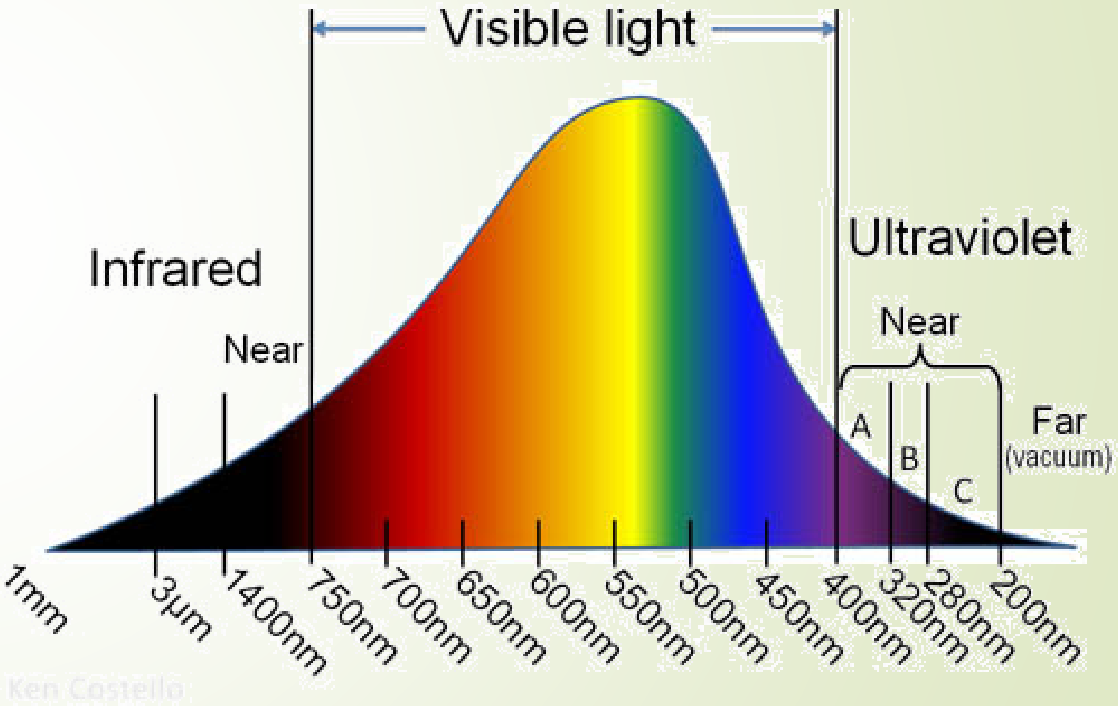
THERMAL *RADIATION*

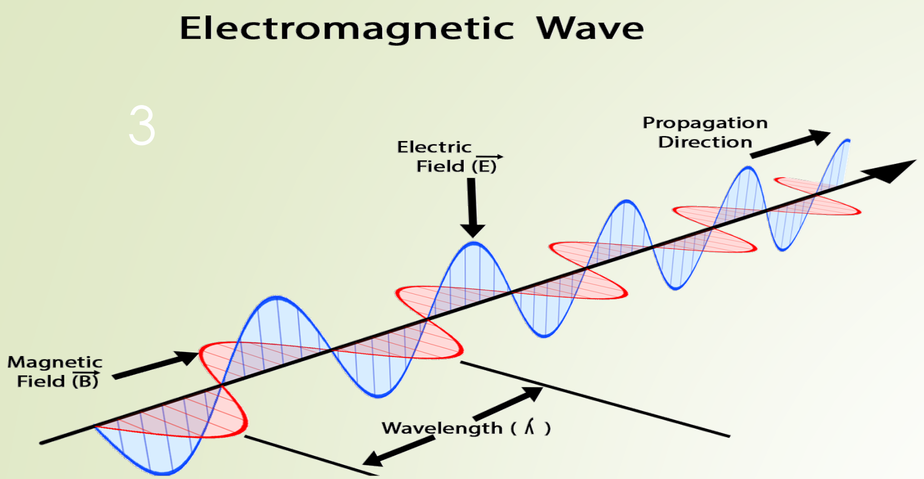
MECH-420 Heat Transfer

Dr. K. J. Berry

THERMAL RADIATION

- We associate thermal RADIATION WITH THE RATE AT WHICH ***ENERGY IS EMITTED BY MATTER AS A RESULT OF ITS FINITE TEMPERATURE***. Thermal radiation is emitted by all matters that surrounds you: by the room walls, by the ground, buildings, and even the atmosphere and the sun.
- The ***MECHANISM OF EMISSION*** is related to energy released as a result of oscillations or translations of the many electrons that constitute matter. These oscillations are, in turn, sustained by the internal energy, and therefore the temperature, of the matter.
- Hence, we associate the emission of thermal radiation with thermally excited conditions within the matter.





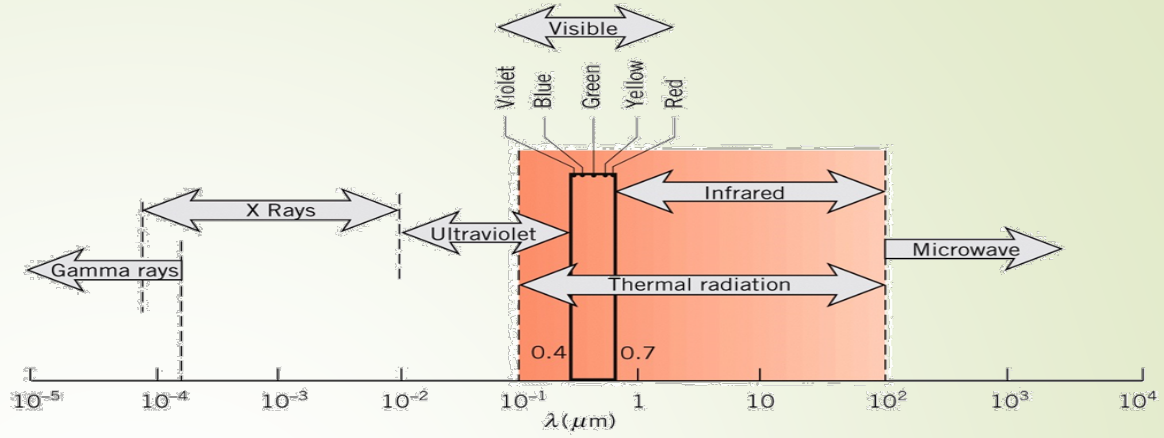


Figure 12.3

Radiation may be viewed as the propagation of "electromagnetic waves" with a frequency of ν and a wavelength of λ, where the properties are related by: $\lambda = \frac{c}{\nu}$, where "c" is the speed of light in the medium. For example, for a vacuum, $c = 2.998x10^8 m/s$. The complete electromagnetic spectrum is delineated below.

WAVE PROPAGATION

BLACKBODY RADIATION

- ***A "BLACKBODY" is an ideal surface with the following attributes:***

- ***A blackbody absorbs all incident radiation, regardless of wavelength and direction.***

- ***For a prescribed temperature and wavelength, no surface can emit more energy than a blackbody.***

✓ ***Although the radiation emitted by a blackbody is a function of wavelength and temperature, it's independent of direction.***

TOTAL EMISSIVE POWER

The total emissive power (radiation heat flux) of a blackbody over all wavelengths can be determined as:

$$E_b[\frac{W}{m^2}] = \int_0^{\infty} E_\lambda(\lambda) d\lambda = \sigma T^4 [K^4]$$

$$\sigma = 5.67x10^{-8} \frac{W}{m^2 - K^4}; \text{ Stefan-Boltmann Constant}$$

Therefore, the total radiation heat transfer rate for a blackbody with area surface, As, and Temperature, Ts is:

$$q[W] = A_s \sigma T_s^4$$

NET RADIATION EXCHANGE

➨Consider a small blackbody object at Temperature Ts and completely enclosed and exchanging radiation with the surroundings at Temperature Tsur < Ts as shown below.

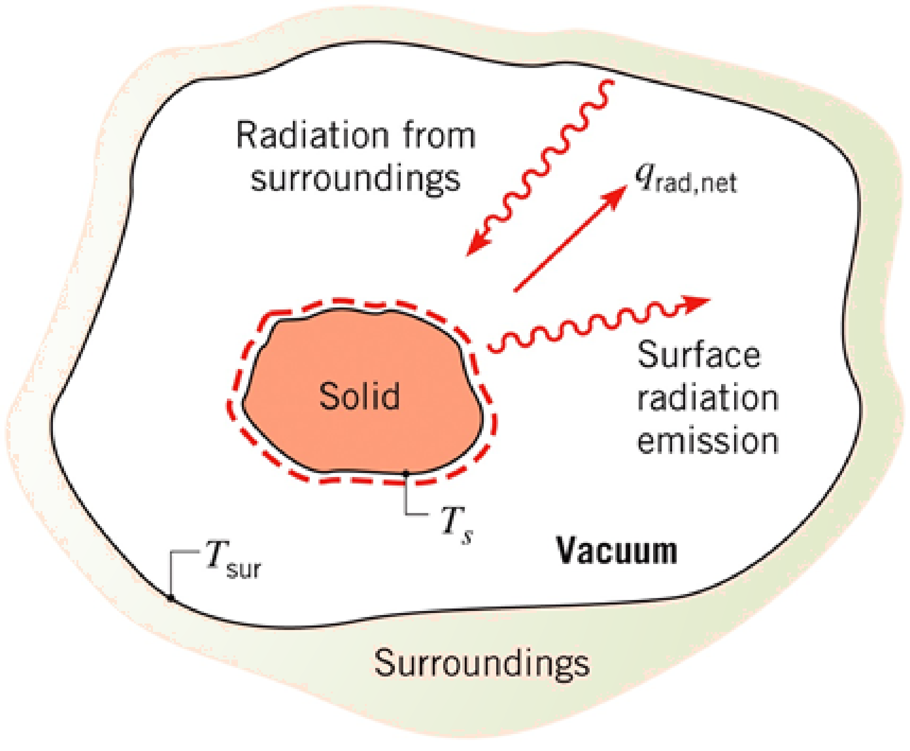


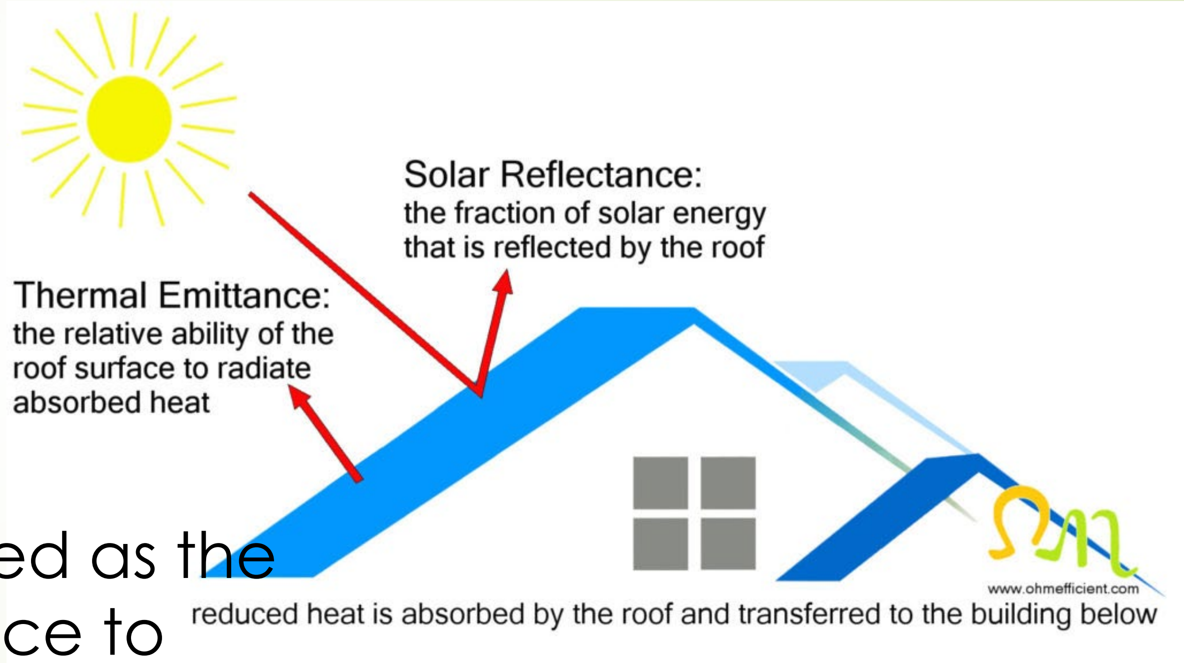
Figure 12.1

The 'net' radiation exchange between the blackbody and the surrounding enclosure is:

$$q''_{rad}\left[\frac{W}{m^2}\right] = \sigma \frac{W}{m^2 - K^4}(T_s^4 - T_{surr}^4)$$

EMISSION FROM REAL SURFACES

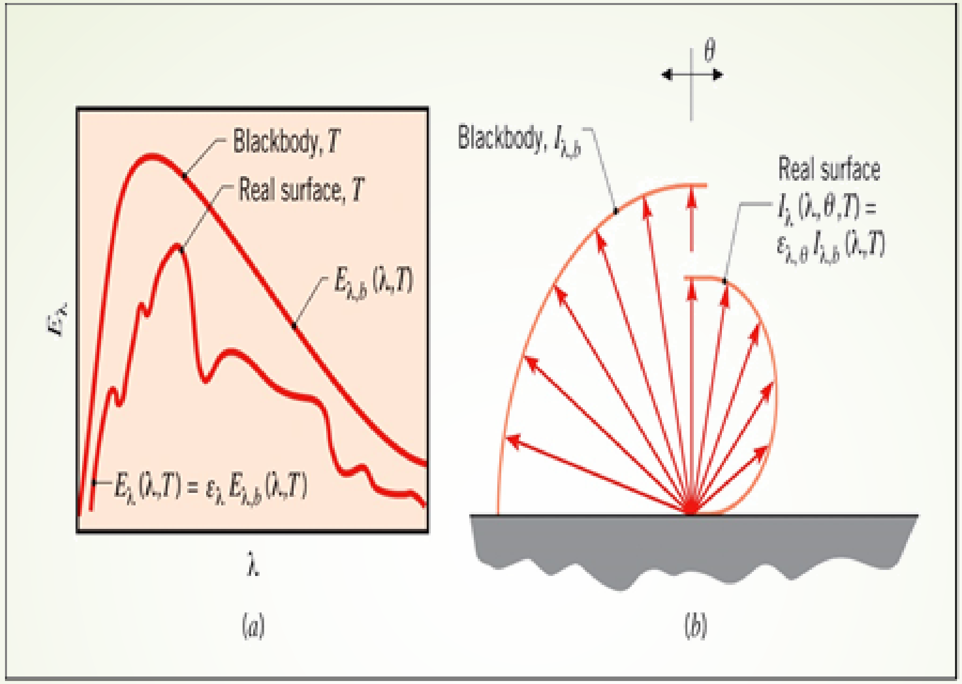
A blackbody is an **ideal emitter** in the sense that no surface can emit more radiation than a blackbody at the same temperature. A "***real" surface has a resistance*** therefore will have a radiative emissive power less than a blackbody and is designated as a surface property known as the surface "emissivity", ε



The ***surface emissivity*** may then be defined as the ratio of the radiation emitted by the surface to the radiation emitted by a blackbody at the same temperature.

The figure shows the comparison between a real surface and a blackbody or ideal surface (a), and the directional distribution comparison (b). Therefore, the emissive power of a ‘real” surface is with area A_s and Temperature T_s is:

$$E[W] = \varepsilon A_s \sigma T_s^4$$



8 Blackbody vs Real Surfaces

REAL SURFACE RESISTANCE

Every "***real***" surface has a resistance to thermal radiation emission. This resistance and net radiation heat transfer exchange can be expressed by:

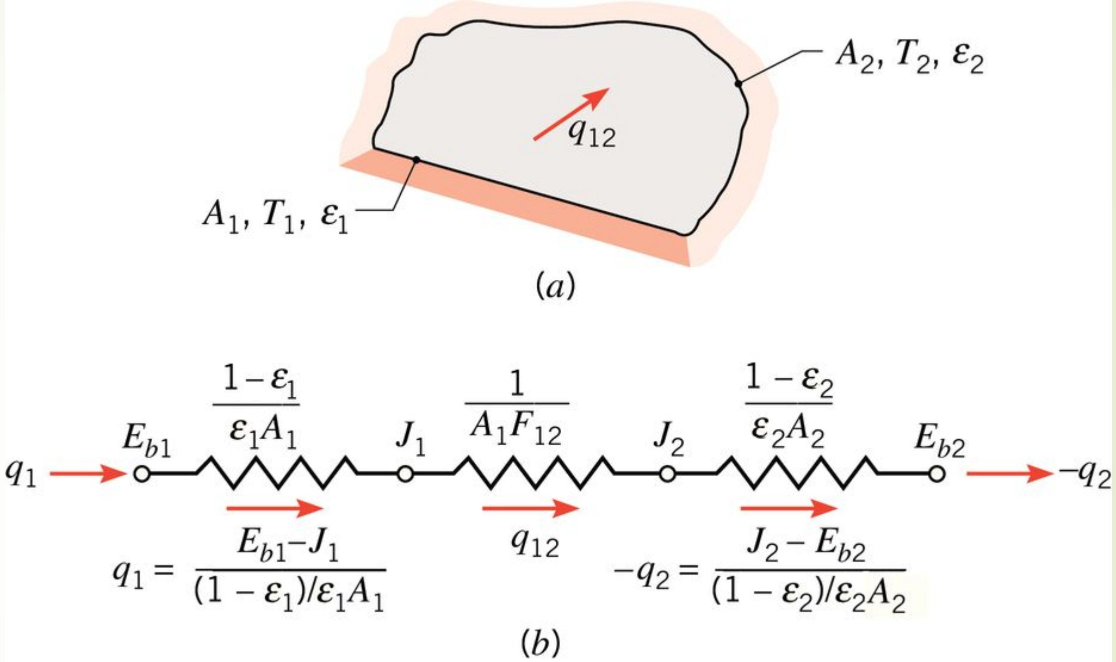
$$q_{net} = \frac{E_b - J}{\dfrac{1-\varepsilon}{\varepsilon A}}$$

Where $E_b - J$ is the driving surface potential and where J is known as the surface Radiosity (W/m2) and $\frac{1-\varepsilon}{\varepsilon A}$ is the surface resistance to radiation emission. Note for a blackbody $\varepsilon = 1$, and the resistance goes to zero.

Radiation Balance – 2 Surface Problem

$$1: q_1 = \frac{E_{b1} - J_1}{\dfrac{1-\varepsilon_1}{\varepsilon_1 A_1}} = \frac{J_1 - J_2}{\dfrac{1}{A_1 F_{12}}}$$

$$2: q_2 = \frac{E_{b2} - J_2}{\dfrac{1-\varepsilon_2}{\varepsilon_2 A_2}} = \frac{J_2 - J_1}{\dfrac{1}{A_2 F_{21}}}$$



Two equations and two unknowns for J_1 and J_2.

Assuming T_1 and T_2 are known.

$\frac{1}{A_i F_{ij}}$

"n" Surfaces Exchange

To complete the exchange analysis we need to consider a radiation energy balance for each surface shown above to the right. Due to the distance between surface and the ***RELATIVE SHAPE*** of each surface, not all the energy that is emitted by surface "1", say will reach surface "2".

This distance and geometry differences result in a "surface" resistance for surface "i" of the form: $\frac{1}{A_i F_{ij}}$

. Where F_{ij} (shape/view factor) is the fraction of energy that leaves surface "I", and strikes surface "j" directly.

So a radiation balance of an arbitrary surface "I" and exchanging radiation with "n" other surfaces (including itself) becomes:

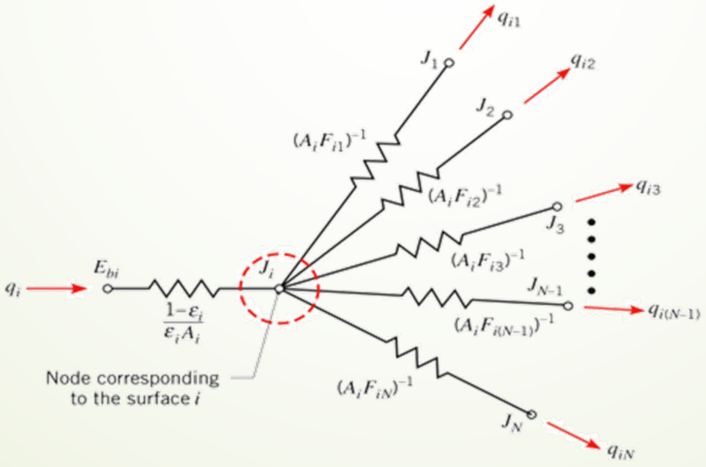


Figure 13.10

$$\frac{E_{bi}-J_i}{\frac{1-\varepsilon_i}{\varepsilon_i A_i}} = \sum_{j=1}^{n} \frac{J_i - J_j}{\frac{1}{A_i F_{ij}}};$$

applied to every surface if "T" is known

and once J's are known of if "q" is known:

$$q_i = \sum_{j=1}^{n} \frac{J_i - J_j}{\frac{1}{A_i F_{ij}}} = \frac{E_{b_i} - J_i}{\frac{1-\varepsilon_i}{\varepsilon_i A_i}}$$

SHAPE FACTORS

SHAPE FACTORS--RECIPROCITY

The shape factor A_iF_{ij} is the fraction of energy that leaves surface “I” and strikes surface “j”. Of course this must be a reciprocal relationship, i.e.:

In general for any two arbitrary surfaces

$$A_iF_{ij} = A_jF_{ji}$$

Example, for surfaces 1 *and* 2

$$A_1F_{12} = A_2F_{21}$$

Also, since the “F” represents a fraction of the total energy leaving a surface and since energy is conserved the following summation rule applies as:

$$\sum_{j=1}^{n} F_{ij} = 1; \text{for every surface}$$

for example for surface 1:

$$F_{11}+F_{12}=1; \text{and}$$

for surface 2, etc.

$$F_{21}+F_{22}=1$$

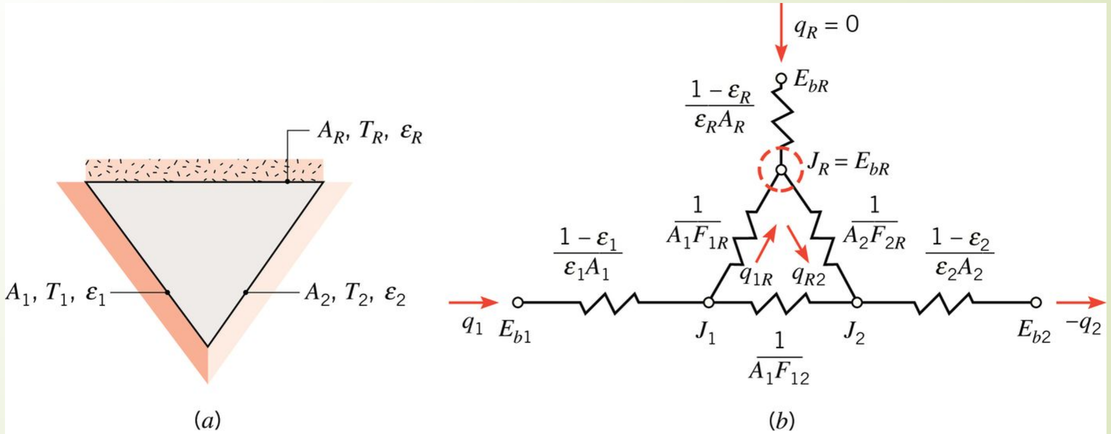
INSULATED SURFACES AND SURFACES WITH LARGE AREAS

- For ***insulated*** surfaces (re-re-radiating), this behaves "like" a ***blackbody*** and as such the surface resistance go to zero and Eb=J (q=0).

- Likewise for "large" areas (i.e. ***LARGE ROOM***), the surface resistance approach zero and once again the reduction in the thermal circuit becomes Eb=J (q=0). For example, consider the thermal circuit for the following 3-surface problem with one insulated surface.

Surface "r" Balance

$$\frac{J_r - J_1}{\frac{1}{A_r F_{r1}}} + \frac{J_r - J_2}{\frac{1}{A_r F_{r2}}} = 0$$



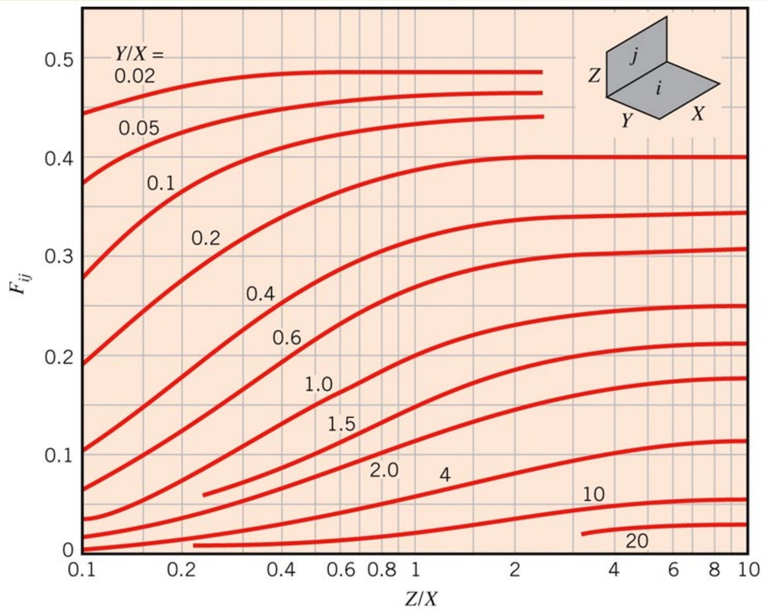


Figure 13.6

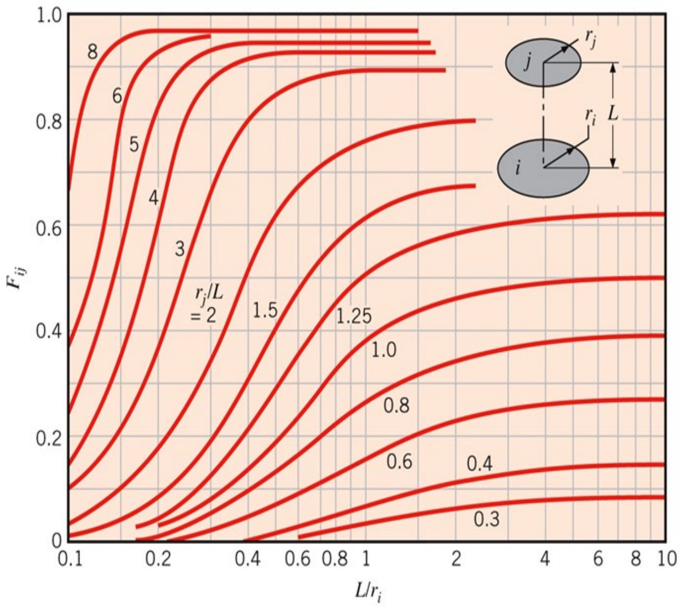


Figure 13.5

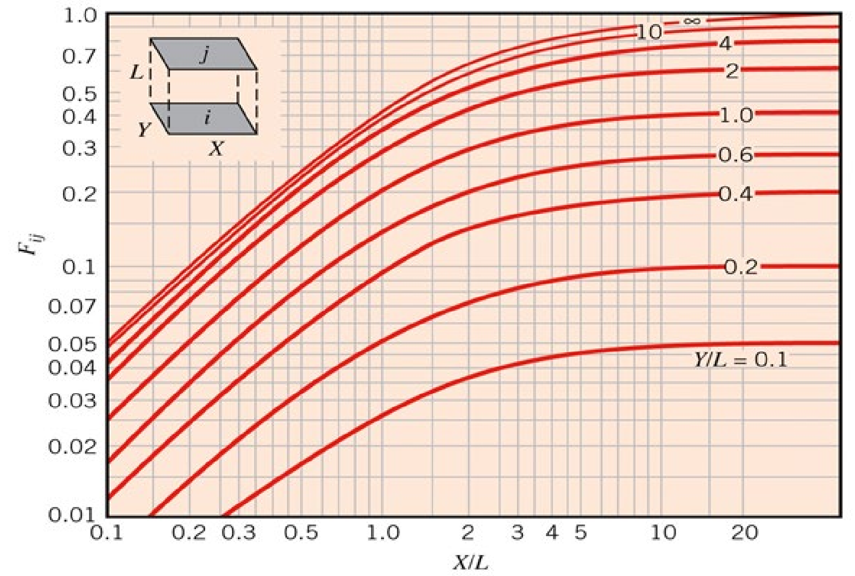


Figure 13.4

14 View Factors Standard Surfaces

A small oven consists of a "cubical" box, with power supplied from the floor.
The walls loose heat to the outside surroundings with wall Temp = 400K.
A spherical object is placed in the center, D = 30mm.
Sometime after the sphere is placed in the oven, the sphere Temp (T1) = 420K.

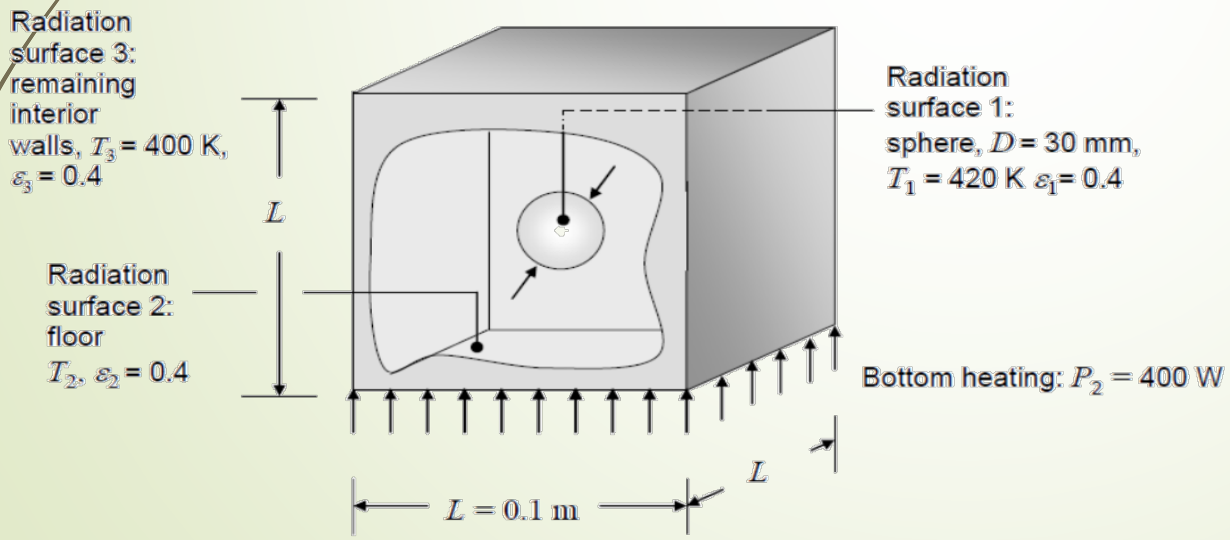
Find:

a. View Factors, F12, F13, F21, F31, F23, F32

b. floor temperature,

c. Is it steady state?

SCHEMATIC:



Assumptions :

Surfaces are grey and diffuse;

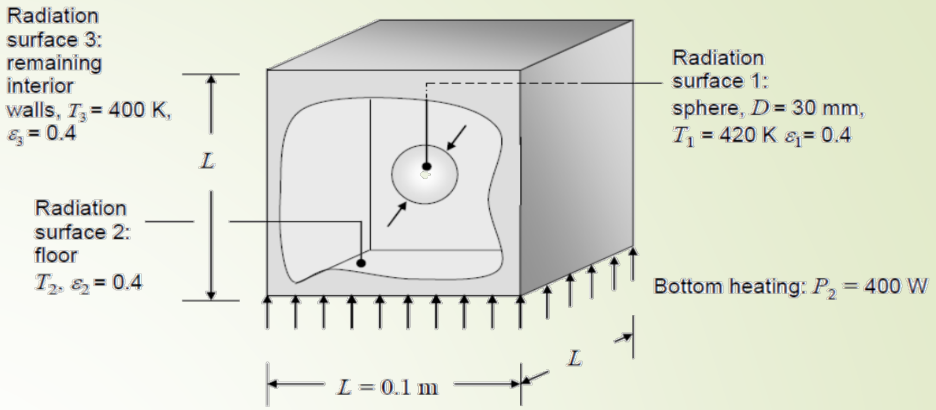
Uniform irradition and radiosity,

All floor power goes to heater, no storage,

No Convection

ANALYSIS

SCHEMATIC:



Due to symmetry, view factor from the sphere to each of the SIX walls must be equal, thus:

Surface: 1 = Sphere, 2 = Floor, 3 = Other Walls

$F_{12} = 1/6, \rightarrow$ fraction leaving "1" and strikes "2"

$F_{13} = 5/6, \rightarrow$ fraction leaving "1" and strikes "3"

APPLY RECIPROCITY

$$A_1F_{12} = A_2F_{21}$$

$$F_{21} = \frac{A_1F_{12}}{A_2} = \frac{4\pi r^2 \bullet F_{12}}{L^2} = \frac{4\pi 0.015^2 \bullet \frac{1}{6}}{0.1^2} = 0.0471$$

$$A_3F_{31} = A_1F_{13}$$

$$F_{31} = \frac{A_1F_{13}}{A_3} = \frac{4\pi r^2 \bullet F_{13}}{5L^2} = \frac{4\pi 0.015^2 \bullet \frac{5}{6}}{5 \bullet 0.1^2} = 0.0471$$

CONSERVATION

$$\sum_i F_{ij} = 1$$

surface 2 does not see itself, i= 2

$$F_{21} + \cancel{F_{22}} + F_{23} = 1$$

$F_{23} = 1 - F_{21} = 0.9529$, and from RECIPROCITY

$$A_3F_{32} = A_2F_{23}$$

$$F_{32} = \frac{A_2F_{23}}{A_3} = \frac{L^2 \bullet 0.9529}{5 \bullet L^2} = 0.19058$$

Finally from Conservation

i=3

$$F_{31} + F_{32} + F_{33} = 1$$

$$F_{33} = 1 - F_{31} - F_{32} = 1 - 0.0471 - 0.19058 = 0.76232$$

(fraction of walls that see itself)

SURFACE ENERGY BALANCE

$$\frac{E_{bi}-J_i}{\frac{1-\varepsilon_i}{\varepsilon_i A_i}}=\sum_{j=1}^{n}\frac{J_i-J_j}{\frac{1}{A_iF_{ij}}};$$

applied to every surface if "T" is known

and once J's are known of if "q" is known:

$$q_i=\sum_{j=1}^{n}\frac{J_i-J_j}{\frac{1}{A_iF_{ij}}}=\frac{E_{b_i}-J_i}{\frac{1-\varepsilon_i}{\varepsilon_i A_i}}$$

Surface 1 and 3 → T is KNOWN

"1"

$$\frac{E_{b1}-J_1}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1}}=\frac{J_1-J_2}{\frac{1}{A_1F_{12}}}+\frac{J_1-J_3}{\frac{1}{A_1F_{13}}}$$

"3"

$$\frac{E_{b3}-J_3}{\frac{1-\varepsilon_3}{\varepsilon_3 A_3}}=\frac{J_3-J_1}{\frac{1}{A_3F_{31}}}+\frac{J_3-J_2}{\frac{1}{A_3F_{32}}}$$

Surface "2" → q is known

$$q_2=\frac{J_2-J_1}{\frac{1}{A_2F_{21}}}+\frac{J_2-J_3}{\frac{1}{A_2F_{23}}}=400W$$

UNKNOWNS

3 Equations, 3 Unknowns

J_1, J_2, J_3

EQUATION SETUP

$$0.00189\left[m^2\right](E_{b1}-J_1)\left[\frac{W}{m^2}\right]=0.000471\left[m^2\right](J_1-J_2)\left[\frac{W}{m^2}\right]+0.00236m^2(J_1-J_3)\left[\frac{W}{m^2}\right]$$

$$0.0333\left[m^2\right](E_{b3}-J_3)\left[\frac{W}{m^2}\right]=0.00236\left[m^2\right](J_3-J_1)\left[\frac{W}{m^2}\right]+0.00953m^2(J_3-J_2)\left[\frac{W}{m^2}\right]$$

$$400W=0.000471\left[m^2\right](J_2-J_1)\left[\frac{W}{m^2}\right]+0.00953m^2(J_2-J_3)\left[\frac{W}{m^2}\right]$$

$$\varepsilon_1=\varepsilon_2=\varepsilon_3=0.4$$

$$E_{b1}=\sigma T_1^4=5.67x10^{-8}\frac{W}{m^2-K^4}\bullet(420)^4K^4=1764\frac{W}{m^2}$$

$$E_{b3}=\sigma T_3^4=1452\frac{W}{m^2}$$

SOLVING

$$J_1=1.24x10^4\frac{W}{m^2}$$

$$J_2=5.28x10^4\frac{W}{m^2}$$

$$J_3=1.29x10^4\frac{W}{m^2}$$

MATRIX SOLUTION

$$0.000471\left[m^2\right](J_1-J_2)\left[\frac{W}{m^2}\right]+0.00236m^2(J_1-J_3)\left[\frac{W}{m^2}\right]=0.00189\left[m^2\right](E_{b1}-J_1)\left[\frac{W}{m^2}\right]$$

$$0.00236\left[m^2\right](J_3-J_1)\left[\frac{W}{m^2}\right]+0.00953m^2(J_3-J_2)\left[\frac{W}{m^2}\right]=0.0333\left[m^2\right](E_{b3}-J_3)\left[\frac{W}{m^2}\right]$$

$$0.000471\left[m^2\right](J_2-J_1)\left[\frac{W}{m^2}\right]+0.00953m^2(J_2-J_3)\left[\frac{W}{m^2}\right]=400W$$

$$\begin{bmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{bmatrix}\begin{Bmatrix} J_1 \\ J_2 \\ J_3 \end{Bmatrix}=\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \end{Bmatrix}$$

$a_1 = 0.000471 + 0.000236 + 0.00189$
$a_2 = -0.000471$
$a_3 = -0.00236$
$F_1 = 0.00189$

$b_1 = -0.00236$
$b_2 = -0.00953$
$b_3 = 0.00236 + 0.00953 + 0.0333$
$F_2 = 0.0333$

$c_1 = -0.000471$
$c_2 = 0.000471 + 0.00953$
$c_3 = -0.00953$
$F_2 = 400$

SOLVING

$J_1 = 1.24x10^4 \frac{W}{m^2}$

$J_2 = 5.28x10^4 \frac{W}{m^2}$

$J_3 = 1.29x10^4 \frac{W}{m^2}$

FLOOR TEMPERATURE

$i = 2$

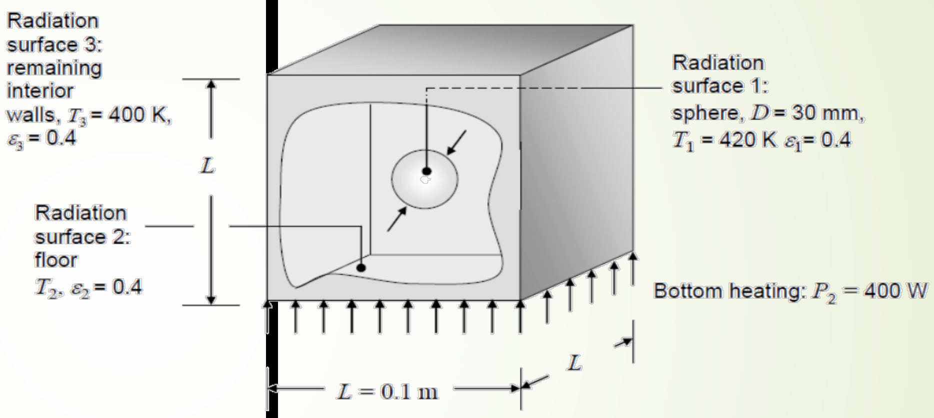
$$q_i = \sum_{j=1}^{n} \frac{J_i - J_j}{\frac{1}{A_i F_{ij}}} = \frac{E_{b_i} - J_i}{\frac{1-\varepsilon_i}{\varepsilon_i A_i}}$$

$$E_{b2} = J_2 + q_2 \frac{1-\varepsilon_2}{\varepsilon_2 A_2} = \sigma T_2^4$$

$$= 5.28x10^4 \frac{W}{m^2} + 400W \frac{1-0.4}{0.4 \bullet 0.1^2} = 1.128x10^5 \frac{W}{m^2}$$

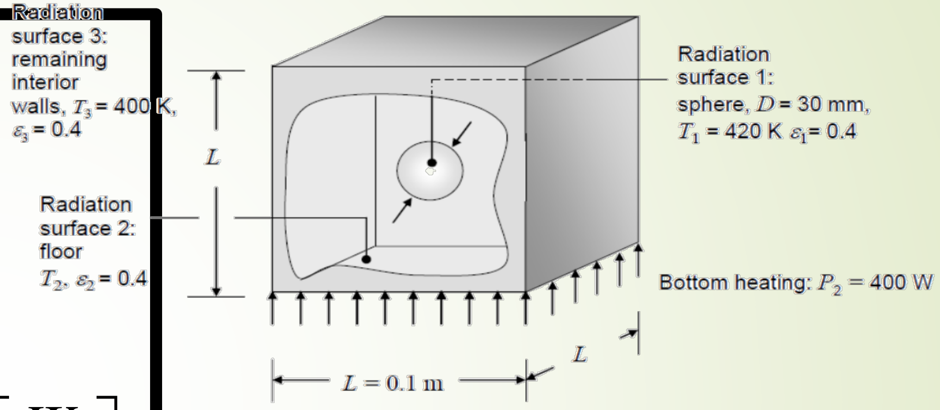
$$T_2 = \left[\frac{E_{b2}}{\sigma}\right]^{1/4} = 1188K$$

SCHEMATIC:



NET RADIATION LEAVING SPHERE

SCHEMATIC:



$$q_i = \sum_{j=1}^{n} \frac{J_i - J_j}{\frac{1}{A_i F_{ij}}} = \frac{E_{b_i} - J_i}{\frac{1-\varepsilon_i}{\varepsilon_i A_i}}$$

$$i = 1$$

$$q_1 = \frac{E_{b_1} - J_1}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1}} = 0.00189m^2 \left(1764\left[\frac{W}{m^2}\right] - 1.24x10^4\left[\frac{W}{m^2}\right]\right)$$

$$= -20W$$

"q" is negative; thus heat is "INCOMING" to the sphere at the rate of 20W.

RADIATION HEAT TRANSFER BETWEEN FLOOR-to-WALLS

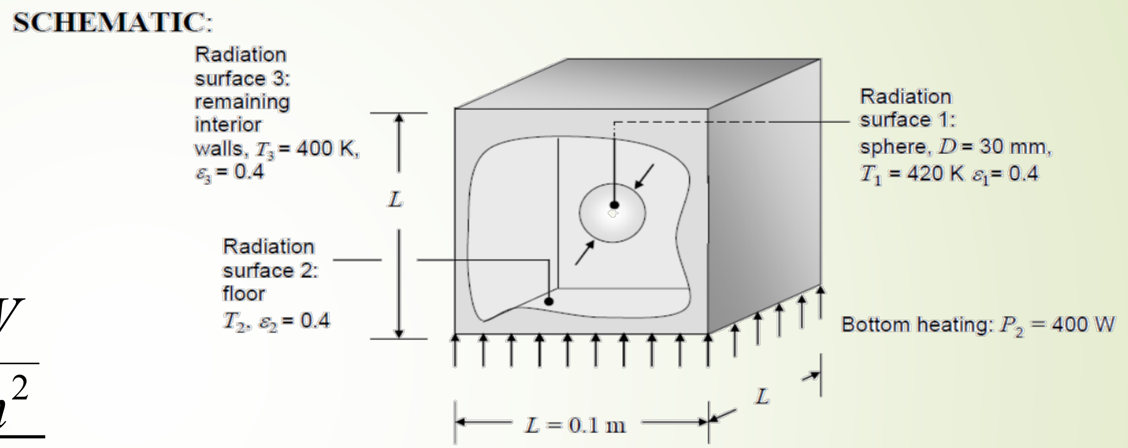
$$q_i = \sum_{j=1}^{n} \frac{J_i - J_j}{\frac{1}{A_i F_{ij}}} = \frac{E_{b_i} - J_i}{\frac{1-\varepsilon_i}{\varepsilon_i A_i}}$$

$$q_{23} = \frac{J_2 - J_3}{\frac{1}{A_2 F_{23}}} = \frac{\left(5.28x10^4 - 1.29x10^4\right)\frac{W}{m^2}}{\frac{1}{\left(0.1^2 \bullet 0.9529\right)\left[m^2\right]}}$$

$$= 0.009529\left[m^2\right] \bullet \left(5.28x10^4 - 1.29x10^4\right)\left[\frac{W}{m^2}\right]$$

$$= 0.0380207x10^4 W$$

$$= 380.2071 W = -q_{32} \text{(WALLS to FLOOR)}$$



RADIATION HEAT TRANSFER BETWEEN FLOOR-to-SPHERE

$$q_i = \sum_{j=1}^{n} \frac{J_i - J_j}{\dfrac{1}{A_i F_{ij}}} = \frac{E_{b_i} - J_i}{\dfrac{1-\varepsilon_i}{\varepsilon_i A_i}}$$

$$q_{21} = \frac{J_2 - J_1}{\dfrac{1}{A_2 F_{21}}} = \frac{(5.28 - 1.24)x10^4}{\dfrac{1}{0.1^2 \bullet 0.0471}} = 19.0284W$$

RADIATION HEAT TRANSFER BETWEEN WALL-to-SPHERE

$$q_i = \sum_{j=1}^{n} \frac{J_i - J_j}{\dfrac{1}{A_i F_{ij}}} = \frac{E_{b_i} - J_i}{\dfrac{1-\varepsilon_i}{\varepsilon_i A_i}}$$

$$q_{31} = \frac{J_3 - J_1}{\dfrac{1}{A_3 F_{31}}} = \frac{(1.29 - 1.24)x10^4}{\dfrac{1}{5\left(0.1^2\right)\bullet 0.0471}} = 1.1175W = -q_{13}$$

NET RADIATION LEAVING WALL

$$q_i = \sum_{j=1}^{n} \frac{J_i - J_j}{\frac{1}{A_i F_{ij}}} = \frac{E_{b_i} - J_i}{\frac{1-\varepsilon_i}{\varepsilon_i A_i}}$$

$$i = 3$$

$$q_3 = \frac{E_{b_3} - J_3}{\frac{1-\varepsilon_3}{\varepsilon_3 A_3}} = \frac{\left(1452 - 1.29x10^4\right)\frac{W}{m^2}}{\frac{1-0.4}{0.4 \bullet 5 \bullet 0.1^2\left[m^2\right]}} = -381.6W$$

"q" is negative: Radiation is STRIKING WALL

TOTAL RADIATION TO/FROM FLOOR

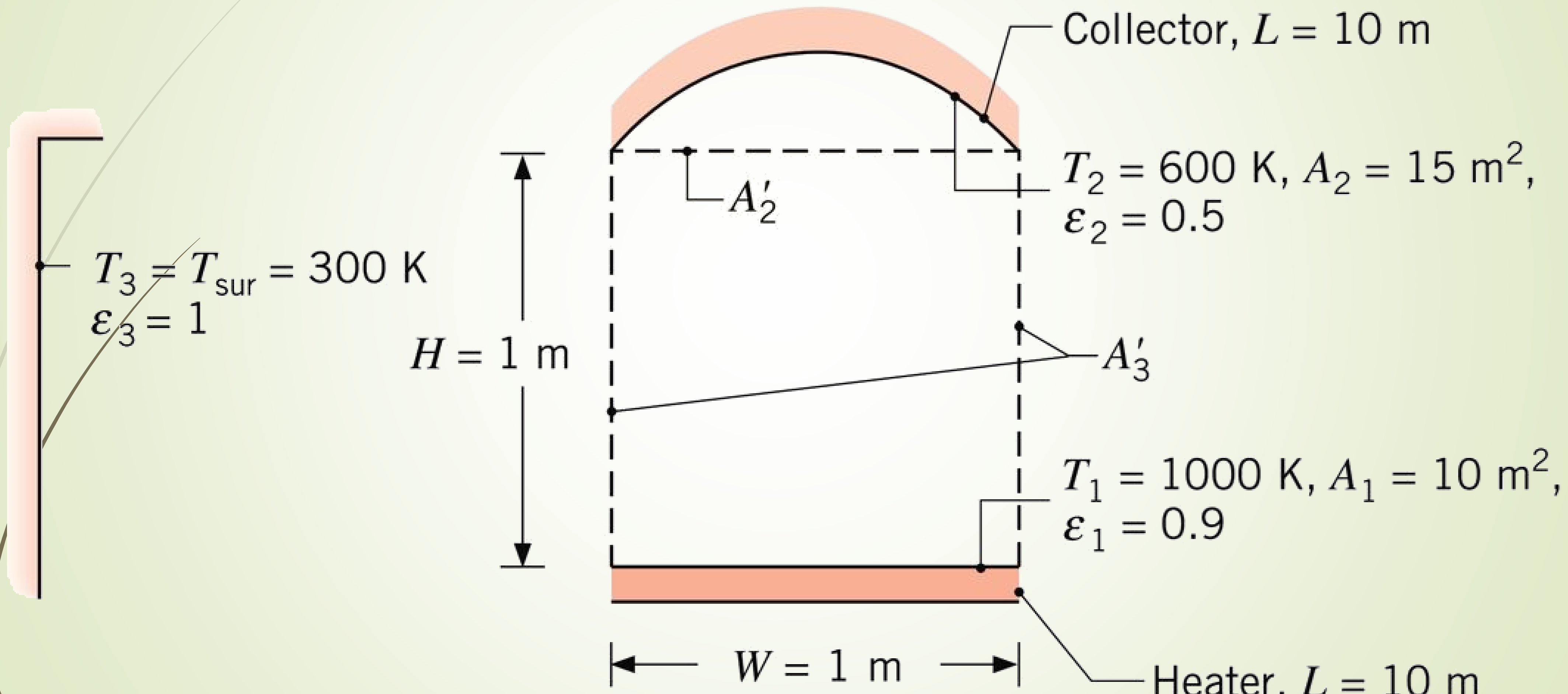
Total Radiation TO/FROM FLOOR

$$\mathrm{q}_{floor} = q_{floor \to walls} + q_{floor \to sphere}$$

$$= 380.2071W\,(\text{page } 21) + 19.0284W\,(\text{page } 22)$$

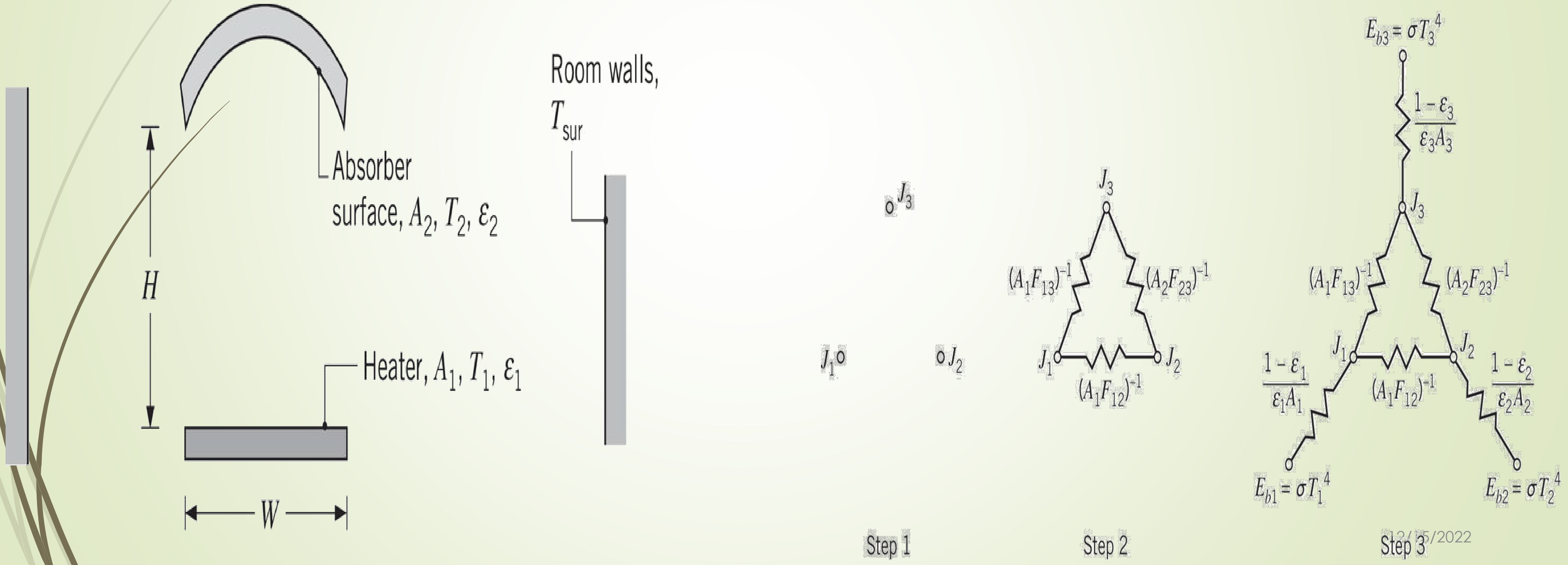
$$= 399.2355W \to \text{SHOULD BE 400W}$$

Curved, solar absorber surface cured by use of infrared heater in a large room.



ANALYSIS

The system is viewed as 3 surface enclosure, with the third surface being the surrounding room, which behaves as a BLACKBODY. What is the net rate of heat transfer to the absorber surface.



$$E_{b1} = \sigma T_1^4 = 56,700 W/m^2$$

$$E_{b2} = \sigma T_2^4 = 7348 W/m^2$$

Surface 3 - Large Room

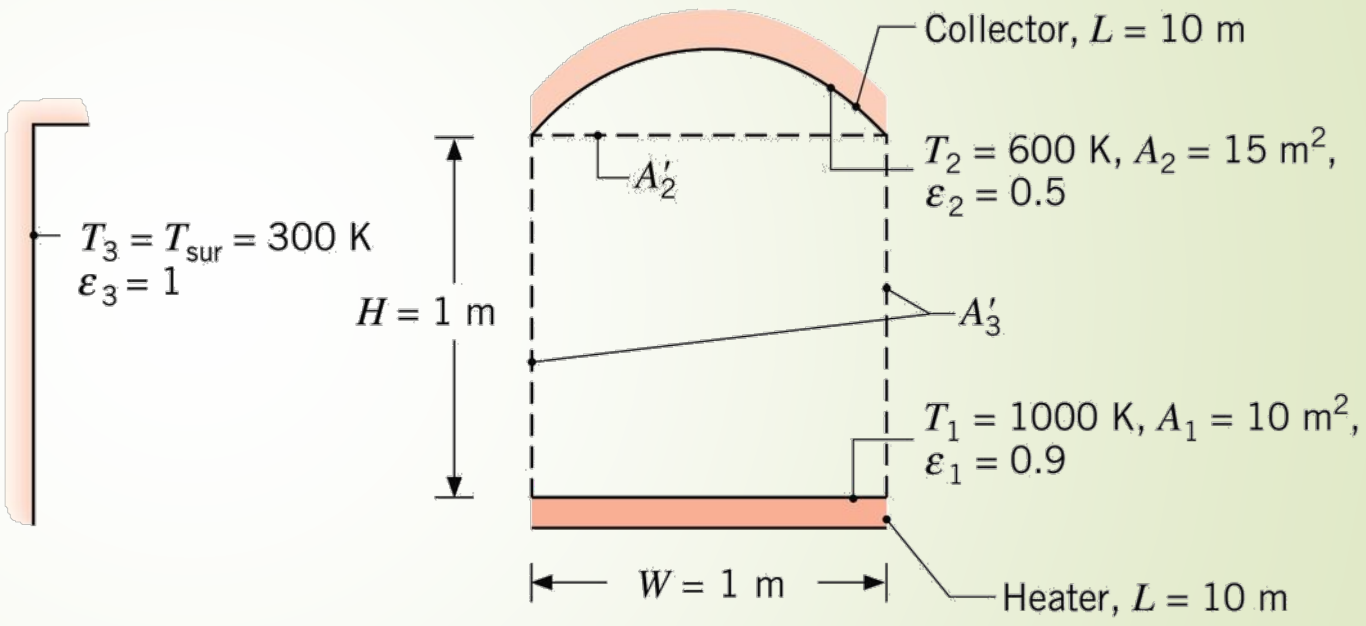
$$J_3 = E_{b3} = \sigma T_3^4 = 459 W/m^2$$

NODAL BALANCE - 1

$$q_1 = \frac{E_{b1} - J_1}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1}} = \frac{J_1 - J_2}{\frac{1}{A_1 F_{12}}} + \frac{J_1 - J_3}{\frac{1}{A_1 F_{13}}}$$

NODAL BALANCE - 2

$$q_2 = \frac{E_{b2} - J_2}{\frac{1-\varepsilon_2}{\varepsilon_2 A_2}} = \frac{J_2 - J_1}{\frac{1}{A_2 F_{21}}} + \frac{J_2 - J_3}{\frac{1}{A_2 F_{23}}}$$



2 Equations, 2 Unknowns

SHAPE FACTORS

$F_{12} = F_{12'} \rightarrow A_2'$ is shown as the rectangular base of the absorber surface

FIGURE 13.2, 13.4

Y/L = 10/1=10,X/L=1/1=1

$F_{12} = 0.39$

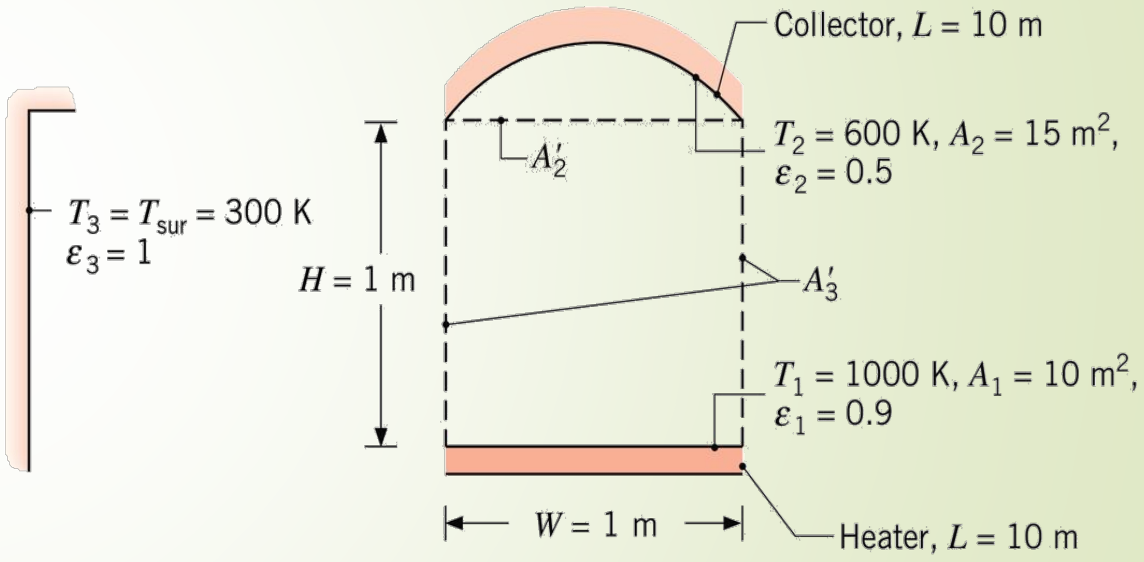
$\cancel{F_{11}} + F_{12} + F_{13} = 1 \rightarrow F_{13} = 1 - F_{12} = 0.61$

Radiation propagating from surface 2 to 3 must pass through htpothetical surface A_2'.

$A_2 F_{23} = A_2' F_{2'3}$

By Symmetry: $F_{2'3} = F_{13}$

$$F_{23} = \frac{A_2'}{A_2} F_{2'3} = \frac{A_2'}{A_2} F_{13} = \frac{10}{15} 0.61 = 0.41$$



NODAL MATRIX SOLUTION

NODAL BALANCE - 1

$$q_1 = \frac{E_{b1}}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1}} + \frac{J_3}{\frac{1}{A_1F_{13}}} = \frac{J_1 - J_2}{\frac{1}{A_1F_{12}}} + \frac{J_1}{\frac{1}{A_1F_{13}}} + \frac{J_1}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1}} = J_1\left[\frac{1}{\frac{1}{A_1F_{12}}} + \frac{1}{\frac{1}{A_1F_{13}}} + \frac{1}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1}}\right] + J_2\left[\frac{-1}{\frac{1}{A_1F_{12}}}\right]$$

NODAL BALANCE - 2

$$q_2 = \frac{E_{b2}}{\frac{1-\varepsilon_2}{\varepsilon_2 A_2}} + \frac{J_3}{\frac{1}{A_2F_{23}}} = \frac{J_2 - J_1}{\frac{1}{A_2F_{21}}} + \frac{J_2}{\frac{1}{A_2F_{23}}} + \frac{J_2}{\frac{1-\varepsilon_2}{\varepsilon_2 A_2}} = J_1\left[\frac{-1}{\frac{1}{A_2F_{21}}}\right] + J_2\left[\frac{1}{\frac{1}{A_2F_{23}}} + \frac{1}{\frac{1}{A_2F_{23}}} \frac{1}{\frac{1-\varepsilon_2}{\varepsilon_2 A_2}}\right]$$

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix}\begin{Bmatrix} J_1 \\ J_2 \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} = \begin{Bmatrix} \frac{E_{b1}}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1}} + \frac{J_3}{\frac{1}{A_1F_{13}}} \\ \frac{E_{b2}}{\frac{1-\varepsilon_2}{\varepsilon_2 A_2}} + \frac{J_3}{\frac{1}{A_2F_{23}}} \end{Bmatrix}$$

NODAL MATRIX SOLUTION

NODAL BALANCE - 1

$$q_1 = J_1\left[\frac{1}{\frac{1}{A_1F_{12}}}+\frac{1}{\frac{1}{A_1F_{13}}}+\frac{1}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1}}\right]+J_2\left[\frac{-1}{\frac{1}{A_1F_{12}}}\right]=J_1a+J_2b$$

NODAL BALANCE - 2

$$q_2 = J_1\left[\frac{-1}{\frac{1}{A_2F_{21}}}\right]+J_2\left[\frac{1}{\frac{1}{A_2F_{23}}}+\frac{1}{\frac{1}{A_2F_{23}}}\,\frac{1}{\frac{1-\varepsilon_2}{\varepsilon_2 A_2}}\right]=J_1c+J_2d$$

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix}\begin{Bmatrix} J_1 \\ J_2 \end{Bmatrix}=\begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix}=\begin{Bmatrix} \frac{E_{b1}}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1}}+\frac{J_3}{\frac{1}{A_1F_{13}}} \\ \frac{E_{b2}}{\frac{1-\varepsilon_2}{\varepsilon_2 A_2}}+\frac{J_3}{\frac{1}{A_2F_{23}}} \end{Bmatrix}$$

$$J_3 = 459 W/m^2$$

$$J_1 = 51,541 W/m^2, J_2 = 12,487 W/m^2$$

$$E_{b1} = \sigma T_1^4 = 56,700 W/m^2$$

$$E_{b2} = \sigma T_2^4 = 7348 W/m^2$$