II. Energy and the First Law of Thermodynamics

A. Energy Transfer as Heat Transfer. Energy is Conserved.

1. Energy can cross the boundary of a closed system by only two mechanisms: heat transfer and work transfer.
2. The change in energy of a closed system is equal to the net heat transferred to the system minus the net work performed by the system.

Net work out, $W_{out,net} = W_{out} - W_{in}$

$$\Delta E_{total} = \Delta E_{system} + \Delta E_{surroundings} = 0$$

$$\Delta E_{system} = -\Delta E_{surroundings}$$

Closed system

$$\Delta E_{sys} = Q_{in,net} - W_{out,net}$$

Net heat in, $Q_{in,net} = Q_{in} - Q_{out}$

lesson 5 (2-34), p. 73; (4-17), p 174

II. Energy and the First Law of Thermodynamics

B. Heat transfer

1. Heat is energy transferred across the boundary of the system due to a difference in temperature between the system and the surroundings.
   a. The heat flux, $\dot{q}$, is the rate of heat transfer per unit area of surface. The units are W/m^2 or kW/m^2 or Btu/(ft^2 h)
   b. The heat transfer rate (kW) is calculated from the heat flux as

$$\dot{Q} = \int_A \dot{q}\, dA$$

A is the area over which heat transfer is occurring.

lesson 5

II. Energy and the First Law of Thermodynamics

c. The energy transferred (kJ) between times t_1 and t_2 is

$$Q = \int_{t_1}^{t_2} \dot{Q} dt \qquad (2\text{-}15)$$

d. The energy transferred (kJ) by heat during a process is

$$Q = \int_1^2 \delta Q$$

lesson 5

II. Energy and the First Law of Thermodynamics

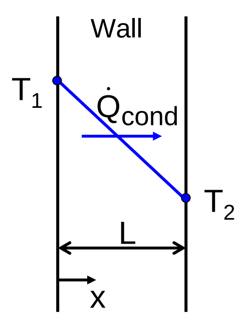
2. Conduction heat transfer (transfer of energy by putting a hotter object in contact with a cooler system)

Fourier's law

$$\dot{Q}_{cond} = -k_t A \frac{dT}{dx} \qquad (2\text{-}52)$$

Steady state, k_t = constant

$$\dot{Q}_{cond} = -k_t A \left(\frac{T_2 - T_1}{L} \right)$$



Steady state
k_t = constant

k_t = thermal conductivity, W/(m K)
k_t(air) = 0.026, k_t(water) = 0.613,
k_t(copper) = 401

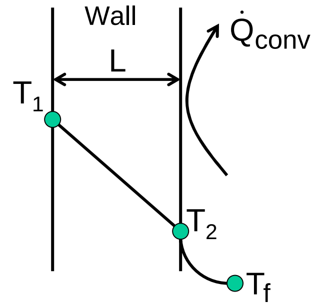
lesson 5

II. Energy and the First Law of Thermodynamics

3. Convection heat transfer (transfer of energy between a solid surface and a moving fluid)

Newton's law of cooling,
h = heat transfer coefficient.

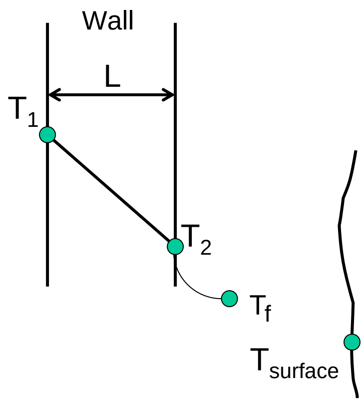
$$\dot{Q}_{conv} = hA(T_2 - T_f) \quad (2\text{-}53)$$



Flow & fluid	h, W/m^{2}K
free conv, air	5-12
forced conv, air	10-300

II. Energy and the First Law of Thermodynamics

4. Radiation heat transfer (transfer of energy due to emission and absorption of electromagnetic radiation)

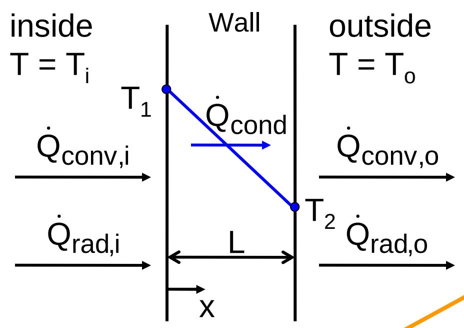


$$\dot{Q}_{rad} = \sigma\varepsilon_2 A\left(T_2^4 - T_{sur}^4\right) \quad (2\text{-}57)$$

σ = Stefan-Boltzmann constant
= 5.67x10^{-8} W/(m^2 K^4).
ε_2 = emissivity of surface 2,
$0 < \varepsilon \leq 1$.
The emissivities of skin, concrete, and stainless steel are 0.95, 0.91, 0.3.

II. Energy and the First Law of Thermodynamics

5. Heat transfer through a simple wall



It is common practice in the building industry to represent all three modes of heat transfer by a single, overall heat transfer equation.

$$\dot{Q} = \frac{A(T_i - T_o)}{R}$$

R = "R value" or overall thermal resistance, hr-ft^2-°F/Btu or m^2-°C/W.

II. Energy and the First Law of Thermodynamics

6. Application

A poorly insulated home with 1300 ft^2 of ceiling is located in a region with an 8-month heating season. The average outdoor temperature during the heating season is 40°F and the inside temperature is fixed at 70°F. The owner will spend $850 to increase the R-value of the insulation in the ceiling from 11 to 40 (hr-ft^2-°F/Btu). The house is heated with electricity that costs 10 cents / kWh. How much energy will the owner save each year and how long will it take for the saved energy to pay for the new insulation?

II. Energy and the First Law of Thermodynamics

6. Application

Heat loss rate with existing insulation:

$$\dot{Q} = \frac{A(T_i - T_o)}{R} = \frac{1300\ ft^2 (70-40)^o F}{11\ (ft^2\ {}^oF\ h/Btu)} = 3545\ Btu/h$$

Heat loss rate with new insulation:

$$\dot{Q} = \frac{A(T_i - T_o)}{R} = \frac{1300\ ft^2 (70-40)^o F}{40\ (ft^2\ {}^oF\ h/Btu)} = 975\ Btu/h$$

Energy saved in one year:

$$Energy\ saved = \frac{(3545-975)\ \frac{Btu}{h}}{3414\ \frac{Btu}{kWh}} 24\frac{h}{day} 30\frac{day}{mo} 8\frac{mo}{yr} = 4339\ \frac{kWh}{yr}$$

II. Energy and the First Law of Thermodynamics

6. Application

$ saved in one year:

$$\$\ saved = 4339\ \frac{kWh}{yr} \$0.10/kWh = \$434/yr$$

Time to recover cost of insulation:

$$\frac{\$850}{\$434/y} = 1.96\ heating\ seasons$$