HEAT TRANSFER MECHANISMS-recap

- *Heat* is the form of energy that can be transferred from one system to another as a result of temperature difference.
- Heat can be transferred in three basic modes:
  - ✓ conduction
  - ✓ convection
  - ✓ radiation
- All modes of heat transfer require the existence of a temperature difference.

CONDUCTION

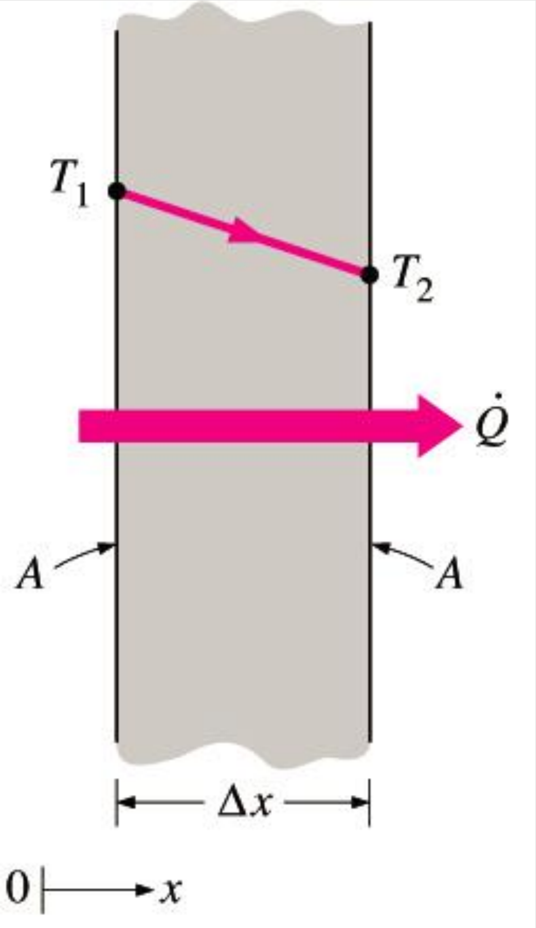
Conduction: The energy transfer from the more energetic particles to the adjacent less energetic particles.

The rate of heat conduction is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer.

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

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

Fourier's law of heat conduction



Heat conduction through a large plane wall of thickness Δx and area A.

Fourier's law of heat conduction

$$\dot{Q}_{\text{cond}} = -kA\frac{dT}{dx}$$

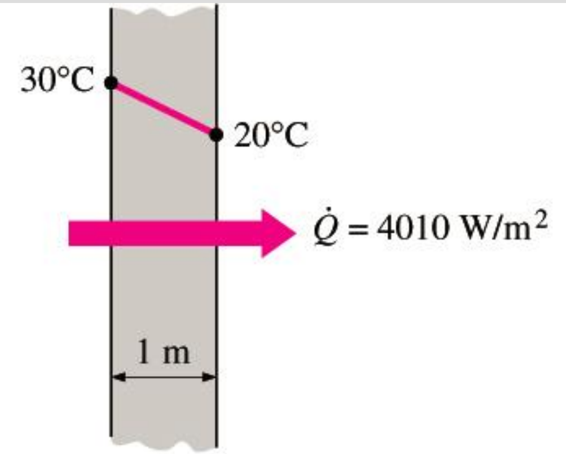
Thermal conductivity, *k*: The ability of a material to conduct heat.

Temperature gradient *dT/dx*: The slope of the temperature curve on a *T*-*x* diagram.

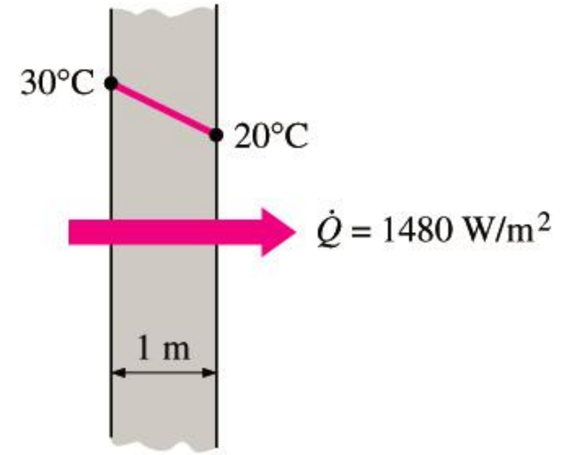
Heat flow in the direction of decreasing temperature.

The temperature gradient becomes negative when temperature decreases with increasing *x.*

Thus, the *negative sign* in the equation ensures that heat transfer in the positive *x* direction is a positive quantity.



(*a*) Copper (*k* = 401 W/m·°C)



(*b*) Silicon (*k* = 148 W/m·°C)

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

Thermal Conductivity : *k*

Thermal conductivity: The rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference.

The thermal conductivity of a material is a measure of the ability of the material to conduct heat and the value is vary with its temperature.

A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or *insulator*.

FYI, pure crystals and metals have the highest thermal conductivities, and gases and insulating materials the lowest.

The thermal conductivities of some materials at room temperature

Material	*k*, W/m · °C*
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

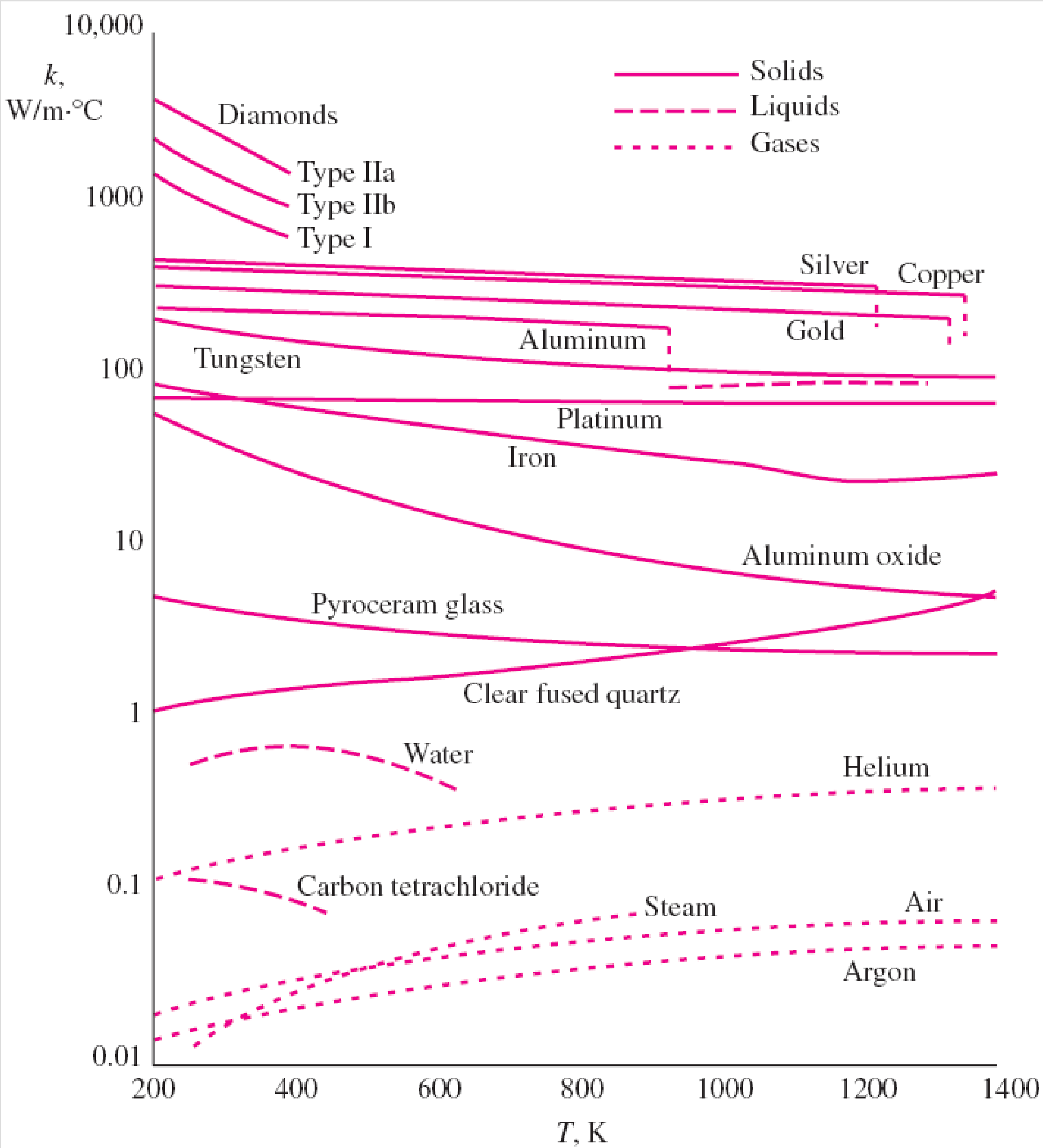


TABLE 1–3

Thermal conductivities of materials vary with temperature

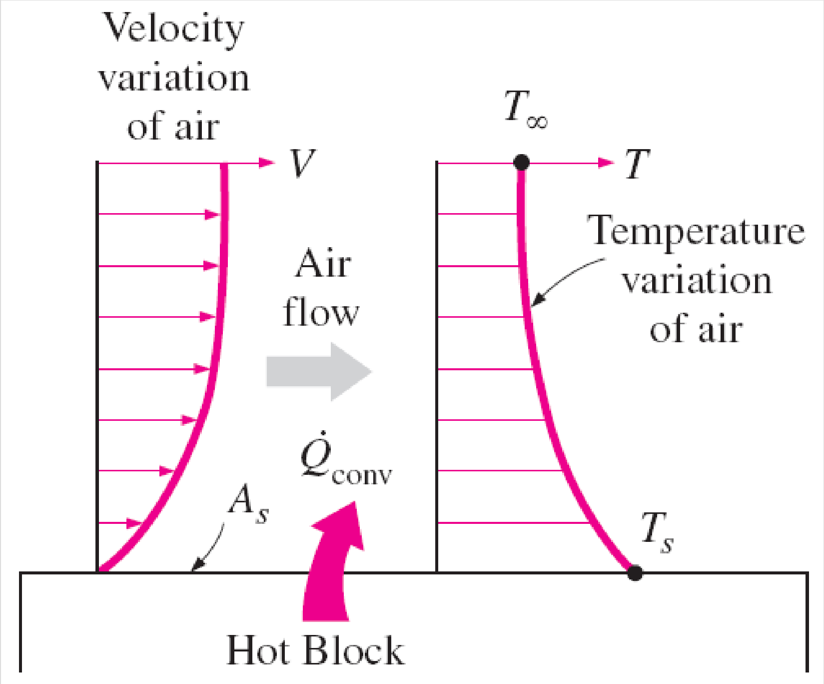
	k, W/m·K	
T, K	Copper	Aluminum
100	482	302
200	413	237
300	401	237
400	393	240
600	379	231
800	366	218

The variation of the thermal conductivity of various solids, liquids, and gases with temperature.

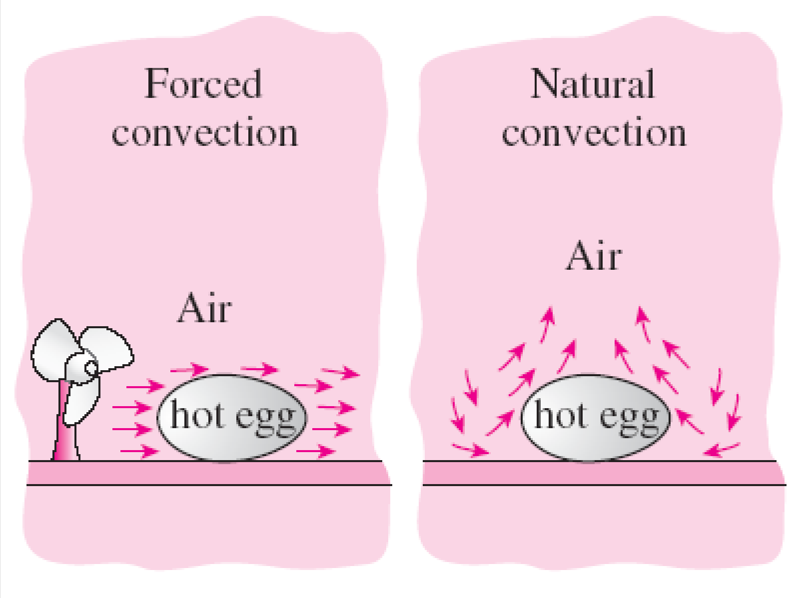
CONVECTION

Convection: The heat transfer between a solid surface and the adjacent liquid or gas that is in motion.

The faster the fluid motion, the greater the convection heat transfer.



Heat transfer from a hot surface to air by convection.



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

Heat transfer processes that involve *change of phase* of a fluid are also considered to be convection because of the fluid motion induced during the process, such as the rise of the vapor bubbles during boiling or the fall of the liquid droplets during condensation.

Newton's law of cooling for convection

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

h	convection heat transfer coefficient, $W/m^2 \cdot °C$
A_s	the surface area through which convection heat transfer takes place
T_s	the surface temperature
T_∞	the temperature of the fluid sufficiently far from the surface

Typical values of convection heat transfer coefficient

Type of convection	h, $W/m^2 \cdot °C$*
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

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.

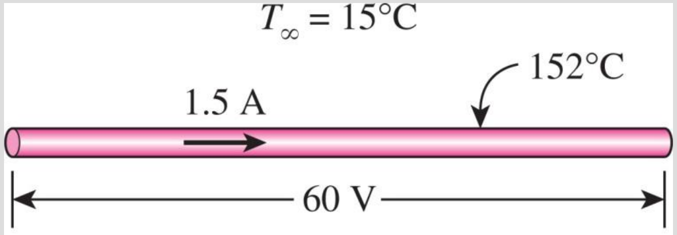


FIGURE 1–37
Schematic for Example 1–8.

SOLUTION The convection heat transfer coefficient for heat transfer from an electrically heated wire to air is to be determined by measuring temperatures when steady operating conditions are reached and the electric power consumed.

Assumptions **1** Steady operating conditions exist since the temperature readings do not change with time. **2** Radiation heat transfer is negligible.

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,

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

The surface area of the wire is

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

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

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

Discussion Note that the simple setup described above can be used to determine the average heat transfer coefficients from a variety of surfaces in air. Also, heat transfer by radiation can be eliminated by keeping the surrounding surfaces at the temperature of the wire.

RADIATION

- **Radiation:** The energy emitted by matter in the form of *electromagnetic waves* (or *photons*).
- Heat transfer by radiation is fastest and does not require the presence of *medium (energy from sun to earth).*

- In heat transfer, we study on *thermal radiation (*radiation emitted by bodies because of their temperature).
- Radiation is a *volumetric phenomenon*, and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees.
- However, radiation is usually considered to be a *surface phenomenon* for solids.

Stefan–Boltzmann law

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

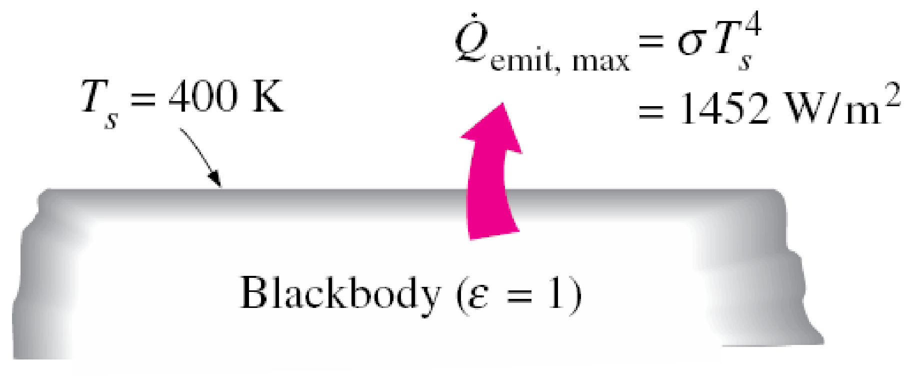
$\sigma = 5.670 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4$
Stefan–Boltzmann constant

Blackbody: The idealized surface that emits radiation at the maximum rate (fig. below)

Radiation emitted by real surfaces

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \qquad \text{(W)}$$

Emissivity ε: the ability of surface to emit energy by radiation (a blackbody $\varepsilon = 1$). **$0 \le \varepsilon \le 1$**.



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

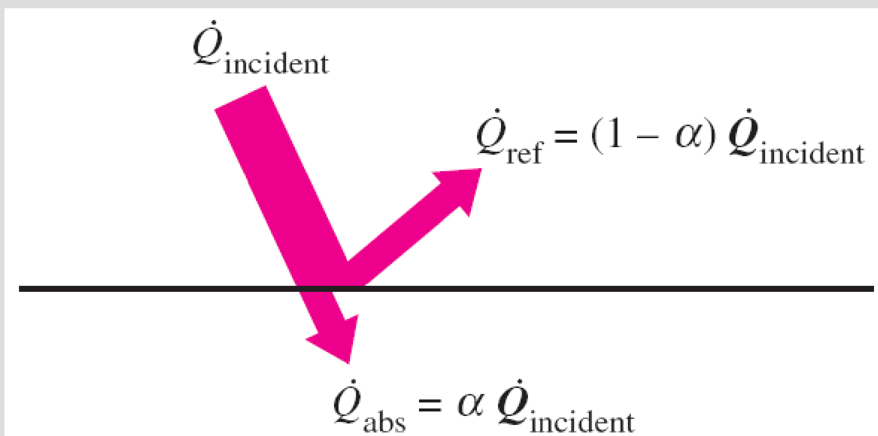
Another important radiation property of a surface is

Absorptivity α : the ability of surface to absorb radiation energy.
$0 \leq \alpha \leq 1$

A blackbody absorbs the entire radiation incident on it (**α = 1**).

Kirchhoff's law: The emissivity and the absorptivity of a surface at a given temperature and wavelength are equal.

$$\dot{Q}_{\text{absorbed}} = \alpha \dot{Q}_{\text{incident}} \qquad \text{(W)}$$

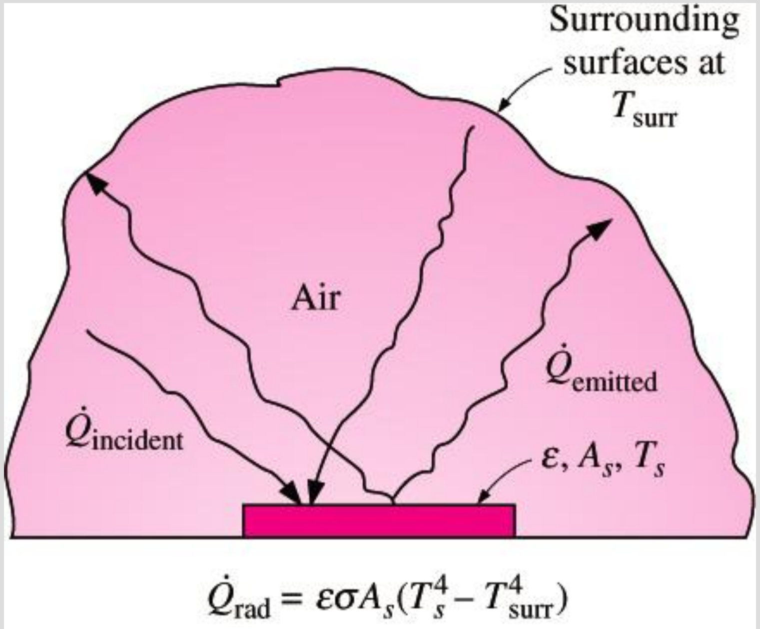


The absorption of radiation incident on an opaque surface of absorptivity.

Net radiation heat transfer: The difference between the rates of radiation emitted by the surface and the radiation absorbed.

When a surface is *completely enclosed* by a large surface at 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

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



ps : radiation is usually significant relative to conduction or natural convection, but not to forced convection.

When radiation and convection occur simultaneously between a surface and a gas:

$$\dot{Q}_{\text{total}} = h_{\text{combined}} A_s (T_s - T_\infty) \qquad \text{(W)}$$

Combined heat transfer coefficient *h*$_{\text{combined}}$ includes the effects of both convection and radiation.

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

$$\dot{Q}_{\text{total}} = h_{\text{combined}} A_s (T_s - T_\infty) \qquad \text{(W)}$$

$$h_{\text{combined}} = h_{\text{conv}} + h_{\text{rad}} = h_{\text{conv}} + \varepsilon\sigma (T_s + T_{\text{surr}})(T_s^2 + T_{\text{surr}}^2)$$

SIMULTANEOUS HEAT TRANSFER MECHANISMS

Heat transfer is only by conduction in *opaque solids,* but by conduction and radiation in *semitransparent solids.*

A solid may involve conduction and radiation but not convection. A solid may involve convection and/or radiation on its surfaces exposed to a fluid or other surfaces.

Heat transfer is by conduction and possibly by radiation in a *still fluid* (no bulk fluid motion) and by convection and radiation in a *flowing fluid.*

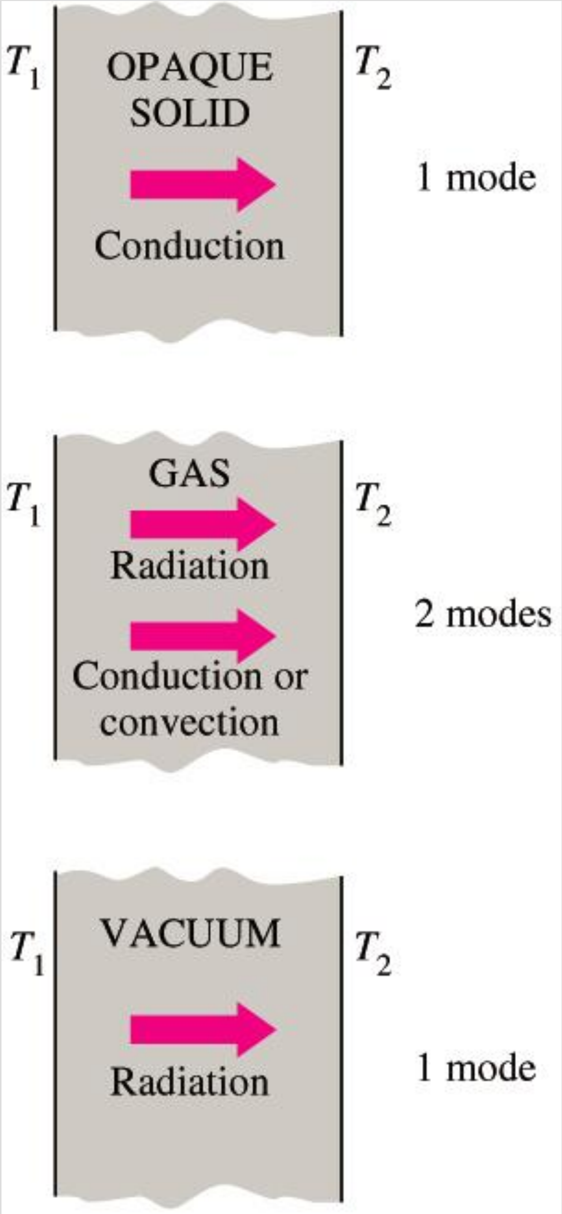
In the absence of radiation, heat transfer through a fluid is either by conduction or convection, depending on the presence of any bulk fluid motion.

Convection = Conduction + Fluid motion

Heat transfer through a *vacuum* is by radiation.

Most gases between two solid surfaces do not interfere with radiation.

Liquids are usually strong absorbers of radiation.



Although there are three mechanisms of heat transfer, a medium may involve only two of them simultaneously.

EXAMPLE 1–3 **Heat Loss from Heating Ducts in a Basement**

A 5-m-long section of an air heating system of a house passes through an unheated space in the basement (Fig. 1–21). The cross section of the rectangular duct of the heating system is 20 cm × 25 cm. Hot air enters the duct at 100 kPa and 60°C at an average velocity of 5 m/s. The temperature of the air in the duct drops to 54°C as a result of heat loss to the cool space in the basement. Determine the rate of heat loss from the air in the duct to the basement under steady conditions. Also, determine the cost of this heat loss per hour if the house is heated by a natural gas furnace that has an efficiency of 80 percent, and the cost of the natural gas in that area is $1.60/therm (1 therm = 105,500 kJ).

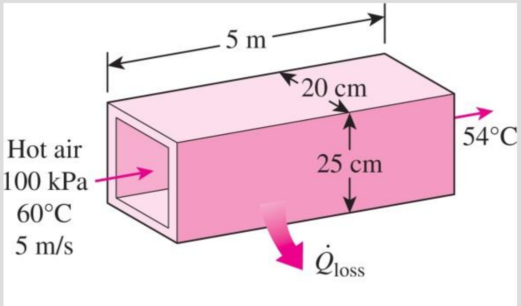


FIGURE 1–21
Schematic for Example 1–3.

SOLUTION The temperature of the air in the heating duct of a house drops as a result of heat loss to the cool space in the basement. The rate of heat loss from the hot air and its cost are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Air can be treated as an ideal gas with constant properties at room temperature.

Properties The constant pressure specific heat of air at the average temperature of (54 + 60)/2 = 57°C is 1.007 kJ/kg·K (Table A–15).

Analysis We take the basement section of the heating system as our system, which is a steady-flow system. The rate of heat loss from the air in the duct can be determined from

$$\dot{Q} = \dot{m} c_p \Delta T$$

where $\dot{m}$ is the mass flow rate and ΔT is the temperature drop. The density of air at the inlet conditions is

$$\rho = \frac{P}{RT} = \frac{100 \text{ kPa}}{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(60 + 273)\text{K}} = 1.046 \text{ kg/m}^3$$

The cross-sectional area of the duct is

$$A_c = (0.20 \text{ m})(0.25 \text{ m}) = 0.05 \text{ m}^2$$

Then the mass flow rate of air through the duct and the rate of heat loss become

$$\dot{m} = \rho V A_c = (1.046 \text{ kg/m}^3)(5 \text{ m/s})(0.05 \text{ m}^2) = 0.2615 \text{ kg/s}$$

and

$$\begin{aligned}\dot{Q}_{\text{loss}} &= \dot{m} c_p (T_{\text{in}} - T_{\text{out}}) \\ &= (0.2615 \text{ kg/s})(1.007 \text{ kJ/kg}\cdot°\text{C})(60 - 54)°\text{C} \\ &= \mathbf{1.58 \text{ kJ/s}}\end{aligned}$$

or 5688 kJ/h. The cost of this heat loss to the home owner is

$$\begin{aligned}\text{Cost of heat loss} &= \frac{(\text{Rate of heat loss})(\text{Unit cost of energy input})}{\text{Furnace efficiency}} \\ &= \frac{(5688 \text{ kJ/h})(\$1.60/\text{therm})}{0.80}\left(\frac{1 \text{ therm}}{105{,}500 \text{ kJ}}\right) \\ &= \mathbf{\$0.108/h}\end{aligned}$$

Discussion The heat loss from the heating ducts in the basement is costing the home owner 10.8 cents per hour. Assuming the heater operates 2000 hours during a heating season, the annual cost of this heat loss adds up to $216. Most of this money can be saved by insulating the heating ducts in the unheated areas.

EXAMPLE 1–4 Electric Heating of a House at High Elevation

Consider a house that has a floor space of 200 m^2 and an average height of 3 m at 1500 m elevation where the standard atmospheric pressure is 84.6 kPa (Fig. 1–22). Initially the house is at a uniform temperature of 10°C. Now the electric heater is turned on, and the heater runs until the air temperature in the house rises to an average value of 20°C. Determine the amount of energy transferred to the air assuming (*a*) the house is air-tight and thus no air escapes during the heating process and (*b*) some air escapes through the cracks as the heated air in the house expands at constant pressure. Also determine the cost of this heat for each case if the cost of electricity in that area is \$0.075/kWh.

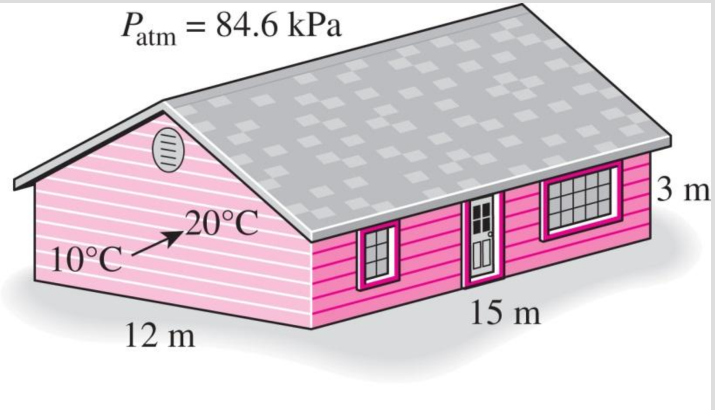


FIGURE 1–22

SOLUTION The air in the house is heated by an electric heater. The amount and cost of the energy transferred to the air are to be determined for constant-volume and constant-pressure cases.

Assumptions **1** Air can be treated as an ideal gas with constant properties. **2** Heat loss from the house during heating is negligible. **3** The volume occupied by the furniture and other things is negligible.

Properties The specific heats of air at the average temperature of (10 + 20)/2 = 15°C are c_p = 1.007 kJ/kg·K and $c_v = c_p - R$ = 0.720 kJ/kg·K (Tables A–1 and A–15).

Analysis The volume and the mass of the air in the house are

$$V = (\text{Floor area})(\text{Height}) = (200 \text{ m}^2)(3 \text{ m}) = 600 \text{ m}^3$$

$$m = \frac{PV}{RT} = \frac{(84.6 \text{ kPa})(600 \text{ m}^3)}{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(10 + 273)\text{K}} = 648 \text{ kg}$$

(*a*) The amount of energy transferred to air at constant volume is simply the change in its internal energy, and is determined from

$$\begin{aligned} E_{in} - E_{out} &= \Delta E_{system} \\ E_{in,\text{ constant volume}} &= \Delta U_{air} = mc_v\Delta T \\ &= (648 \text{ kg})(0.720 \text{ kJ/kg}\cdot°\text{C})(20 - 10)°\text{C} \\ &= \mathbf{4666 \text{ kJ}} \end{aligned}$$

At a unit cost of \$0.075/kWh, the total cost of this energy is

$$\begin{aligned} \text{Cost of energy} &= (\text{Amount of energy})(\text{Unit cost of energy}) \\ &= (4666 \text{ kJ})(\$0.075/\text{kWh})\left(\frac{1 \text{ kWh}}{3600 \text{ kJ}}\right) \\ &= \mathbf{\$0.097} \end{aligned}$$

(*b*) The amount of energy transferred to air at constant pressure is the change in its enthalpy, and is determined from

$$\begin{aligned} E_{in,\text{ constant pressure}} &= \Delta H_{air} = mc_p\Delta T \\ &= (648 \text{ kg})(1.007 \text{ kJ/kg}\cdot°\text{C})(20 - 10)°\text{C} \\ &= \mathbf{6525 \text{ kJ}} \end{aligned}$$

At a unit cost of \$0.075/kWh, the total cost of this energy is

$$\begin{aligned} \text{Cost of energy} &= (\text{Amount of energy})(\text{Unit cost of energy}) \\ &= (6525 \text{ kJ})(\$0.075/\text{kWh})\left(\frac{1 \text{ kWh}}{3600 \text{ kJ}}\right) \\ &= \mathbf{\$0.136} \end{aligned}$$

Discussion It costs about 10 cents in the first case and 14 cents in the second case to raise the temperature of the air in this house from 10°C to 20°C. The second answer is more realistic since every house has cracks, especially around the doors and windows, and the pressure in the house remains essentially constant during a heating process. Therefore, the second approach is used in practice. This conservative approach somewhat overpredicts the amount of energy used, however, since some of the air escapes through the cracks before it is heated to 20°C.