Chapter 12
RADIATION HEAT TRANSFER

View Factors

12-1C The view factor $F_{i \to j}$ represents the fraction of the radiation leaving surface i that strikes surface j directly. The view factor from a surface to itself is non-zero for concave surfaces.

12-2C The pair of view factors $F_{i \to j}$ and $F_{j \to i}$ are related to each other by the reciprocity rule $A_i F_{ij} = A_j F_{ji}$ where A_i is the area of the surface i and A_j is the area of the surface j. Therefore,

$$A_1 F_{12} = A_2 F_{21} \longrightarrow F_{12} = \frac{A_2}{A_1} F_{21}$$

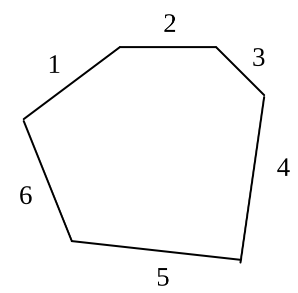
12-3C The summation rule for an enclosure and is expressed as $\sum_{j=1}^{N} F_{i \to j} = 1$ where N is the number of surfaces of the enclosure. It states that the sum of the view factors from surface i of an enclosure to all surfaces of the enclosure, including to itself must be equal to unity.

The superposition rule is stated as the view factor from a surface i to a surface j is equal to the sum of the view factors from surface i to the parts of surface j, $F_{1 \to (2,3)} = F_{1 \to 2} + F_{1 \to 3}$.

12-4C The cross-string method is applicable to geometries which are very long in one direction relative to the other directions. By attaching strings between corners the Crossed-Strings Method is expressed as

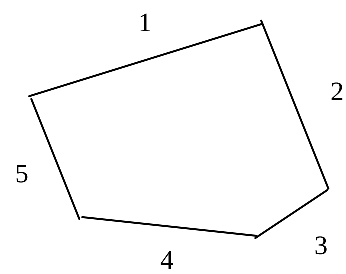
$$F_{i \to j} = \frac{\sum \text{Crossed strings} - \sum \text{Uncrossed strings}}{2 \times \text{string on surface } i}$$

12-5 An enclosure consisting of six surfaces is considered. The number of view factors this geometry involves and the number of these view factors that can be determined by the application of the reciprocity and summation rules are to be determined.



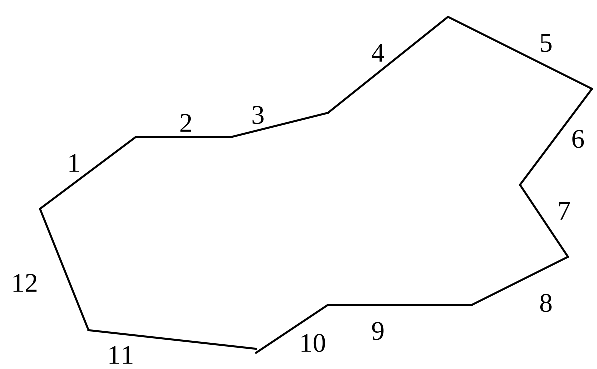
Analysis A seven surface enclosure (N=6) involves $N^2 = 6^2 = \mathbf{36}$ view factors and we need to determine $\frac{N(N-1)}{2} = \frac{6(6-1)}{2} = 15$ view factors directly. The remaining 36-15 = **21** of the view factors can be determined by the application of the reciprocity and summation rules.

12-6 An enclosure consisting of five surfaces is considered. The number of view factors this geometry involves and the number of these view factors that can be determined by the application of the reciprocity and summation rules are to be determined.



Analysis A five surface enclosure (N=5) involves $N^2 = 5^2 = \mathbf{25}$ view factors and we need to determine $\frac{N(N-1)}{2} = \frac{5(5-1)}{2} = 10$ view factors directly. The remaining 25-10 = **15** of the view factors can be determined by the application of the reciprocity and summation rules.

12-7 An enclosure consisting of twelve surfaces is considered. The number of view factors this geometry involves and the number of these view factors that can be determined by the application of the reciprocity and summation rules are to be determined.



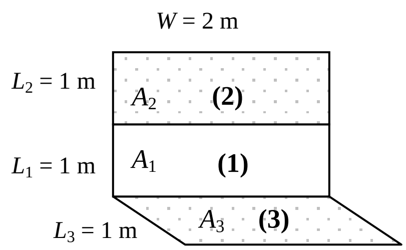
Analysis A twelve surface enclosure (N=12) involves $N^2 = 12^2 = \mathbf{144}$ view factors and we need to determine $\frac{N(N-1)}{2} = \frac{12(12-1)}{2} = 66$ view factors directly. The remaining 144-66 = **78** of the view factors can be determined by the application of the reciprocity and summation rules.

12-8 The view factors between the rectangular surfaces shown in the figure are to be determined.

Assumptions The surfaces are diffuse emitters and reflectors.

Analysis From Fig. 12-6,

$$\left.\begin{aligned}\frac{L_3}{W}=\frac{1}{2}=0.5\\ \frac{L1}{W}=\frac{1}{2}=0.5\end{aligned}\right\}F_{31}=0.24$$



and

$$\left.\begin{aligned}\frac{L_3}{W}=\frac{1}{2}=0.5\\ \frac{L_1+L_2}{W}=\frac{2}{2}=1\end{aligned}\right\}F_{3\to(1+2)}=0.29$$

We note that $A_1 = A_3$. Then the reciprocity and superposition rules gives

$$\mathrm{A}_1F_{13}=A_3F_{31}\longrightarrow F_{13}=F_{31}=\mathbf{0.24}$$

$$F_{3\to(1+2)}=F_{31}+F_{32}\longrightarrow\quad 0.29=0.24+F_{32}\longrightarrow F_{32}=0.05$$

Finally, $A_2=A_3\longrightarrow F_{23}=F_{32}=\mathbf{0.05}$

12-9 A cylindrical enclosure is considered. The view factor from the side surface of this cylindrical enclosure to its base surface is to be determined.

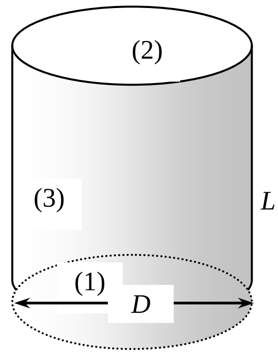
Assumptions The surfaces are diffuse emitters and reflectors.

Analysis We designate the surfaces as follows:

Base surface by (1),

top surface by (2), and

side surface by (3).



Then from Fig. 12-7 (or Table 12-1 for better accuracy)

$$\left.\begin{array}{l} \dfrac{L}{r_1} = \dfrac{r_1}{r_1} = 1 \\ \dfrac{r_2}{L} = \dfrac{r_2}{r_2} = 1 \end{array}\right\} F_{12} = F_{21} = 0.38$$

$$\text{summation rule}: F_{11} + F_{12} + F_{13} = 1$$

$$0 + 0.38 + F_{13} = 1 \longrightarrow F_{13} = 0.62$$

$$\text{reciprocity rule}: A_1 F_{13} = A_3 F_{31} \longrightarrow F_{31} = \frac{A_1}{A_3} F_{13} = \frac{\pi r_1^2}{2\pi r_1 L} F_{13} = \frac{\pi r_1^2}{2\pi r_1 (r_1)} F_{13} = \frac{1}{2}(0.62) = \mathbf{0.31}$$

Discussion This problem can be solved more accurately by using the view factor relation from Table 12-1 to be

$$R_1 = \frac{r_1}{L} = \frac{r_1}{r_1} = 1$$

$$R_2 = \frac{r_2}{L} = \frac{r_2}{r_2} = 1$$

$$S = 1 + \frac{1 + R_2^2}{R_1^2} = 1 + \frac{1 + 1^2}{1^2} = 3$$

$$F_{12} = \tfrac{1}{2}\left\{ S - \left[S^2 - 4\left(\frac{R_2}{R_1}\right)^2 \right]^{0.5} \right\} = \tfrac{1}{2}\left\{ 3 - \left[3^2 - 4\left(\frac{1}{1}\right)^2 \right]^{0.5} \right\} = 0.382$$

$$F_{13} = 1 - F_{12} = 1 - 0.382 = 0.618$$

$$\text{reciprocity rule}: A_1 F_{13} = A_3 F_{31} \longrightarrow F_{31} = \frac{A_1}{A_3} F_{13} = \frac{\pi r_1^2}{2\pi r_1 L} F_{13} = \frac{\pi r_1^2}{2\pi r_1 (r_1)} F_{13} = \frac{1}{2}(0.618) = \mathbf{0.309}$$

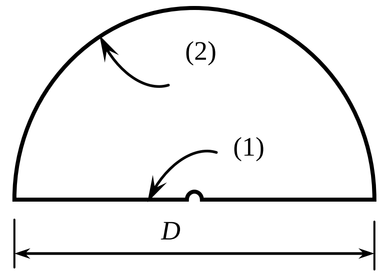
12-10 A semispherical furnace is considered. The view factor from the dome of this furnace to its flat base is to be determined.

Assumptions The surfaces are diffuse emitters and reflectors.

Analysis We number the surfaces as follows:

(1): circular base surface

(2): dome surface



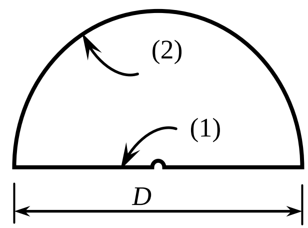
Surface (1) is flat, and thus $F_{11} = 0$.

Summation rule : $F_{11} + F_{12} = 1 \rightarrow F_{12} = 1$

reciprocity rule : $A_1 F_{12} = A_2 F_{21} \longrightarrow F_{21} = \frac{A_1}{A_2} F_{12} = \frac{A_1}{A_2}(1) = \frac{\frac{\pi D^2}{4}}{\frac{\pi D^2}{2}} = \frac{1}{2} = \mathbf{0.5}$

12-11 Two view factors associated with three very long ducts with different geometries are to be determined.

Assumptions **1** The surfaces are diffuse emitters and reflectors. **2** End effects are neglected.

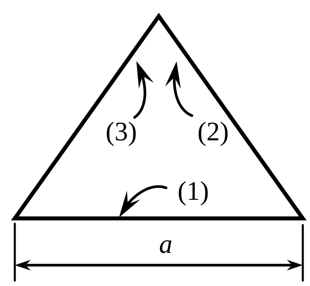


Analysis (*a*) Surface (1) is flat, and thus $F_{11} = 0$.

summation rule : $F_{11} + F_{12} = 1 \rightarrow F_{12} = \mathbf{1}$

reciprocity rule : $A_1 F_{12} = A_2 F_{21} \longrightarrow F_{21} = \frac{A_1}{A_2} F_{12} = \frac{Ds}{\left(\frac{\pi D}{2}\right)s}(1) = \frac{2}{\pi} = \mathbf{0.64}$

(*b*) Noting that surfaces 2 and 3 are symmetrical and thus $F_{12} = F_{13}$, the summation rule gives



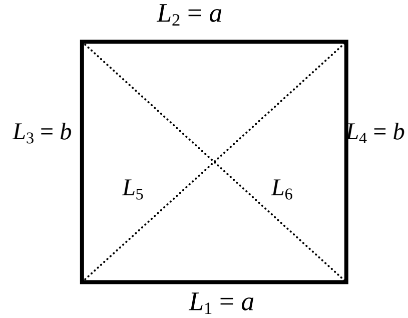
$$F_{11} + F_{12} + F_{13} = 1 \longrightarrow 0 + F_{12} + F_{13} = 1 \longrightarrow F_{12} = \mathbf{0.5}$$

Also by using the equation obtained in Example 12-4,

$$F_{12} = \frac{L_1 + L_2 - L_3}{2L_1} = \frac{a + b - b}{2a} = \frac{a}{2a} = \frac{1}{2} = \mathbf{0.5}$$

reciprocity rule : $A_1 F_{12} = A_2 F_{21} \longrightarrow F_{21} = \frac{A_1}{A_2} F_{12} = \frac{a}{b}\left(\frac{1}{2}\right) = \mathbf{\frac{a}{2b}}$

(*c*) Applying the crossed-string method gives



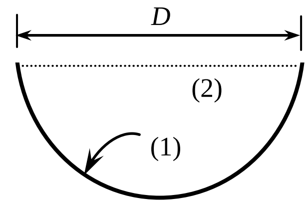
$$F_{12} = F_{21} = \frac{(L_5 + L_6) - (L_3 + L_4)}{2L_1}$$

$$= \frac{2\sqrt{a^2 + b^2} - 2b}{2a} = \mathbf{\frac{\sqrt{a^2 + b^2} - b}{a}}$$

12-12 View factors from the very long grooves shown in the figure to the surroundings are to be determined.

Assumptions **1** The surfaces are diffuse emitters and reflectors. **2** End effects are neglected.

Analysis (*a*) We designate the circular dome surface by (1) and the imaginary flat top surface by (2). Noting that (2) is flat,

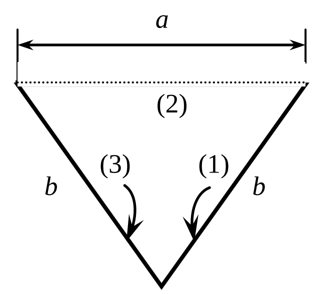


$$F_{22} = 0$$

$$\text{summation rule}: \; F_{21} + F_{22} = 1 \longrightarrow F_{21} = 1$$

$$\text{reciprocity rule}: A_1 F_{12} = A_2 F_{21} \longrightarrow F_{12} = \frac{A_2}{A_1} F_{21} = \frac{D}{\frac{\pi D}{2}}(1) = \frac{2}{\pi} = \mathbf{0.64}$$

(*b*) We designate the two identical surfaces of length *b* by (1) and (3), and the imaginary flat top surface by (2). Noting that (2) is flat,



$$F_{22} = 0$$

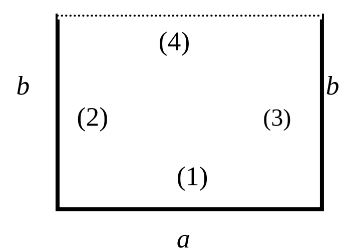
$$\text{summation rule}: \; F_{21} + F_{22} + F_{23} = 1 \longrightarrow F_{21} = F_{23} = 0.5 \quad \text{(symmetry)}$$

$$\text{summation rule}: F_{22} + F_{2\to(1+3)} = 1 \longrightarrow F_{2\to(1+3)} = 1$$

$$\text{reciprocity rule}: A_2 F_{2\to(1+3)} = A_{(1+3)} F_{(1+3)\to 2}$$

$$\longrightarrow F_{(1+3)\to 2} = F_{(1+3)\to surr} = \frac{A_2}{A_{(1+3)}}(1) = \frac{\mathbf{a}}{\mathbf{2b}}$$

(*c*) We designate the bottom surface by (1), the side surfaces by (2) and (3), and the imaginary top surface by (4). Surface 4 is flat and is completely surrounded by other surfaces. Therefore, $F_{44} = 0$ and $F_{4\to(1+2+3)} = 1$.

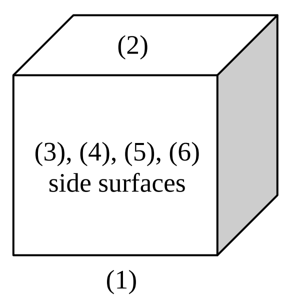


$$\text{reciprocity rule}: A_4 F_{4\to(1+2+3)} = A_{(1+2+3)} F_{(1+2+3)\to 4}$$

$$\longrightarrow F_{(1+2+3)\to 4} = F_{(1+2+3)\to surr} = \frac{A_4}{A_{(1+2+3)}}(1) = \frac{\mathbf{a}}{\mathbf{a+2b}}$$

12-13 The view factors from the base of a cube to each of the other five surfaces are to be determined.

Assumptions The surfaces are diffuse emitters and reflectors.



Analysis Noting that $L_1 / w = L_2 / w = 1$, from Fig. 12-6 we read

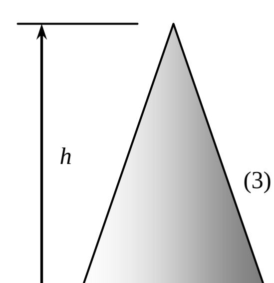
$$F_{12} = 0.2$$

Because of symmetry, we have

$$F_{12} = F_{13} = F_{14} = F_{15} = F_{16} = \mathbf{0.2}$$

12-14 The view factor from the conical side surface to a hole located at the center of the base of a conical enclosure is to be determined.

Assumptions The conical side surface is diffuse emitter and reflector.



Analysis We number different surfaces as

the hole located at the center of the base (1)

the base of conical enclosure (2)

conical side surface (3)

Surfaces 1 and 2 are flat , and they have no direct view of each other. Therefore,

$$F_{11} = F_{22} = F_{12} = F_{21} = 0$$

$$\text{summation rule}: \; F_{11} + F_{12} + F_{13} = 1 \longrightarrow F_{13} = 1$$

$$\text{reciprocity rule}: \; A_1 F_{13} = A_3 F_{31} \longrightarrow \frac{\pi d^2}{4}(1) = \frac{\pi D h}{2} F_{31} \longrightarrow F_{31} = \mathbf{\frac{d^2}{2Dh}}$$

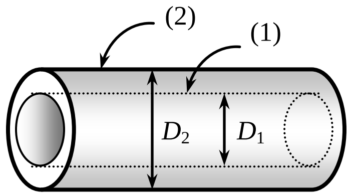
12-15 The four view factors associated with an enclosure formed by two very long concentric cylinders are to be determined.

Assumptions **1** The surfaces are diffuse emitters and reflectors. **2** End effects are neglected.

Analysis We number different surfaces as

the outer surface of the inner cylinder (1)

the inner surface of the outer cylinder (2)



No radiation leaving surface 1 strikes itself and thus $F_{11} = \mathbf{0}$

All radiation leaving surface 1 strikes surface 2 and thus $F_{12} = \mathbf{1}$

$$\text{reciprocity rule}: \; A_1 F_{12} = A_2 F_{21} \longrightarrow F_{21} = \frac{A_1}{A_2} F_{12} = \frac{\pi D_1 h}{\pi D_2 h}(1) = \mathbf{\frac{D_1}{D_2}}$$

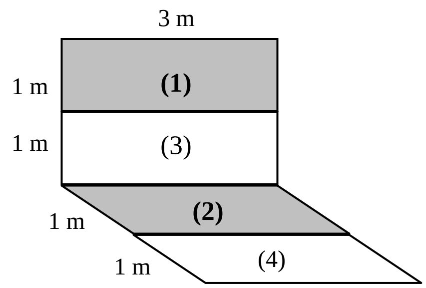
$$\text{summation rule}: \; F_{21} + F_{22} = 1 \longrightarrow F_{22} = 1 - F_{21} = \mathbf{1 - \frac{D_1}{D_2}}$$

12-16 The view factors between the rectangular surfaces shown in the figure are to be determined.

Assumptions The surfaces are diffuse emitters and reflectors.

Analysis We designate the different surfaces as follows:

shaded part of perpendicular surface by (1),
bottom part of perpendicular surface by (3),
shaded part of horizontal surface by (2), and
front part of horizontal surface by (4).



(*a*) From Fig.12-6

$$\left.\begin{array}{l}\dfrac{L_2}{W}=\dfrac{1}{3}\\[2mm] \dfrac{L_1}{W}=\dfrac{1}{3}\end{array}\right\}F_{23}=0.25 \quad \text{and} \quad \left.\begin{array}{l}\dfrac{L_2}{W}=\dfrac{2}{3}\\[2mm] \dfrac{L_1}{W}=\dfrac{1}{3}\end{array}\right\}F_{2\to(1+3)}=0.32$$

$$\text{superposition rule: } F_{2\to(1+3)}=F_{21}+F_{23}\longrightarrow F_{21}=F_{2\to(1+3)}-F_{23}=0.32-0.25=0.07$$

$$\text{reciprocity rule: } A_1=A_2\longrightarrow A_1F_{12}=A_2F_{21}\longrightarrow F_{12}=F_{21}=\mathbf{0.07}$$

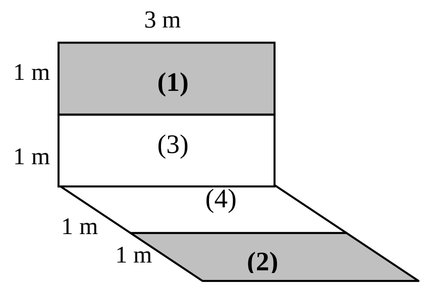
(*b*) From Fig.12-6,

$$\frac{L_2}{W}=\frac{1}{3} \text{ and } \left.\frac{L_1}{W}=\frac{2}{3}\right\}F_{(4+2)\to 3}=0.15 \quad \text{and} \quad \frac{L_2}{W}=\frac{2}{3} \text{ and } \left.\frac{L_1}{W}=\frac{2}{3}\right\}F_{(4+2)\to(1+3)}=0.22$$

$$\text{superposition rule: } F_{(4+2)\to(1+3)}=F_{(4+2)\to 1}+F_{(4+2)\to 3}\longrightarrow F_{(4+2)\to 1}=0.22-0.15=0.07$$

$$\text{reciprocity rule: } A_{(4+2)}F_{(4+2)\to 1}=A_1F_{1\to(4+2)}$$

$$\longrightarrow F_{1\to(4+2)}=\frac{A_{(4+2)}}{A_1}F_{(4+2)\to 1}=\frac{6}{3}(0.07)=0.14$$



$$\text{superposition rule: } F_{1\to(4+2)}=F_{14}+F_{12}$$

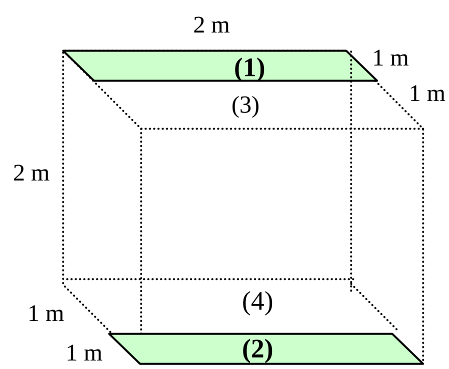
$$\longrightarrow F_{14}=0.14-0.07=\mathbf{0.07}$$

since F_{12} = 0.07 (from part *a*). Note that F_{14} in part (*b*) is equivalent to F_{12} in part (*a*).

(*c*) We designate

shaded part of top surface by (1),
remaining part of top surface by (3),
remaining part of bottom surface by (4), and
shaded part of bottom surface by (2).

From Fig.12-5,



$$\left.\begin{array}{l}\dfrac{L_2}{D}=\dfrac{2}{2}\\[2mm] \dfrac{L_1}{D}=\dfrac{2}{2}\end{array}\right\}F_{(2+4)\to(1+3)}=0.20 \quad \text{and} \quad \left.\begin{array}{l}\dfrac{L_2}{D}=\dfrac{2}{2}\\[2mm] \dfrac{L_1}{D}=\dfrac{1}{2}\end{array}\right\}F_{14}=0.12$$

$$\text{superposition rule: } F_{(2+4)\to(1+3)}=F_{(2+4)\to 1}+F_{(2+4)\to 3}$$

$$\text{symmetry rule: } F_{(2+4)\to 1}=F_{(2+4)\to 3}$$

Substituting symmetry rule gives

$$F_{(2+4)\to 1}=F_{(2+4)\to 3}=\frac{F_{(2+4)\to(1+3)}}{2}=\frac{0.20}{2}=0.10$$

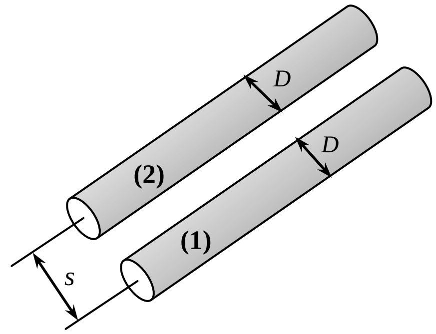
$$\text{reciprocity rule: } A_1F_{1\to(2+4)}=A_{(2+4)}F_{(2+4)\to 1}\longrightarrow(2)F_{1\to(2+4)}=(4)(0.10)\longrightarrow F_{1\to(2+4)}=0.20$$

$$\text{superposition rule: } F_{1\to(2+4)}=F_{12}+F_{14}\longrightarrow 0.20=F_{12}+0.12\longrightarrow F_{12}=0.20-0.12=\mathbf{0.08}$$

12-17 The view factor between the two infinitely long parallel cylinders located a distance *s* apart from each other is to be determined.

Assumptions The surfaces are diffuse emitters and reflectors.

Analysis Using the crossed-strings method, the view factor between two cylinders facing each other for $s/D > 3$ is determined to be

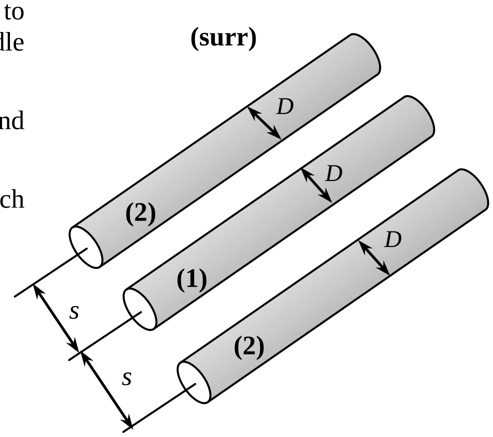


$$F_{1-2} = \frac{\sum \text{Crossed strings} - \sum \text{Uncrossed strings}}{2 \times \text{String on surface 1}}$$

$$= \frac{2\sqrt{s^2 + D^2} - 2s}{2(\pi D/2)}$$

or $$F_{1-2} = \frac{2\left(\sqrt{s^2 + D^2} - s\right)}{\pi D}$$

12-18 Three infinitely long cylinders are located parallel to each other. The view factor between the cylinder in the middle and the surroundings is to be determined.



Assumptions The cylinder surfaces are diffuse emitters and reflectors.

Analysis The view factor between two cylinder facing each other is, from Prob. 12-17,

$$F_{1-2} = \frac{2\left(\sqrt{s^2 + D^2} - s\right)}{\pi D}$$

Noting that the radiation leaving cylinder 1 that does not strike the cylinder will strike the surroundings, and this is also the case for the other half of the cylinder, the view factor between the cylinder in the middle and the surroundings becomes

$$F_{1-surr} = 1 - 2F_{1-2} = 1 - \frac{4\left(\sqrt{s^2 + D^2} - s\right)}{\pi D}$$

Radiation Heat Transfer Between Surfaces

12-19C The analysis of radiation exchange between black surfaces is relatively easy because of the absence of reflection. The rate of radiation heat transfer between two surfaces in this case is expressed as $\dot{Q} = A_1 F_{12} \sigma (T_1^{\,4} - T_2^{\,4})$ where A_1 is the surface area, F_{12} is the view factor, and T_1 and T_2 are the temperatures of two surfaces.

12-20C Radiosity is the total radiation energy leaving a surface per unit time and per unit area. Radiosity includes the emitted radiation energy as well as reflected energy. Radiosity and emitted energy are equal for blackbodies since a blackbody does not reflect any radiation.

12-21C Radiation surface resistance is given as $R_i = \dfrac{1-\varepsilon_i}{A_i \varepsilon_i}$ and it represents the resistance of a surface to the emission of radiation. It is zero for black surfaces. The space resistance is the radiation resistance between two surfaces and is expressed as $R_i = \dfrac{1-\varepsilon_i}{A_i \varepsilon_i}$

12-22C The two methods used in radiation analysis are the matrix and network methods. In matrix method, equations 12-34 and 12-35 give N linear algebraic equations for the determination of the N unknown radiosities for an N -surface enclosure. Once the radiosities are available, the unknown surface temperatures and heat transfer rates can be determined from these equations respectively. This method involves the use of matrices especially when there are a large number of surfaces. Therefore this method requires some knowledge of linear algebra.

The network method involves drawing a surface resistance associated with each surface of an enclosure and connecting them with space resistances. Then the radiation problem is solved by treating it as an electrical network problem where the radiation heat transfer replaces the current and the radiosity replaces the potential. The network method is not practical for enclosures with more than three or four surfaces due to the increased complexity of the network.

12-23C Some surfaces encountered in numerous practical heat transfer applications are modeled as being adiabatic as the back sides of these surfaces are well insulated and net heat transfer through these surfaces is zero. When the convection effects on the front (heat transfer) side of such a surface is negligible and steady-state conditions are reached, the surface must lose as much radiation energy as it receives. Such a surface is called reradiating surface. In radiation analysis, the surface resistance of a reradiating surface is taken to be zero since there is no heat transfer through it.

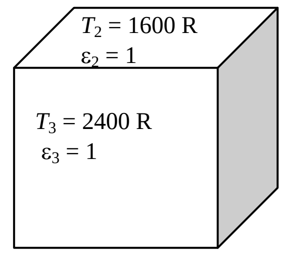
12-24E Top and side surfaces of a cubical furnace are black, and are maintained at uniform temperatures. Net radiation heat transfer rate to the base from the top and side surfaces are to be determined.

Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray. **3** Convection heat transfer is not considered.

Properties The emissivities are given to be ε = 0.7 for the bottom surface and 1 for other surfaces.

Analysis We consider the base surface to be surface 1, the top surface to be surface 2 and the side surfaces to be surface 3. The cubical furnace can be considered to be three-surface enclosure with a radiation network shown in the figure. The areas and blackbody emissive powers of surfaces are

$$A_1 = A_2 = (10\,\text{ft})^2 = 100\,\text{ft}^2 \qquad A_3 = 4(10\,\text{ft})^2 = 400\,\text{ft}^2$$



$$E_{b1} = \sigma T_1^4 = (0.1714\times10^{-8}\ \text{Btu/h.ft}^2.\text{R}^4)(800\,\text{R})^4 = 702\,\text{Btu/h.ft}^2$$

$$E_{b2} = \sigma T_2^4 = (0.1714\times10^{-8}\ \text{Btu/h.ft}^2.\text{R}^4)(1600\,\text{R})^4 = 11{,}233\,\text{Btu/h.ft}^2$$

$$E_{b3} = \sigma T_3^4 = (0.1714\times10^{-8}\ \text{Btu/h.ft}^2.\text{R}^4)(2400\,\text{R})^4 = 56{,}866\,\text{Btu/h.ft}^2$$

The view factor from the base to the top surface of the cube is $F_{12} = 0.2$. From the summation rule, the view factor from the base or top to the side surfaces is

$$F_{11} + F_{12} + F_{13} = 1 \longrightarrow F_{13} = 1 - F_{12} = 1 - 0.2 = 0.8$$

since the base surface is flat and thus $F_{11} = 0$. Then the radiation resistances become

$$R_1 = \frac{1-\varepsilon_1}{A_1\varepsilon_1} = \frac{1-0.7}{(100\,\text{ft}^2)(0.7)} = 0.0043\,\text{ft}^{-2} \qquad R_{12} = \frac{1}{A_1F_{12}} = \frac{1}{(100\,\text{ft}^2)(0.2)} = 0.0500\,\text{ft}^{-2}$$

$$R_{13} = \frac{1}{A_1F_{13}} = \frac{1}{(100\,\text{ft}^2)(0.8)} = 0.0125\,\text{ft}^{-2}$$

Note that the side and the top surfaces are black, and thus their radiosities are equal to their emissive powers. The radiosity of the base surface is determined

$$\frac{E_{b1}-J_1}{R_1} + \frac{E_{b2}-J_1}{R_{12}} + \frac{E_{b3}-J_1}{R_{13}} = 0$$

Substituting, $$\frac{702-J_1}{0.0043} + \frac{11{,}233-J_1}{0.500} + \frac{56{,}866-J_1}{0.0125} = 0 \longrightarrow J_1 = 15{,}054\ \text{W/m}^2$$

(*a*) The net rate of radiation heat transfer between the base and the side surfaces is

$$\dot{Q}_{31} = \frac{E_{b3}-J_1}{R_{13}} = \frac{(56{,}866-15{,}054)\ \text{Btu/h.ft}^2}{0.0125\,\text{ft}^{-2}} = \mathbf{3.345\times10^6\ Btu/h}$$

(*b*) The net rate of radiation heat transfer between the base and the top surfaces is

$$\dot{Q}_{12} = \frac{J_1-E_{b2}}{R_{12}} = \frac{(15{,}054-11{,}233)\ \text{Btu/h.ft}^2}{0.05\,\text{ft}^{-2}} = \mathbf{7.642\times10^4\ Btu/h}$$

The net rate of radiation heat transfer to the base surface is finally determined from

$$\dot{Q}_1 = \dot{Q}_{21} + \dot{Q}_{31} = -76{,}420 + 3{,}344{,}960 = \mathbf{3.269\times10^6\ Btu/h}$$

Discussion The same result can be found form

$$\dot{Q}_1 = \frac{J_1-E_{b1}}{R_1} = \frac{(15{,}054-702)\ \text{Btu/h.ft}^2}{0.0043\,\text{ft}^{-2}} = 3.338\times10^6\ \text{Btu/h}$$

The small difference is due to round-off error.

12-25E

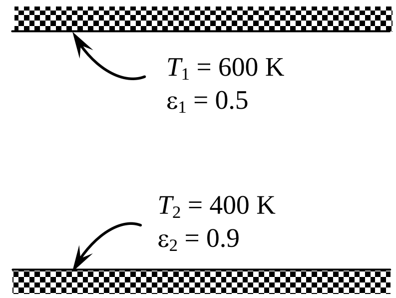
```
"!PROBLEM 12-25E"

"GIVEN"
a=10 "[ft]"
"epsilon_1=0.7 parameter to be varied"
T_1=800 "[R]"
T_2=1600 "[R]"
T_3=2400 "[R]"
sigma=0.1714E-8 "[Btu/h-ft^2-R^4], Stefan-Boltzmann constant"

"ANALYSIS"
"Consider the base surface 1, the top surface 2, and the side surface 3"
E_b1=sigma*T_1^4
E_b2=sigma*T_2^4
E_b3=sigma*T_3^4
A_1=a^2
A_2=A_1
A_3=4*a^2
F_12=0.2 "view factor from the base to the top of a cube"
F_11+F_12+F_13=1 "summation rule"
F_11=0 "since the base surface is flat"
R_1=(1-epsilon_1)/(A_1*epsilon_1) "surface resistance"
R_12=1/(A_1*F_12) "space resistance"
R_13=1/(A_1*F_13) "space resistance"
(E_b1-J_1)/R_1+(E_b2-J_1)/R_12+(E_b3-J_1)/R_13=0 "J_1 : radiosity of base surface"
"(a)"
Q_dot_31=(E_b3-J_1)/R_13
"(b)"
Q_dot_12=(J_1-E_b2)/R_12
Q_dot_21=-Q_dot_12
Q_dot_1=Q_dot_21+Q_dot_31
```

ε_1	Q_{31} [Btu/h]	Q_{12} [Btu/h]	Q_1 [Btu/h]
0.1	1.106E+06	636061	470376
0.15	1.295E+06	589024	705565
0.2	1.483E+06	541986	940753
0.25	1.671E+06	494948	1.176E+06
0.3	1.859E+06	447911	1.411E+06
0.35	2.047E+06	400873	1.646E+06
0.4	2.235E+06	353835	1.882E+06
0.45	2.423E+06	306798	2.117E+06
0.5	2.612E+06	259760	2.352E+06
0.55	2.800E+06	212722	2.587E+06
0.6	2.988E+06	165685	2.822E+06
0.65	3.176E+06	118647	3.057E+06
0.7	3.364E+06	71610	3.293E+06
0.75	3.552E+06	24572	3.528E+06
0.8	3.741E+06	-22466	3.763E+06
0.85	3.929E+06	-69503	3.998E+06
0.9	4.117E+06	-116541	4.233E+06

12-26 Two very large parallel plates are maintained at uniform temperatures. The net rate of radiation heat transfer between the two plates is to be determined.



Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray. **3** Convection heat transfer is not considered.

Properties The emissivities ε of the plates are given to be 0.5 and 0.9.

Analysis The net rate of radiation heat transfer between the two surfaces per unit area of the plates is determined directly from

$$\frac{\dot{Q}_{12}}{A_s}=\frac{\sigma(T_1^{\,4}-T_2^{\,4})}{\dfrac{1}{\varepsilon_1}+\dfrac{1}{\varepsilon_2}-1}=\frac{(5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)[(600\,\text{K})^4-(400\,\text{K})^4]}{\dfrac{1}{0.5}+\dfrac{1}{0.9}-1}=\mathbf{2795\ W/m^2}$$

12-27 "!PROBLEM 12-27"

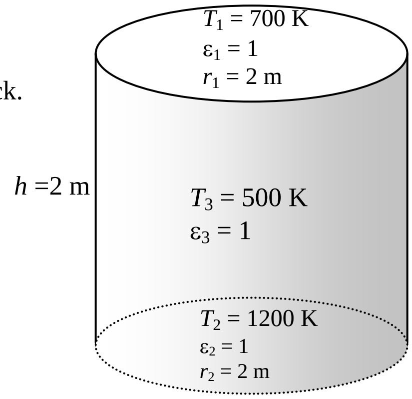
```
"GIVEN"
T_1=600 "[K], parameter to be varied"
T_2=400 "[K]"
epsilon_1=0.5 "parameter to be varied"
epsilon_2=0.9
sigma=5.67E-8 "[W/m^2-K^4], Stefan-Boltzmann constant"

"ANALYSIS"
q_dot_12=(sigma*(T_1^4-T_2^4))/(1/epsilon_1+1/epsilon_2-1)
```

T_1 [K]	q_{12} [W/m^2]
500	991.1
525	1353
550	1770
575	2248
600	2793
625	3411
650	4107
675	4888
700	5761
725	6733
750	7810
775	9001
800	10313
825	11754
850	13332
875	15056
900	16934
925	18975
950	21188
975	23584
1000	26170

ε_1	q_{12} [W/m^2]
0.1	583.2
0.15	870
0.2	1154
0.25	1434
0.3	1712
0.35	1987
0.4	2258
0.45	2527
0.5	2793
0.55	3056
0.6	3317
0.65	3575
0.7	3830
0.75	4082
0.8	4332
0.85	4580
0.9	4825

12-28 The base, top, and side surfaces of a furnace of cylindrical shape are black, and are maintained at uniform temperatures. The net rate of radiation heat transfer to or from the top surface is to be determined.



Assumptions **1** Steady operating conditions exist **2** The surfaces are black. **3** Convection heat transfer is not considered.

Properties The emissivity of all surfaces are ε = 1 since they are black.

Analysis We consider the top surface to be surface 1, the base surface to be surface 2 and the side surfaces to be surface 3. The cylindrical furnace can be considered to be three-surface enclosure. We assume that steady-state conditions exist. Since all surfaces are black, the radiosities are equal to the emissive power of surfaces, and the net rate of radiation heat transfer from the top surface can be determined from

$$\dot{Q} = A_1 F_{12}\sigma(T_1^4 - T_2^4) + A_1 F_{13}\sigma(T_1^4 - T_3^4)$$

and $$A_1 = \pi r^2 = \pi(2\text{ m})^2 = 12.57\text{ m}^2$$

The view factor from the base to the top surface of the cylinder is $F_{12} = 0.38$ (From Figure 12-44). The view factor from the base to the side surfaces is determined by applying the summation rule to be

$$F_{11} + F_{12} + F_{13} = 1 \longrightarrow F_{13} = 1 - F_{12} = 1 - 0.38 = 0.62$$

Substituting,

$$\begin{aligned}\dot{Q} &= A_1 F_{12}\sigma(T_1^4 - T_2^4) + A_1 F_{13}\sigma(T_1^4 - T_3^4)\\ &= (12.57\text{m}^2)(0.38)(567\times10^{-8}\text{ W/m}^2.\text{K}^4)(700\text{K}^4 - 500\text{K}^4)\\ &\quad + (12.57\text{ m}^2)(0.62)(5.67\times10^{-8}\text{ W/m}^2.\text{K}^4)(700\text{K}^4 - 1200\text{K}^4)\\ &= -7.62\times10^5\text{ W} = \mathbf{-762\ kW}\end{aligned}$$

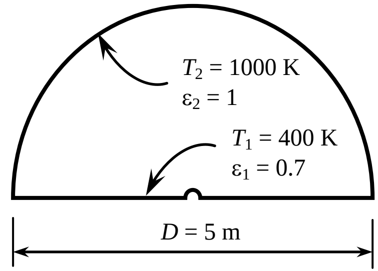
Discussion The negative sign indicates that net heat transfer is to the top surface.

12-29 The base and the dome of a hemispherical furnace are maintained at uniform temperatures. The net rate of radiation heat transfer from the dome to the base surface is to be determined.

Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray. **3** Convection heat transfer is not considered.

Analysis The view factor is first determined from

$$F_{11} = 0 \text{ (flat surface)}$$
$$F_{11} + F_{12} = 1 \rightarrow F_{12} = 1 \text{ (summation rule)}$$



Noting that the dome is black, net rate of radiation heat transfer from dome to the base surface can be determined from

$$\begin{aligned}\dot{Q}_{21} &= -\dot{Q}_{12} = -\varepsilon A_1 F_{12}\sigma(T_1^{\ 4} - T_2^{\ 4}) \\ &= -(0.7)[\pi(5\text{ m})^2/4](1)(5.67\times10^{-8}\text{ W/m}^2\cdot\text{K}^4)[(400\text{ K})^4 - (1000\text{ K})^4] \\ &= 7.594\times10^5\text{ W} \\ &= \mathbf{759.4\ kW}\end{aligned}$$

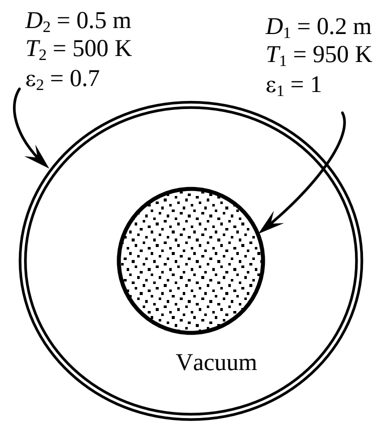
The positive sign indicates that the net heat transfer is from the dome to the base surface, as expected.

12-30 Two very long concentric cylinders are maintained at uniform temperatures. The net rate of radiation heat transfer between the two cylinders is to be determined.

Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray. **3** Convection heat transfer is not considered.

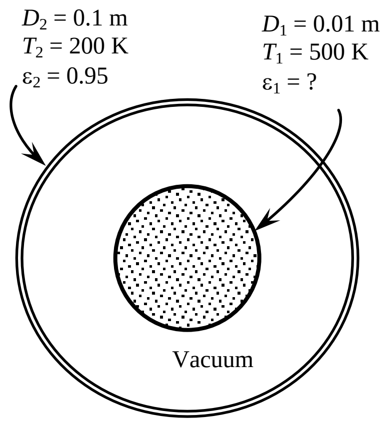
Properties The emissivities of surfaces are given to be ε_1 = 1 and ε_2 = 0.7.

Analysis The net rate of radiation heat transfer between the two cylinders per unit length of the cylinders is determined from



$$\dot{Q}_{12} = \frac{A_1\sigma(T_1^{\ 4} - T_2^{\ 4})}{\dfrac{1}{\varepsilon_1} + \dfrac{1-\varepsilon_2}{\varepsilon_2}\left(\dfrac{r_1}{r_2}\right)} = \frac{[\pi(0.2\text{ m})(1\text{m})](5.67\times10^{-8}\text{ W/m}^2\cdot\text{K}^4)[(950\text{ K})^4 - (500\text{ K})^4]}{\dfrac{1}{1} + \dfrac{1-0.7}{0.7}\left(\dfrac{2}{5}\right)}$$
$$= 22{,}870\text{ W} = \mathbf{22.87\ kW}$$

12-31 A long cylindrical rod coated with a new material is placed in an evacuated long cylindrical enclosure which is maintained at a uniform temperature. The emissivity of the coating on the rod is to be determined.



Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray.

Properties The emissivity of the enclosure is given to be ε_2 = 0.95.

Analysis The emissivity of the coating on the rod is determined from

$$\dot{Q}_{12} = \frac{A_1\sigma(T_1^{\ 4} - T_2^{\ 4})}{\dfrac{1}{\varepsilon_1} + \dfrac{1-\varepsilon_2}{\varepsilon_2}\left(\dfrac{r_1}{r_2}\right)}$$

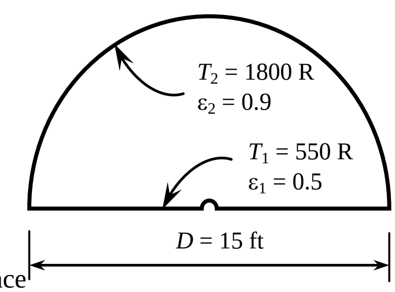
$$8\text{ W} = \frac{[\pi(0.01\text{m})(1\text{m})](5.67\times10^{-8}\text{ W/m}^2\cdot\text{K}^4)[(500\text{ K})^4 - (200\text{ K})^4]}{\dfrac{1}{\varepsilon_1} + \dfrac{1-0.95}{0.95}\left(\dfrac{1}{10}\right)}$$

which gives

ε_1 = **0.074**

12-32E The base and the dome of a long semicylindrical duct are maintained at uniform temperatures. The net rate of radiation heat transfer from the dome to the base surface is to be determined.

Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray. **3** Convection heat transfer is not considered.



Properties The emissivities of surfaces are given to be ε_1 = 0.5 and ε_2 = 0.9.

Analysis The view factor from the base to the dome is first determined from

$$F_{11} = 0 \text{ (flat surface)}$$
$$F_{11} + F_{12} = 1 \rightarrow F_{12} = 1 \text{ (summation rule)}$$

The net rate of radiation heat transfer from dome to the base surface can be determined from

$$\dot{Q}_{21} = -\dot{Q}_{12} = -\frac{\sigma(T_1^{\ 4} - T_2^{\ 4})}{\dfrac{1-\varepsilon_1}{A_1\varepsilon_1} + \dfrac{1}{A_1F_{12}} + \dfrac{1-\varepsilon_2}{A_2\varepsilon_2}} = -\frac{(0.1714\times10^{-8}\text{ Btu/h.ft}^2\cdot\text{R}^4)[(550\text{ R})^4 - (1800\text{ R})^4]}{\dfrac{1-0.5}{(15\text{ ft}^2)(0.5)} + \dfrac{1}{(15\text{ ft}^2)(1)} + \dfrac{1-0.9}{\left[\dfrac{\pi(15\text{ ft})(1\text{ ft})}{2}\right](0.9)}}$$

$$= \mathbf{1.311\times10^6\ Btu/h}$$

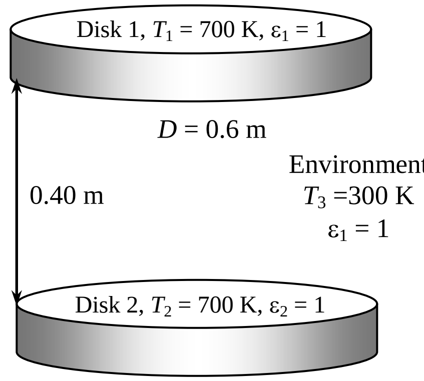
The positive sign indicates that the net heat transfer is from the dome to the base surface, as expected.

12-33 Two parallel disks whose back sides are insulated are black, and are maintained at a uniform temperature. The net rate of radiation heat transfer from the disks to the environment is to be determined.

Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray. **3** Convection heat transfer is not considered.

Properties The emissivities of all surfaces are ε = 1 since they are black.

Analysis Both disks possess same properties and they are black. Noting that environment can also be considered to be blackbody, we can treat this geometry as a three surface enclosure. We consider the two disks to be surfaces 1 and 2 and the environment to be surface 3. Then from Figure 12-7, we read



$$F_{12} = F_{21} = 0.26$$
$$F_{13} = 1 - 0.26 = 0.74 \quad \text{(summation rule)}$$

The net rate of radiation heat transfer from the disks into the environment then becomes

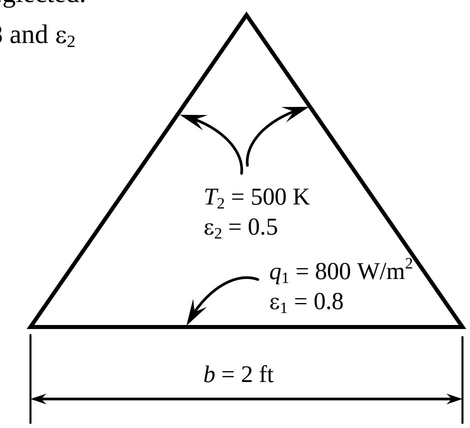
$$\dot{Q}_3 = \dot{Q}_{13} + \dot{Q}_{23} = 2\dot{Q}_{13}$$
$$\dot{Q}_3 = 2F_{13}A_1\sigma(T_1^{\,4} - T_3^{\,4})$$
$$= 2(0.74)[\pi(0.3\,\text{m})^2](5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)[(700\,\text{K})^4 - (300\,\text{K})^4]$$
$$= \mathbf{5505\ W}$$

12-34 A furnace shaped like a long equilateral-triangular duct is considered. The temperature of the base surface is to be determined.

Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray. **3** Convection heat transfer is not considered. **4** End effects are neglected.

Properties The emissivities of surfaces are given to be ε_1 = 0.8 and ε_2 = 0.5.

Analysis This geometry can be treated as a two surface enclosure since two surfaces have identical properties. We consider base surface to be surface 1 and other two surface to be surface 2. Then the view factor between the two becomes $F_{12} = 1$. The temperature of the base surface is determined from



$$\dot{Q}_{12} = \frac{\sigma(T_1^{\,4} - T_2^{\,4})}{\dfrac{1-\varepsilon_1}{A_1\varepsilon_1} + \dfrac{1}{A_1F_{12}} + \dfrac{1-\varepsilon_2}{A_2\varepsilon_2}}$$

$$800\,\text{W} = \frac{(5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)[(T_1)^4 - (500\,\text{K})^4]}{\dfrac{1-0.8}{(1\,\text{m}^2)(0.8)} + \dfrac{1}{(1\,\text{m}^2)(1)} + \dfrac{1-0.5}{(2\,\text{m}^2)(0.5)}} \longrightarrow \mathbf{T_1 = 543\ K}$$

Note that $A_1 = 1\,\text{m}^2$ and $A_2 = 2\,\text{m}^2$.

12-35 "!PROBLEM 12-35"

```
"GIVEN"
a=2 "[m]"
epsilon_1=0.8
epsilon_2=0.5
Q_dot_12=800 "[W], parameter to be varied"
T_2=500 "[K], parameter to be varied"
sigma=5.67E-8 "[W/m^2-K^4], Stefan-Boltzmann constant"

"ANALYSIS"
"Consider the base surface to be surface 1, the side surfaces to be surface 2"
Q_dot_12=(sigma*(T_1^4-T_2^4))/((1-epsilon_1)/(A_1*epsilon_1)+1/(A_1*F_12)+(1-
epsilon_2)/(A_2*epsilon_2))
F_12=1
A_1=1 "[m^2], since rate of heat supply is given per meter square area"
A_2=2*A_1
```

Q_{12} [W]	T_1 [K]
500	528.4
525	529.7
550	531
575	532.2
600	533.5
625	534.8
650	536
675	537.3
700	538.5
725	539.8
750	541
775	542.2
800	543.4
825	544.6
850	545.8
875	547
900	548.1
925	549.3
950	550.5
975	551.6
1000	552.8

T_2 [K]	T_1 [K]
300	425.5
325	435.1
350	446.4
375	459.2
400	473.6
425	489.3
450	506.3
475	524.4
500	543.4
525	563.3
550	583.8
575	605
600	626.7
625	648.9

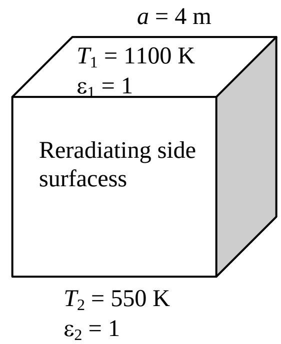
650	671.4
675	694.2
700	717.3

12-36 The floor and the ceiling of a cubical furnace are maintained at uniform temperatures. The net rate of radiation heat transfer between the floor and the ceiling is to be determined.

Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray. **3** Convection heat transfer is not considered.

Properties The emissivities of all surfaces are $\varepsilon = 1$ since they are black or reradiating.

Analysis We consider the ceiling to be surface 1, the floor to be surface 2 and the side surfaces to be surface 3. The furnace can be considered to be three-surface enclosure with a radiation network shown in the figure. We assume that steady-state conditions exist. Since the side surfaces are reradiating, there is no heat transfer through them, and the entire heat lost by the ceiling must be gained by the floor. The view factor from the ceiling to the floor of the furnace is $F_{12} = 0.2$. Then the rate of heat loss from the ceiling can be determined from



$$\dot{Q}_1 = \frac{E_{b1} - E_{b2}}{\left(\dfrac{1}{R_{12}} + \dfrac{1}{R_{13} + R_{23}}\right)^{-1}}$$

where

$$E_{b1} = \sigma T_1^{\,4} = (5.67\times10^{-8}\ \text{W/m}^2.\text{K}^4)(1100\,\text{K})^4 = 83{,}015\,\text{W/m}^2$$

$$E_{b2} = \sigma T_2^{\,4} = (5.67\times10^{-8}\ \text{W/m}^2.\text{K}^4)(550\,\text{K})^4 = 5188\,\text{W/m}^2$$

and

$$A_1 = A_2 = (4\ \text{m})^2 = 16\ \text{m}^2$$

$$R_{12} = \frac{1}{A_1F_{12}} = \frac{1}{(16\ \text{m}^2)(0.2)} = 0.3125\ \text{m}^{-2}$$

$$R_{13} = R_{23} = \frac{1}{A_1F_{13}} = \frac{1}{(16\ \text{m}^2)(0.8)} = 0.078125\ \text{m}^{-2}$$

Substituting,

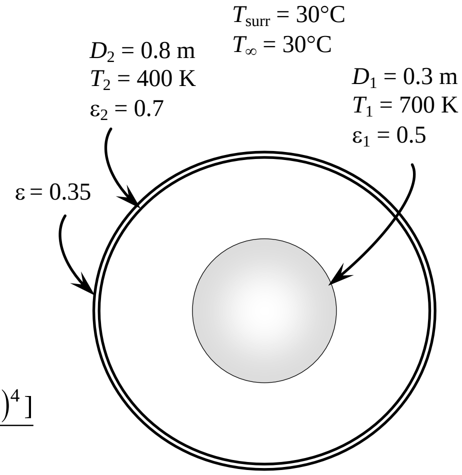
$$\dot{Q}_{12} = \frac{(83{,}015 - 5188)\ \text{W/m}^2}{\left(\dfrac{1}{0.3125\text{m}^{-2}} + \dfrac{1}{2(0.078125\text{m}^{-2})}\right)^{-1}} = 7.47\times10^5\ \text{W} = \mathbf{747\ kW}$$

12-37 Two concentric spheres are maintained at uniform temperatures. The net rate of radiation heat transfer between the two spheres and the convection heat transfer coefficient at the outer surface are to be determined.

Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray.

Properties The emissivities of surfaces are given to be $\varepsilon_1 = 0.1$ and $\varepsilon_2 = 0.8$.

Analysis The net rate of radiation heat transfer between the two spheres is



$$\dot{Q}_{12} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\dfrac{1}{\varepsilon_1} + \dfrac{1-\varepsilon_2}{\varepsilon_2}\left(\dfrac{r_1^2}{r_2^2}\right)}$$

$$= \frac{[\pi(0.3\,\text{m})^2](5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)[(700\,\text{K})^4 - (400\,\text{K})^4]}{\dfrac{1}{0.5} + \dfrac{1-0.7}{0.7}\left(\dfrac{0.15\,\text{m}}{0.4\,\text{m}}\right)^2}$$

$$= \mathbf{1669\ W}$$

Radiation heat transfer rate from the outer sphere to the surrounding surfaces are

$$\dot{Q}_{rad} = \varepsilon F A_2 \sigma(T_2^4 - T_{surr}^4)$$
$$= (0.35)(1)[\pi(0.8\,\text{m})^2](5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)[(400\,\text{K})^4 - (30+273\,\text{K})^4] = 685\,\text{W}$$

The convection heat transfer rate at the outer surface of the cylinder is determined from requirement that heat transferred from the inner sphere to the outer sphere must be equal to the heat transfer from the outer surface of the outer sphere to the environment by convection and radiation. That is,

$$\dot{Q}_{conv} = \dot{Q}_{12} - \dot{Q}_{rad} = 1669 - 685 = 9845\,\text{W}$$

Then the convection heat transfer coefficient becomes

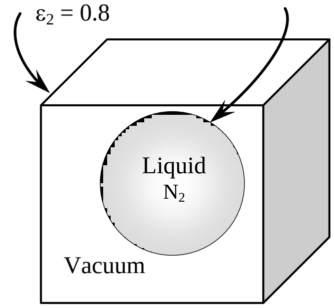
$$\dot{Q}_{conv.} = hA_2(T_2 - T_\infty)$$
$$984\,\text{W} = h\left[\pi(0.8\,\text{m})^2\right](400\,\text{K} - 303\,\text{K}) \longrightarrow h = \mathbf{5.04\ W/m^2\cdot{}^\circ C}$$

12-38 A spherical tank filled with liquid nitrogen is kept in an evacuated cubic enclosure. The net rate of radiation heat transfer to the liquid nitrogen is to be determined.

Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray. **3** Convection heat transfer is not considered. **4** The thermal resistance of the tank is negligible.

Properties The emissivities of surfaces are given to be $\varepsilon_1 = 0.1$ and $\varepsilon_2 = 0.8$.

Analysis We take the sphere to be surface 1 and the surrounding cubic enclosure to be surface 2. Noting that $F_{12} = 1$, for this two-surface enclosure, the net rate of radiation heat transfer to liquid nitrogen can be determined from



$$\dot{Q}_{21} = -\dot{Q}_{12} = -\frac{A_1\sigma\left(T_1^{\,4} - T_2^{\,4}\right)}{\dfrac{1}{\varepsilon_1} + \dfrac{1-\varepsilon_2}{\varepsilon_2}\left(\dfrac{A_1}{A_2}\right)}$$

$$= -\frac{\left[\pi(2\text{ m})^2\right]\left(5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4\right)\left[(100\,\text{K})^4 - (240\,\text{K})^4\right]}{\dfrac{1}{0.1} + \dfrac{1-0.8}{0.8}\left[\dfrac{\pi(2\text{ m})^2}{6(3\text{m})^2}\right]}$$

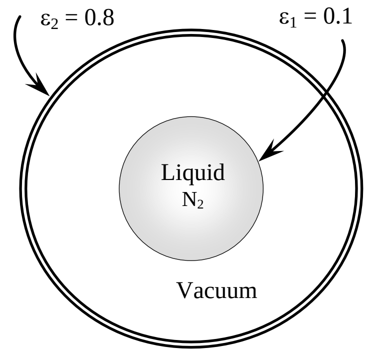
$$= \mathbf{228\ \ W}$$

12-39 A spherical tank filled with liquid nitrogen is kept in an evacuated spherical enclosure. The net rate of radiation heat transfer to the liquid nitrogen is to be determined.

Assumptions **1** Steady operating conditions exist **2** The surfaces are opaque, diffuse, and gray. **3** Convection heat transfer is not considered. **4** The thermal resistance of the tank is negligible.

Properties The emissivities of surfaces are given to be $\varepsilon_1 = 0.1$ and $\varepsilon_2 = 0.8$.

Analysis The net rate of radiation heat transfer to liquid nitrogen can be determined from



$$\dot{Q}_{12} = \frac{A_1\sigma(T_1^{\,4} - T_2^{\,4})}{\dfrac{1}{\varepsilon_1} + \dfrac{1-\varepsilon_2}{\varepsilon_2}\left(\dfrac{r_1^{\,2}}{r_2^{\,2}}\right)}$$

$$= \frac{[\pi(2\text{ m})^2](5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)[(240\,\text{K})^4 - (100\,\text{K})^4]}{\dfrac{1}{0.1} + \dfrac{1-0.8}{0.8}\left(\dfrac{(1\text{ m})^2}{(1.5\text{ m})^2}\right)}$$

$$= \mathbf{227\ W}$$

12-40 "!PROBLEM 12-40"

"GIVEN"
D=2 "[m]"
a=3 "[m], parameter to be varied"
T_1=100 "[K]"
T_2=240 "[K]"
epsilon_1=0.1 "parameter to be varied"
epsilon_2=0.8 "parameter to be varied"
sigma=5.67E-8 "[W/m^2-K^4], Stefan-Boltzmann constant"

"ANALYSIS"
"Consider the sphere to be surface 1, the surrounding cubic enclosure to be surface 2"
Q_dot_12=(A_1*sigma*(T_1^4-T_2^4))/(1/epsilon_1+(1-epsilon_2)/epsilon_2*(A_1/A_2))
Q_dot_21=-Q_dot_12
A_1=pi*D^2
A_2=6*a^2

a [m]	Q_{21} [W]
2.5	227.4
2.625	227.5
2.75	227.7
2.875	227.8
3	227.9
3.125	228
3.25	228.1
3.375	228.2
3.5	228.3
3.625	228.4
3.75	228.4
3.875	228.5
4	228.5
4.125	228.6
4.25	228.6
4.375	228.6
4.5	228.7
4.625	228.7
4.75	228.7
4.875	228.8
5	228.8

ε_1	**Q_{21} [W]**
0.1	227.9
0.15	340.9
0.2	453.3
0.25	565
0.3	676
0.35	786.4
0.4	896.2
0.45	1005
0.5	1114
0.55	1222
0.6	1329
0.65	1436
0.7	1542
0.75	1648
0.8	1753
0.85	1857
0.9	1961

ε_2	**Q_{21} [W]**
0.1	189.6
0.15	202.6
0.2	209.7
0.25	214.3
0.3	217.5
0.35	219.8
0.4	221.5
0.45	222.9
0.5	224.1
0.55	225
0.6	225.8
0.65	226.4
0.7	227
0.75	227.5
0.8	227.9
0.85	228.3
0.9	228.7