Thermal Fluid Engineering
ENMC4411
Chapter 7 Modes of heat transfer

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Outline

- Heat Transfer Modes
- Conduction
- Convection
- Radiation
- Energy balance

What is heat

- **Heat**: It is energy in transit as a result of a temperature difference.
- Heat transfer is the science dealing with the determination of the rate of such energy transfer. It is a non- equilibrium phenomena.
- Heat transfer from higher temperature to lower temperature and it stops when two objects reach the same temperature.

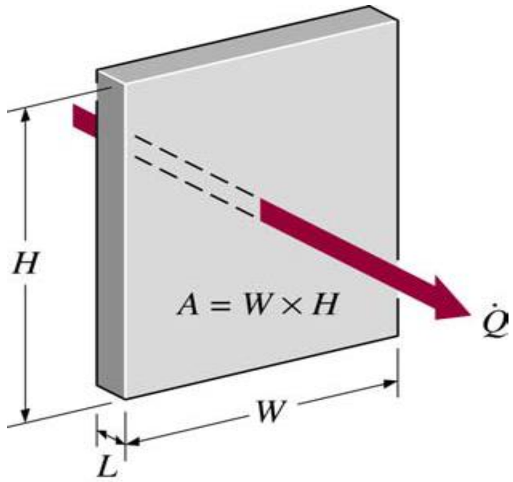
Models of Heat Transfer

- ***Conduction***: when temperature gradient exists in a stationary medium; such as solid or a stationary fluid.
- ***Convection***: between a surface and adjacent fluid – liquid or gas- "a moving" fluid when they are at a different temperature.
- ***Thermal radiation***: all surfaces of finite temperature emit energy in the form of electromagnetic waves.

Conduction heat transfer

- If temperature gradient exists in a body, then energy is transferred from high temperature to low temperature.
- Fourier law: $$q_x = -kA\frac{dT}{dx}$$

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



- Minus sign because heat flows from high to low Temperature.

q''_x: heat flux (W/m^2), heat transfer rate in x-direction per unit area perpendicular to direction of heat transfer.

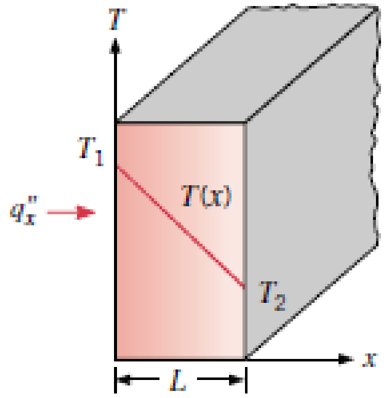
dT/dx: temperature gradient in x-direction.

k: thermal conductivity W/m.K; characteristic of wall material.

Conduction heat transfer

- Minus sign is a consequence of heat being transferred in direction of decreasing temperature. If the system losses energy, then its sign will be (-).

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



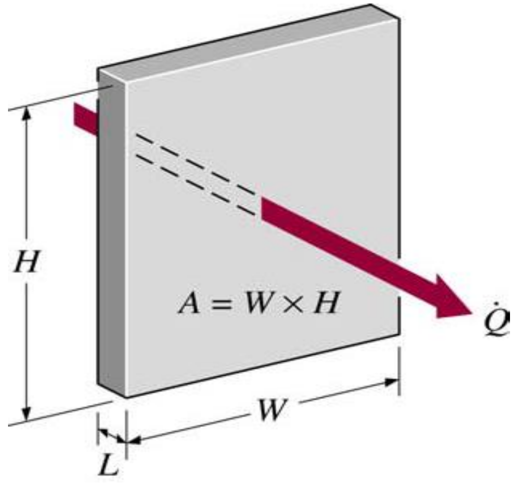
$$q''_x = k\frac{T_1 - T_2}{L} = k\frac{\Delta T}{L}$$

Example (1.1) p.4

- Furnace wall is 0.15m thick, k= 1.7W/m.k, T_1= 1400 K inner wall, T_2=1150K outer wall. Find q if it is 0.5x3m on a side.

$$q''_x = k\frac{T_1 - T_2}{L} = k\frac{\Delta T}{L}$$

= (1.7)(250/0.15)= 2833 W/m^2



Total heat transfer

q = A q''_x

= (0.5x3) (2833) = 4250 W

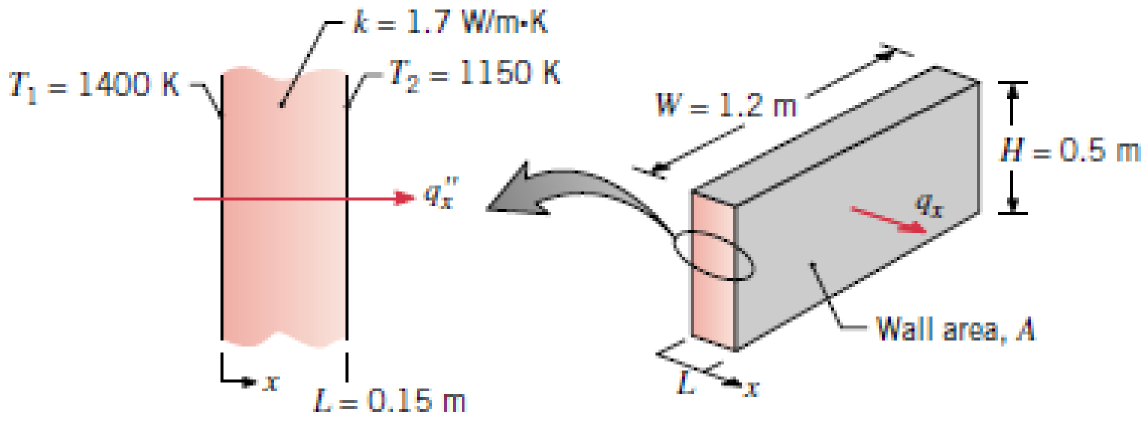
Example 15.1 The Conduction Rate Equation

- The wall of an industrial furnace is constructed from 0.15-m-thick fireclay brick having a thermal conductivity of 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 transfer through a wall that is 0.5 m by 1.2 m on a side?

Solution

Known: Steady-state conditions with prescribed wall thickness, area, thermal conductivity, and surface temperatures.

Find: Heat transfer rate through the wall.



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

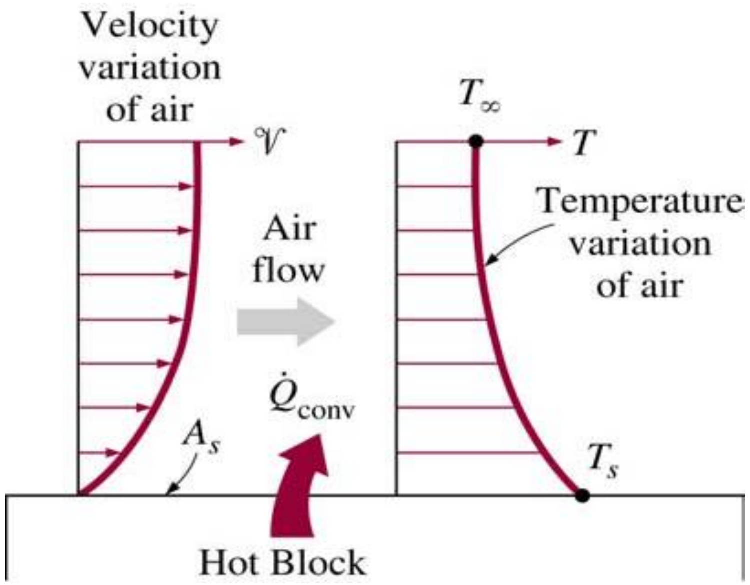
$$q_x = (HW)\, q_x'' = (0.5\ \text{m} \times 1.2\ \text{m})\, 2833\ \text{W/m}^2 = 1700\ \text{W}$$

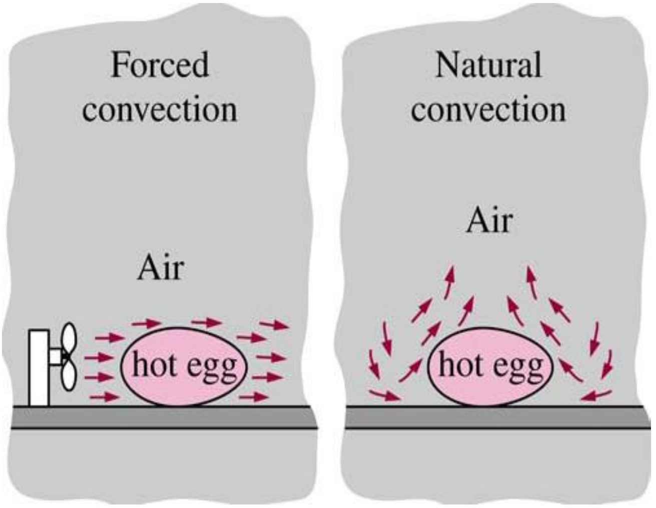
Convection heat transfer

The term ***convection*** refers to heat transfer that will occur between a surface and a moving or stationary fluid when they are at different temperatures

(a) Forced convection; flow is caused by external force such as a pump, a fan, wind ….etc.

(b) Free (natural) convection: if flow is induced by buoyancy forces in the fluid, which arises from density difference due to temperature difference.





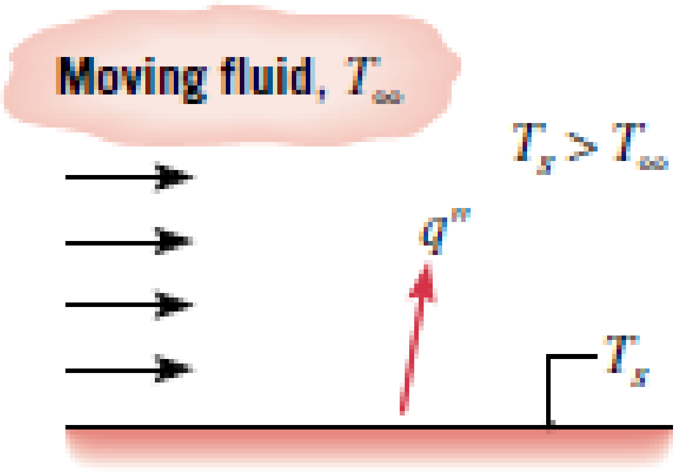
Convection heat transfer

- If fluid is in motion (forced convection) and there is a temperature difference between a surface Ts and fluid temperature T∞ then heat flux is given by Newton law of cooling/heating

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

h= heat transfer coefficient or film coefficient.

- h: depends on flow conditions, surface geometry, fluid motion, transport properties.



Convection heat transfer

- Convection heat transfer may involve:
  - Sensible or internal thermal energy.
  - Latent heat exchange: associated with phase change. Liquid to Vapor; for example boiling & condensation.
- See typical values of "h" table 1.5, below.

TABLE 1–5

Typical values of convection heat transfer coefficient

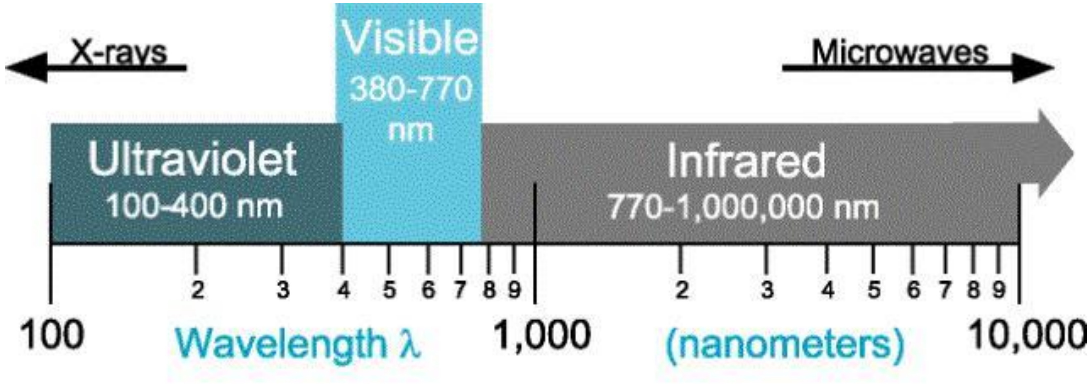
Type of convection	h, W/m^2 · °C*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

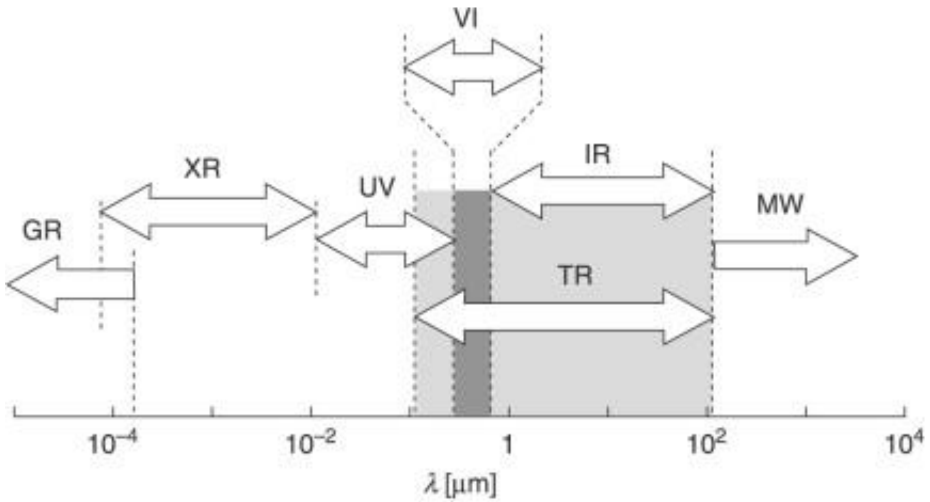
*Multiply by 0.176 to convert to Btu/h · ft^2 · °F.

Radiation heat transfer

- Thermal radiation is energy emitted by a surface at a given temperature.
- Energy emitted in form of electromagnetic waves as a result of electrons moving to lower energy levels.
- Radiation doesn't require presence of a material medium for energy transfer in contrast to convection and conduction heat transfer.

Thermal radiation spectrum range: 0.1 to 100 μm





Radiation heat transfer

- Maximum emitted energy is given by Stefan-Boltzmann law

$$E_b = q'' = \sigma T_s^4$$

Ts: surface absolute temperature (K).

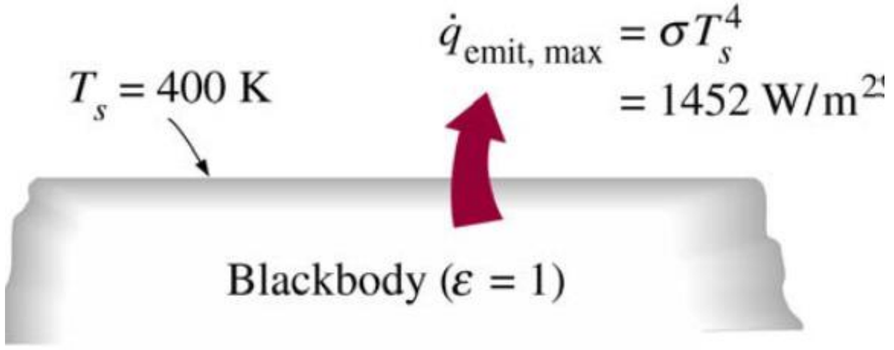
$\sigma = 5.6 \times 10^{-8}$ w/m^2.K^4 Stefan –Boltzmann constant.

Real surfaces emits $E = \varepsilon \sigma Ts^4$

Where ε is the emissivity; property of surface .

Irradiation= $G = \sigma T^4_{surr}$. Incident rad. /m^2; absorbed = αG,

Where α is the absorptivity , and for gray surface $\varepsilon = \alpha$.



$$E = \varepsilon \sigma T_s^4$$

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

Radiation heat transfer

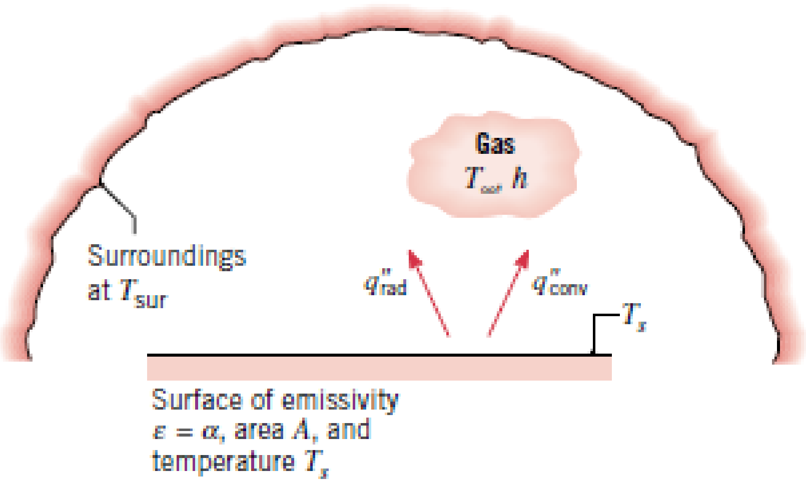
- Energy exchange between a surface and its surrounding is given by

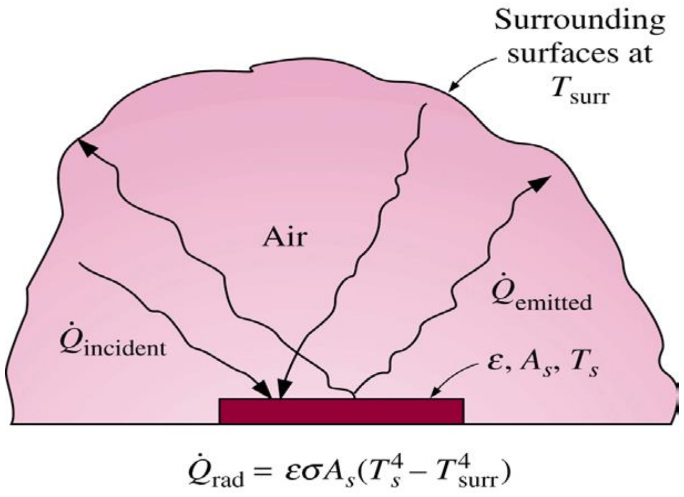
$$q''_{rad} = \frac{q}{A} = \varepsilon E_b(T_s) - \alpha G = \varepsilon\sigma(T_s^4 - T_{sur}^4)$$

$q = \varepsilon\sigma A(T_s^4 - T_{surr.}^4)$,

$q_{rad.} = h_r A(T_s - T_{surr.})$

$h_r = \varepsilon\sigma (T_s + T_{surr.})(T_s^2 + T_{surr.}^2)$.

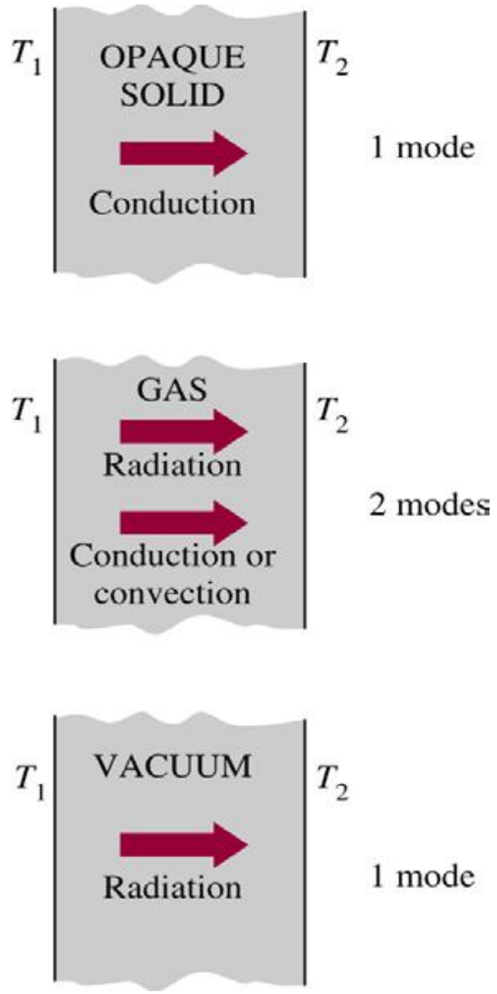




Radiation and convection

$q = q_{conv} + q_{rad}$.

$$q = q_{conv} + q_{rad} = hA(T_s - T_\infty) + \varepsilon A\sigma(T_s^4 - T_{sur}^4)$$



Example 15.2 Convection and Radiation Exchange

An uninsulated steam pipe passes through a large room in which the air and walls are at 25C. The outside diameter of the pipe is 70 mm, and its surface temperature and emissivity are 200C 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/m2 K and the surface is gray, what is the rate of heat transfer from the surface per unit length of pipe?

Assumptions:

1. Steady-state conditions.

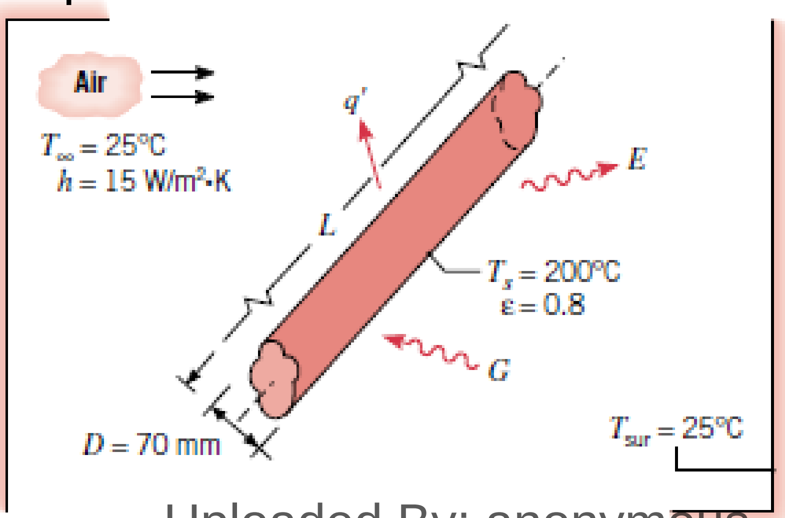
2. Radiation exchange between the pipe and the room is between a small surface and large, isothermal surroundings.

3. The surface is diffuse-gray; that is, the emissivity and absorptivity are equal.

Solution

Known: Uninsulated pipe of prescribed diameter, emissivity, and surface temperature in a large room with fixed wall and air temperatures.

Find: Surface emissive power, *E*, and irradiation, *G*. Pipe heat transfer per unit length, *q*.



Analysis:

The surface emissive power may be evaluated from Equation 15.5, while the irradiation corresponds to $G = \sigma T_{sur}^4$. Hence

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

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

Heat transfer 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 15.10, with $A = \pi DL$

$$q = h(\pi DL)(T_s - T_\infty) + \varepsilon(\pi DL)\sigma(T_s^4 - T_{sur}^4)$$

The heat transfer per unit length of pipe is then

$$q' = \frac{q}{L} = 15\ \mathrm{W/m^2\cdot K}(\pi \times 0.07\ \mathrm{m})(200 - 25)^\circ\mathrm{C} + 0.8(\pi \times 0.07\ \mathrm{m})\ 5.67 \times 10^{-8}\ \mathrm{W/m^2\cdot K^4}\ (473^4 - 298^4)\ \mathrm{K^4}$$

$$q' = 577\ \mathrm{W/m} + 421\ \mathrm{W/m} = 998\ \mathrm{W/m} \ \lhd$$

Comments:

1. Note that temperature may be expressed in units of °C or K when evaluating the *temperature difference* for a convection (or conduction) heat transfer rate. However, temperature must be expressed in kelvins (K) when evaluating a radiation transfer rate.
2. In this situation the radiation and convection heat transfer rates are comparable because T_s is large compared to T_{sur}, and the coefficient associated with free convection is small. For more moderate values of T_s and the larger values of h associated with forced convection, the effect of radiation may often be neglected. The radiation heat transfer coefficient may be computed from Equation 15.9, and for the conditions of this problem its value is $h_{rad} = 11\ \mathrm{W/m^2\cdot K}$.

Conservation of energy for control volume energy balance

- Rate at which thermal and mechanical energy enters a control volume minus the rate at which this energy leaves the control volume must equal the rate at which this energy is stored in the control volume. If there is energy generation (source of energy) in the control volume then this must be added to the equation as given below in the “rate form”.

$$\dot{E}_{in} + \dot{E}_{g} - \dot{E}_{out} = \dot{E}_{st} = \frac{dE_{st}}{dt} = \rho V \frac{du}{dt} = \rho V C \frac{dT}{dt}.$$

$\dot{E}_{in}, \dot{E}_{out}$ may include heat transfer by conduction, convection or radiation. It is surface phenomena, if material is crossing system boundary (C.V open system) energy associated with flow is included, such energy could be kinetic, potential or thermal (enthalpy)

$\dot{E}_{g}$ = heat generation, volumetric phenomenon such as exothermic chemical reactions (endothermic have a negative generation), electrical energy converted to thermal heating due to resistance heating.

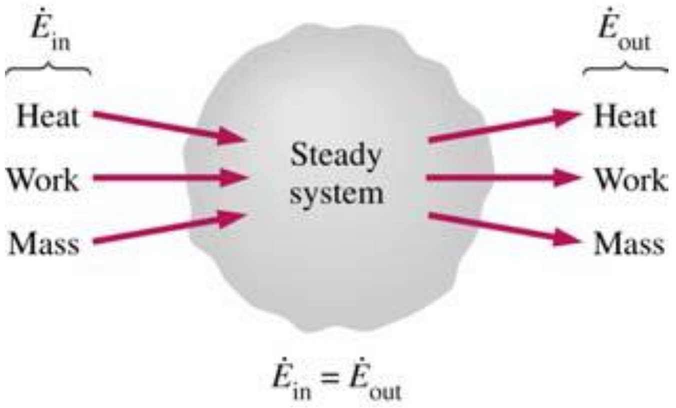
Energy balance

Volumetric generation rate (W/m^3) $\dot{q} = \dfrac{\dot{E}_g}{V}$

electrical power dissipation $\dot{E}_g = I^2 R_e$

$$\dot{E}_g = I^2 R'_e L$$

For systems at steady state, the internal energy storage term reduces to zero

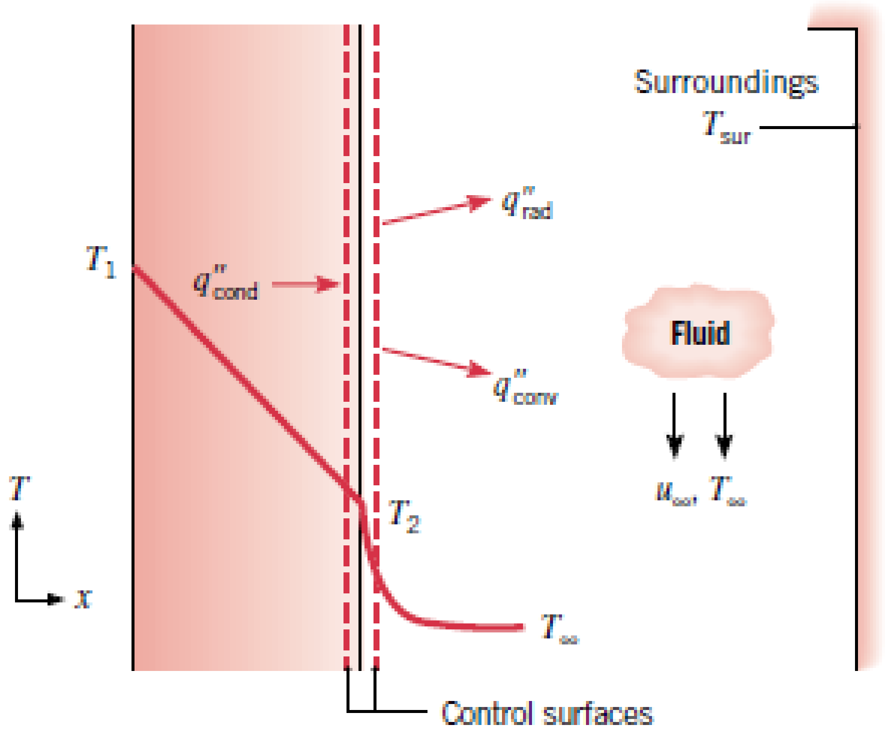


Surface Energy Balance

- Apply energy conservation at a surface of a medium, as a special case for energy conservation of the c.v .In this case there is no mass or volume for energy storage, and surface phenomena are only included.

$$\dot{E}_{in} - \dot{E}_{out} = 0 \qquad \dot{E}_{in} + \dot{E}_{g} - \dot{E}_{out} = \dot{E}_{st}$$

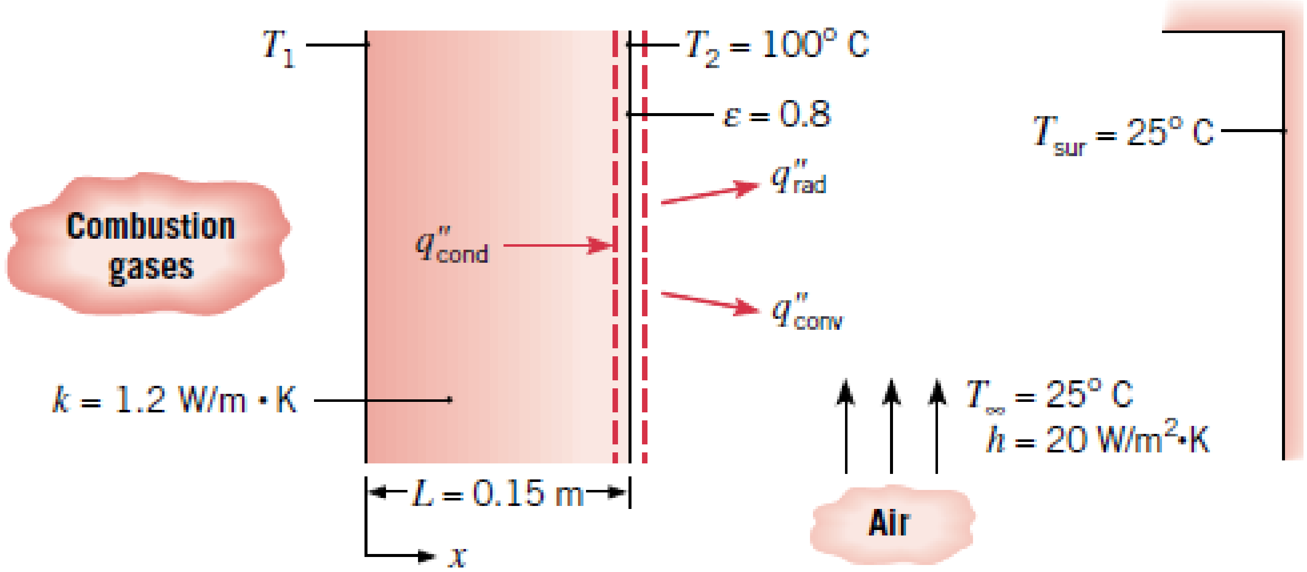
$$q''_{cond} - q''_{conv} - q''_{rad} = 0$$



Example 15.5 Applying the Surface Energy Balance with Multiple Heat Transfer Modes

The hot combustion gases of a furnace are separated from the ambient air and its surroundings, which are at 25C, by a brick wall 0.15 m thick. The brick has a thermal conductivity of 1.2 W/m . K and a surface emissivity of 0.8. Under steady-state conditions an outer surface temperature of 100C is measured. Free convection heat transfer to the air adjoining the surface is characterized by a convection coefficient of *h*= 20 W/m2
What is the brick inner surface temperature?

Assumptions:
1. Steady-state conditions.
2. One-dimensional heat transfer by conduction across the wall.
3. Radiation exchange between the outer surface of the wall and the surroundings is between a small, diffuse-gray surface and large, isothermal surroundings.



Analysis: The inner surface temperature T_1 may be obtained by performing an energy balance at the outer surface. From Eq. 15.14

$$\dot{E}_{in} - \dot{E}_{out} = 0$$

it follows that, on a unit area basis

$$q''_{cond} - q''_{conv} - q''_{rad} = 0$$

or, rearranging and substituting from Eqs. 15.2, 15.3a, and 15.7

$$k\,\frac{T_1 - T_2}{L} = h(T_2 - T_\infty) + \varepsilon\sigma(T_2^4 - T_{sur}^4)$$

Therefore, substituting the appropriate numerical values, we find

$$1.2\ \mathrm{W/m\cdot K}\,\frac{(T_1 - 373)\ \mathrm{K}}{0.15\ \mathrm{m}} = 20\ \mathrm{W/m^2\cdot K}\,(373 - 298)\ \mathrm{K}$$

$$+\ 0.8(5.67 \times 10^{-8}\ \mathrm{W/m^2\cdot K^4})(373^4 - 298^4)\ \mathrm{K^4}$$

$$= 1500\ \mathrm{W/m^2} + 520\ \mathrm{W/m^2} = 2020\ \mathrm{W/m^2}$$

Solving for T_1, find the inner wall temperature as

$$T_1 = 373\ \mathrm{K} + \frac{0.15\ \mathrm{m}}{1.2\ \mathrm{W/m\cdot K}}(2020\ \mathrm{W/m^2}) = 625\ \mathrm{K} = 352^\circ\mathrm{C} \quad \triangleleft$$

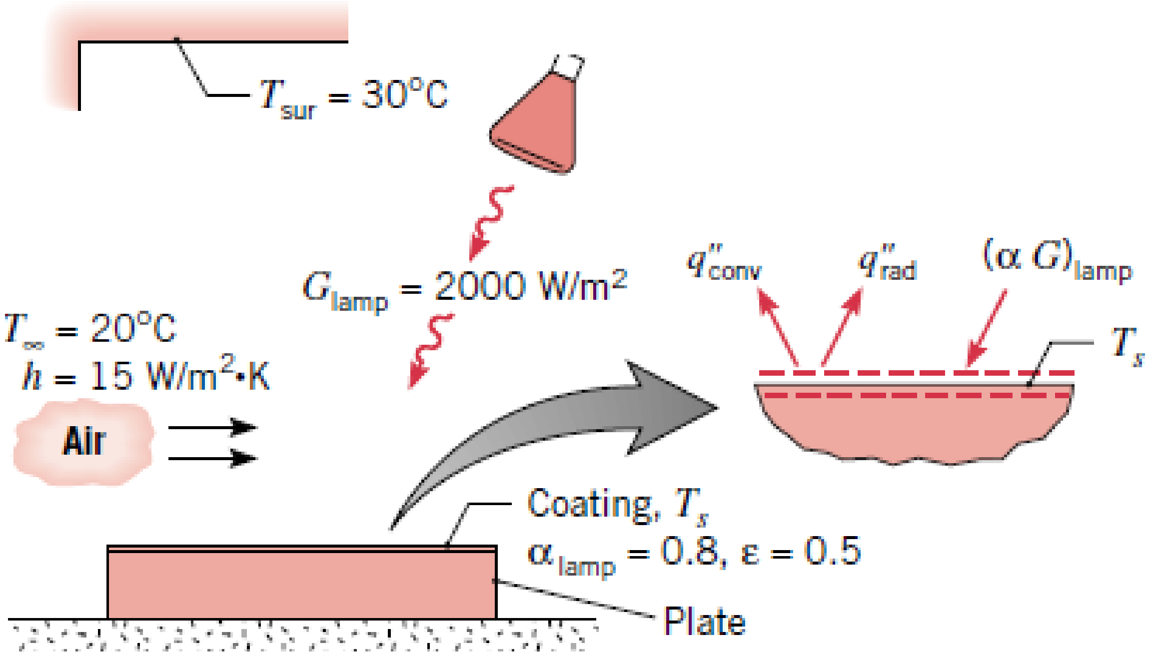
When using energy balances involving radiation exchange and other modes of heat transfer, it is good practice to express all temperatures in kelvin units. This practice is *necessary* when the unknown temperature appears in the radiation term and in one or more of the other terms.

Example 15.6 Curing a Coating with a Radiant Source

The coating on a plate is cured by exposure to an infrared lamp providing an irradiation of 2000 W/m2. It absorbs 80% of the irradiation from the lamp and has an emissivity of 0.50. It is also exposed to an air flow and large surroundings for which temperatures are 20C and 30C, respectively. The convection coefficient between the coating and the ambient air is 15 W/m2 . K and the back side of the plate is insulated. What is the temperature of the coated plate?

Assumptions:

1. Steady-state conditions.
2. Negligible heat loss from back side of the plate.
3. Plate is small object in large surroundings. Coating is diffuse-gray, having an absorptivity of $\alpha = 0.5$ with respect to irradiation from the surroundings.
4. Absorptivity of lamp irradiation is lamp $\alpha = 0.80$.



Analysis: Since the process corresponds to steady-state conditions and there is no heat transfer at the plate back side, the plate and the coating are both at T_s. Hence the coating temperature may be determined by placing a control surface about the exposed surface and applying Eq. 15.14

$$\dot{E}_{in} - \dot{E}_{out} = 0$$

With energy inflow due to absorption of the lamp irradiation and outflow due to convection and net radiation transfer to the surroundings, it follows that

$$(\alpha G)_{lamp} - q''_{conv} - q''_{rad} = 0$$

Substituting the rate equations from Eqs. 15.3a and 15.7, we obtain

$$(\alpha G)_{lamp} - h(T_s - T_\infty) - \varepsilon\sigma(T_s^4 - T_{sur}^4) = 0$$

Substituting numerical values

$$0.8 \times 2000 \text{ W/m}^2 - 15 \text{ W/m}^2 \cdot \text{K}(T_s - 293)\text{ K} - 0.5 \times 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4(T_s^4 - 303^4)\text{ K}^4 = 0$$

and solving iteratively, we obtain the coating temperature

$$T_s = 377 \text{ K} = 104°\text{C} \quad \triangleleft$$

Comments: The coating (plate) temperature may be elevated by increasing T_∞ and T_{sur}, as well as by decreasing the air velocity and hence the convection coefficient.

Table 15.2 Summary of heat transfer processes

Mode	Mechanism(s)	Rate Equation	Equation Number	Transport Property or Coefficient
Conduction	Energy transfer due to molecular/atomic activity	$q''_x(\text{W/m}^2) = -k\dfrac{dT}{dx}$	(15.1)	k (W/m · K)
Convection	Energy transfer due to molecular motion (conduction) plus energy transfer due to bulk motion (advection)	$q''(\text{W/m}^2) = h(T_s - T_\infty)$	(15.3a)	h (W/m^2 · K)
Radiation	Energy transfer by electromagnetic waves; radiation exchange, diffuse-gray surface-large surroundings	$q''(\text{W/m}^2) = \varepsilon\sigma(T_s^4 - T_{\text{sur}}^4)$ or $q''(W) = h_{\text{rad}}(T_s - T_{\text{sur}})$	(15.7) (15.8)	ε h_{rad} (W/m^2 · K)

End of heat transfer modes