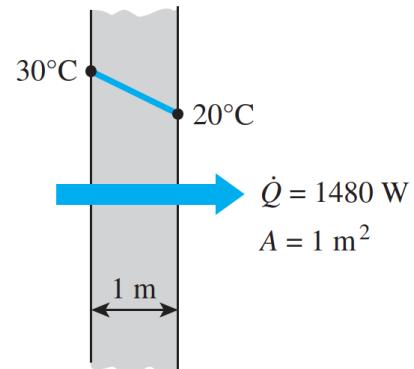
where the constant of proportionality k is the **thermal conductivity** of the material, which is a *measure of the ability of a material to conduct heat* (Fig. 1–24). In the limiting case of $\Delta x \rightarrow 0$, the equation above reduces to the differential form

$$\dot{Q}_{\text{cond}} = -kA \frac{dT}{dx} \quad (\text{W}) \quad (1-22)$$

which is called Fourier's law of heat conduction.



(a) Copper ($k = 401 \text{ W/m}\cdot\text{K}$)



(b) Silicon ($k = 148 \text{ W/m}\cdot\text{K}$)

FIGURE 1–24

The rate of heat conduction through a solid is directly proportional to its thermal conductivity.

EXAMPLE 1–5 The Cost of Heat Loss through a Roof

The roof of an electrically heated home is 6 m long, 8 m wide, and 0.25 m thick, and is made of a flat layer of concrete whose thermal conductivity is $k = 0.8 \text{ W/m}\cdot\text{K}$ (Fig. 1–27). The temperatures of the inner and the outer surfaces of the roof one night are measured to be 15°C and 4°C, respectively, for a period of 10 hours. Determine (a) the rate of heat loss through the roof that night and (b) the cost of that heat loss to the home owner if the cost of electricity is \$0.08/kWh.

Analysis (a) Noting that heat transfer through the roof is by conduction and the area of the roof is $A = 6 \text{ m} \times 8 \text{ m} = 48 \text{ m}^2$, the steady rate of heat transfer through the roof is

$$\dot{Q} = kA \frac{T_1 - T_2}{L} = (0.8 \text{ K})(48 \text{ m}^2) \frac{(15 - 4)^\circ\text{C}}{0.25 \text{ m}} = \mathbf{1690 \text{ W} = 1.69 \text{ kW}}$$

(b) The amount of heat lost through the roof during a 10-hour period and its cost is

$$Q = \dot{Q} \Delta t = (1.69 \text{ kW})(10 \text{ h}) = 16.9 \text{ kWh}$$

$$\begin{aligned} \text{Cost} &= (\text{Amount of energy})(\text{Unit cost of energy}) \\ &= (16.9 \text{ kWh})(\$0.08/\text{kWh}) = \mathbf{\$1.35} \end{aligned}$$

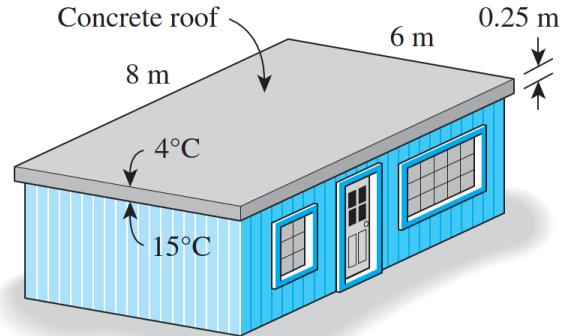


FIGURE 1–27

Schematic for Example 1–5.

TABLE 1–1

The thermal conductivities of some materials at room temperature

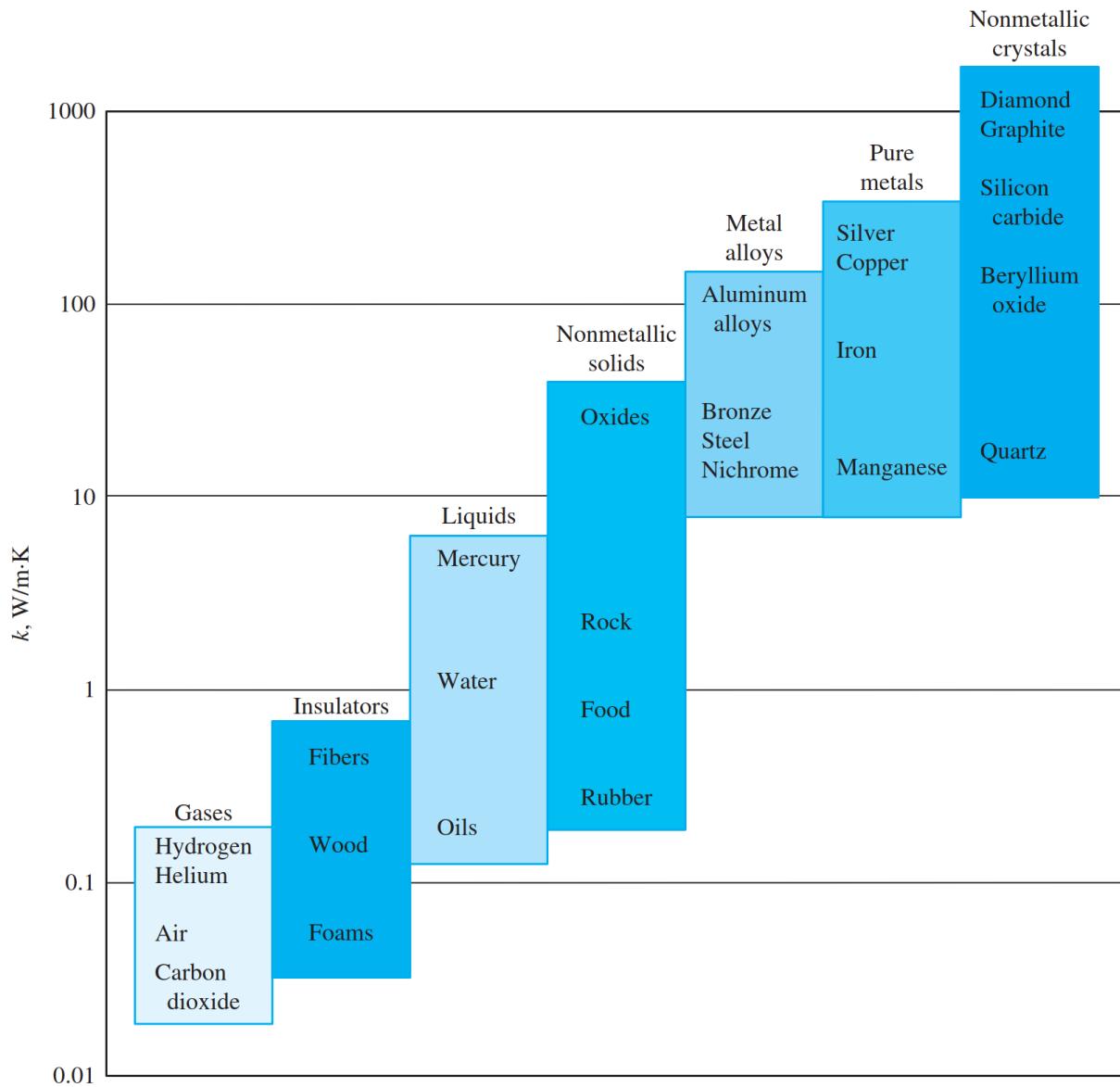
Material	$k, \text{ W/m}\cdot\text{K}^*$
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminum	237
Iron	80.2
Mercury (l)	8.54
Glass	0.78
Brick	0.72
Water (l)	0.607
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026

*Multiply by 0.5778 to convert to $\text{Btu}/\text{h}\cdot\text{ft}\cdot^\circ\text{F}$.



EES

- How much is the cost of the heat loss to the home owner if the cost of electricity varies between \$0.02/kWh to \$2/kWh?
- Calculate the cost of heat loss for electricity cost of \$0.08/kWh and k from 0.5 W/m.K to 5 W/m.K.



nano Copper Oxide CuO Nanoparticles
(CuO, high purity, 99.9%min, 25-55nm)



FIGURE 1-29
The range of thermal conductivity of various materials at room temperature.

Another material property that appears in the transient heat conduction analysis is the **thermal diffusivity**, which represents how fast heat diffuses through a material and is defined as:

$$\alpha = \frac{\text{Heat conduction}}{\text{Heat storage}} = \frac{k}{\rho c_p} \quad (\text{m}^2/\text{s}) \quad (1-23)$$

Note that the thermal conductivity k represents how well a material conducts heat, and the heat capacity ρc_p represents how much energy a material stores per unit volume.

TABLE 1-4

The thermal diffusivities of some materials at room temperature

Material	$\alpha, \text{m}^2/\text{s}^*$
Silver	149×10^{-6}
Gold	127×10^{-6}
Copper	113×10^{-6}
Aluminum	97.5×10^{-6}
Iron	22.8×10^{-6}
Mercury (l)	4.7×10^{-6}
Marble	1.2×10^{-6}
Ice	1.2×10^{-6}
Concrete	0.75×10^{-6}
Brick	0.52×10^{-6}
Heavy soil (dry)	0.52×10^{-6}
Glass	0.34×10^{-6}
Glass wool	0.23×10^{-6}
Water (l)	0.14×10^{-6}
Beef	0.14×10^{-6}
Wood (oak)	0.13×10^{-6}

*Multiply by 10.76 to convert to ft^2/s .

CONVECTION

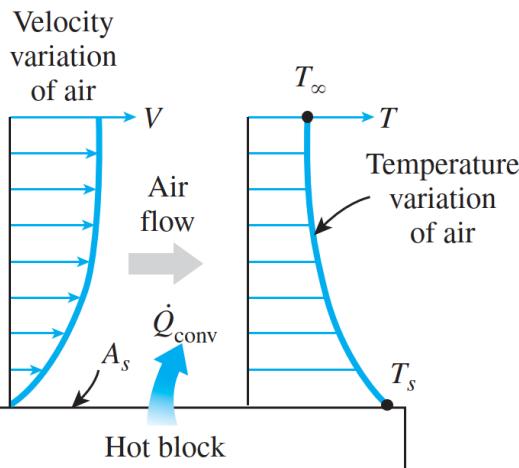


FIGURE 1–34

Heat transfer from a hot surface to air by convection.

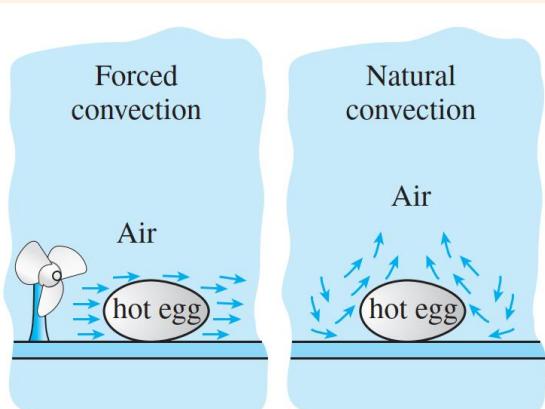


FIGURE 1–35

The cooling of a boiled egg by forced and natural convection.

Convection is the mode of energy transfer **between a solid surface and the adjacent liquid or gas that is in motion**, and it involves the combined effects of conduction and fluid motion. The faster the fluid motion, the greater the convection heat transfer. In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction. The presence of bulk motion of the fluid enhances the heat transfer between the solid surface and the fluid, but it also complicates the determination of heat transfer rates.

Despite the complexity of convection, the rate of *convection heat transfer* is observed to be proportional to the temperature difference, and is conveniently expressed by **Newton's law of cooling** as (Fig. 1–36)

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty) \quad (\text{W}) \quad (1-24)$$

where h is the *convection heat transfer coefficient* in $\text{W/m}^2 \cdot \text{K}$ or $\text{Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$, A_s is the surface area through which convection heat transfer takes place, T_s is the surface temperature, and T_∞ is the temperature of the fluid sufficiently far from the surface. Note that at the surface, the fluid temperature equals the surface temperature of the solid.

TABLE 1–5

Typical values of convection heat transfer coefficient

Type of convection	$h, \text{W/m}^2 \cdot \text{K}^*$
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

*Multiply by 0.176 to convert to $\text{Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$.

EXAMPLE 1–8 Measuring Convection Heat Transfer Coefficient

A 2-m-long, 0.3-cm-diameter electrical wire extends across a room at 15°C, as shown in Fig. 1–37. Heat is generated in the wire as a result of resistance heating, and the surface temperature of the wire is measured to be 152°C in steady operation. Also, the voltage drop and electric current through the wire are measured to be 60 V and 1.5 A, respectively. Disregarding any heat transfer by radiation, determine the convection heat transfer coefficient for heat transfer between the outer surface of the wire and the air in the room.

Analysis When steady operating conditions are reached, the rate of heat loss from the wire equals the rate of heat generation in the wire as a result of resistance heating. That is,

$$\dot{Q} = \dot{E}_{\text{generated}} = VI = (60 \text{ V})(1.5 \text{ A}) = 90 \text{ W}$$

The surface area of the wire is *For a cylinder we have:*

$$A_s = \pi DL = \pi(0.003 \text{ m})(2 \text{ m}) = 0.01885 \text{ m}^2$$

Newton's law of cooling for convection heat transfer is expressed as

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty)$$

Disregarding any heat transfer by radiation and thus assuming all the heat loss from the wire to occur by convection, the convection heat transfer coefficient is determined to be

$$h = \frac{\dot{Q}_{\text{conv}}}{A_s(T_s - T_\infty)} = \frac{90 \text{ W}}{(0.01885 \text{ m}^2)(152 - 15)^\circ\text{C}} = 34.9 \text{ W/m}^2\cdot\text{K}$$

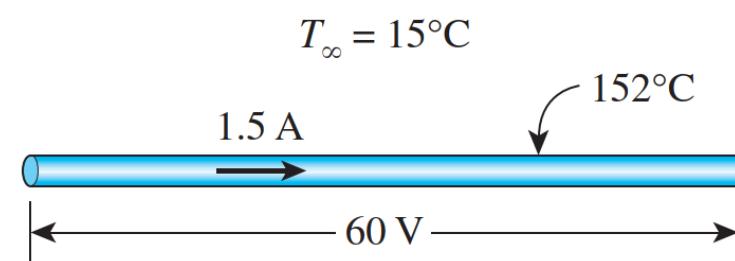


FIGURE 1–37
Schematic for Example 1–8.



EES

- How much is the convective heat transfer coefficient if V varies from 60 V to 120 V?

RADIATION

K → R → multiply the temperature value by 1.8

Radiation is 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. Unlike conduction and convection, the transfer of heat by radiation does not require the presence of an intervening medium. In fact, heat transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.

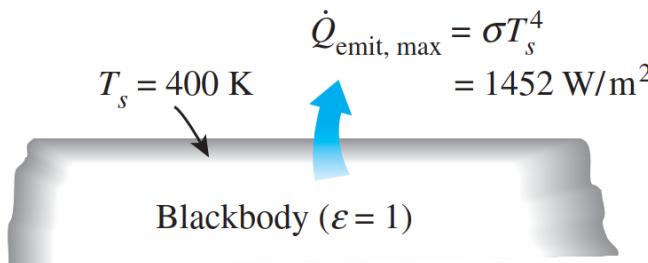


FIGURE 1–38

Blackbody radiation represents the maximum amount of radiation that can be emitted from a surface at a specified temperature.

The maximum rate of radiation that can be emitted from a surface at a thermodynamic temperature T_s (in K or R) is given by the **Stefan–Boltzmann law** as

Rankine scale

$$\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4 \quad (\text{W}) \quad (1-25)$$

where $\sigma = 5.670 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ or $0.1714 \times 10^{-8} \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4$ is the **Stefan–Boltzmann constant**. The idealized surface that emits radiation at this maximum rate is called a **blackbody**, and the radiation emitted by a blackbody is called **blackbody radiation** (Fig. 1–38). The radiation emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as

This is the radiation emitted by
a real surface:

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \quad (\text{W}) \quad (1-26)$$

where ε is the **emissivity** of the surface. The property emissivity, whose value is in the range $0 \leq \varepsilon \leq 1$, is a measure of how closely a surface approximates a blackbody for which $\varepsilon = 1$. The emissivities of some surfaces are given in Table 1–6.

TABLE 1–6

Emissivities of some materials at 300 K

Material	Emissivity
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

Another important radiation property of a surface is its **absorptivity α** , which is the fraction of the radiation energy incident on a surface that is absorbed by the surface. Like emissivity, its value is in the range $0 \leq \alpha \leq 1$. A blackbody absorbs the entire radiation incident on it. That is, a **blackbody** is a perfect absorber ($\alpha = 1$) as it is a perfect emitter.

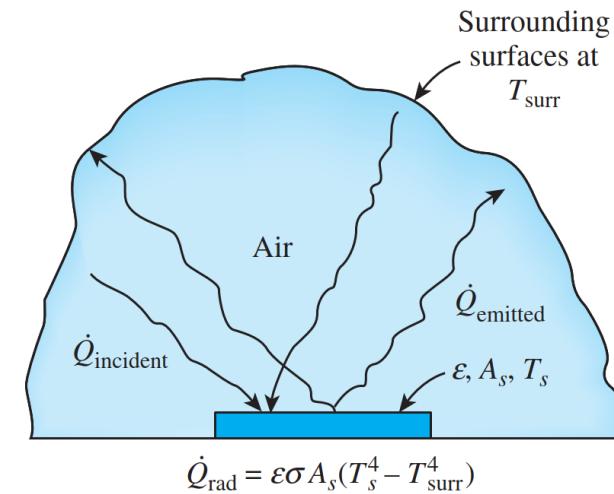
In general, both ε and α of a surface depend on the **temperature and the wavelength of the radiation**. **Kirchhoff's law** of radiation states that the emissivity and the absorptivity of a surface at a given temperature and wavelength are equal. In many practical applications, the surface temperature and the temperature of the source of incident radiation are of the same order of magnitude, and the average absorptivity of a surface is taken to be equal to its average emissivity. The rate at which a surface absorbs radiation is determined from (Fig. 1–39)

$$\dot{Q}_{\text{absorbed}} = \alpha \dot{Q}_{\text{incident}} \quad (\text{W}) \quad (1-27)$$

where $\dot{Q}_{\text{incident}}$ is the rate at which radiation is incident on the surface and α is the absorptivity of the surface. For opaque (nontransparent) surfaces, the portion of incident radiation not absorbed by the surface is reflected back.

When a surface of emissivity ε and surface area A_s at a *thermodynamic temperature* T_s is completely enclosed by a much larger (or black) surface at thermodynamic temperature T_{surr} separated by a gas (such as air) that does not intervene with radiation, the net rate of radiation heat transfer between these two surfaces is given by (Fig. 1–40)

$$\dot{Q}_{\text{rad}} = \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) \quad (\text{W}) \quad (1-28)$$



$$\dot{Q}_{\text{rad}} = \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4)$$

FIGURE 1–40

Radiation heat transfer between a surface and the surfaces surrounding it.

EXAMPLE 1–9 Radiation Effect on Thermal Comfort

It is a common experience to feel “chilly” in winter and “warm” in summer in our homes even when the thermostat setting is kept the same. This is due to the so called “radiation effect” resulting from radiation heat exchange between our bodies and the surrounding surfaces of the walls and the ceiling.

Consider a person standing in a room maintained at 22°C at all times. The inner surfaces of the walls, floors, and the ceiling of the house are observed to be at an average temperature of 10°C in winter and 25°C in summer. Determine the rate of radiation heat transfer between this person and the surrounding surfaces if the exposed surface area and the average outer surface temperature of the person are 1.4 m² and 30°C, respectively (Fig. 1–41).

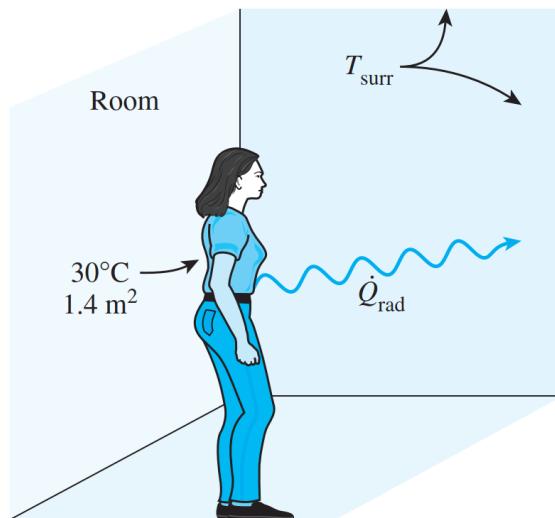


FIGURE 1–41
Schematic for Example 1–9.

Analysis The net rates of radiation heat transfer from the body to the surrounding walls, ceiling, and floor in winter and summer are

$$\begin{aligned}\dot{Q}_{\text{rad, winter}} &= \varepsilon\sigma A_s (T_s^4 - T_{\text{surr, winter}}^4) \\ &= (0.95)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.4 \text{ m}^2) \\ &\quad \times [(30 + 273)^4 - (10 + 273)^4] \text{ K}^4 \\ &= \mathbf{152 \text{ W}}\end{aligned}$$

and

$$\begin{aligned}\dot{Q}_{\text{rad, summer}} &= \varepsilon\sigma A_s (T_s^4 - T_{\text{surr, summer}}^4) \\ &= (0.95)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.4 \text{ m}^2) \\ &\quad \times [(30 + 273)^4 - (25 + 273)^4] \text{ K}^4 \\ &= \mathbf{40.9 \text{ W}}\end{aligned}$$

Example 1-10

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 $h = 6.5 \text{ W/m}^2 \cdot ^\circ\text{C}$. The surface area is πdL , so the convection loss per unit length is

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

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

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

The total heat loss is therefore

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

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

SAM Example: Solar Power Tower System

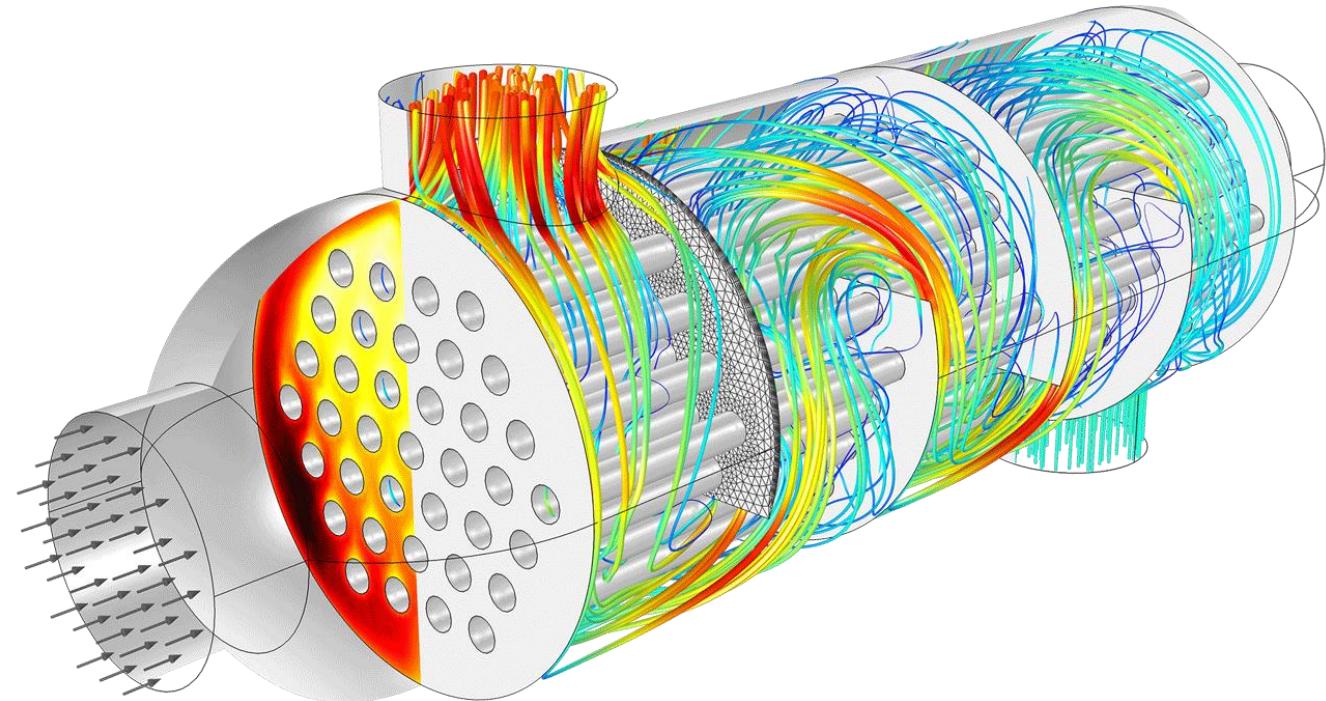
Calculate the receiver power loss for a solar power tower system.

Heat Transfer Modeling

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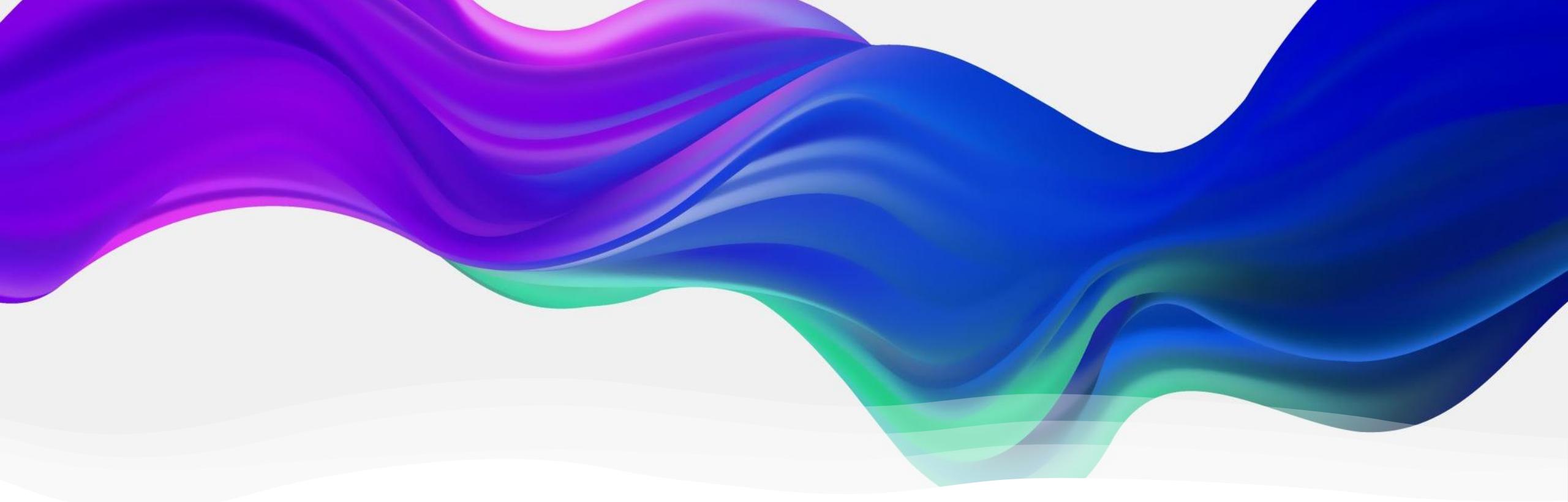


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Thank you

Ali Khosravi