Chapter 10: Radiation

Section 10.2: Emission of Radiation by a Blackbody

10.2-1 (10-1 in text) Radiation that passes through the atmosphere surrounding our planet is absorbed to an extent that depends on its wavelength due to the presence of gases such as water vapor, oxygen, carbon dioxide and methane. However, there is a relatively large range of wavelengths between 8 and 13 microns for which there is relatively little absorption in the atmosphere and thus, the transmittance of atmosphere is high. This wavelength band is called the atmospheric window. Infrared detectors on satellites measure the relative amount of infrared radiation emitted from the ground in this wavelength band in order provide an indication of the ground temperature.

a) What fraction of the radiation from sun is in the atmospheric window? The sun can be approximated as a blackbody source at 5780 K.
b) Prepare a plot of the fraction of the thermal radiation emitted between 8 and 13 microns to the total radiation emitted by the ground for temperatures between -10°C to 30°C.
c) Based on your answers to a) and b), indicate whether radiation in the atmospheric window can provides a clear indication of surface temperature to satellite detectors.

10.2-2 A new stove top uses a halogen lamp that is placed under a glass surface as the heat source for each burner. The advantages of this design are that the lamp delivers instant heat and responds very quickly to changes in the temperature setting. The heating element of the lamp is a circular disk that is insulated on its back and has a diameter of D_l = 2.4 cm. The design specification for the stove top requires that it be capable of heating V_w = 2 liters of water from T_{ini} = 25°C to boiling in less than t_b = 8 minutes at a location that is at sea level. Assume that the heating element radiates a blackbody and that all of the radiation emitted by the heating element is absorbed by the water. Ignore convection for this problem.

a) If the efficiency of the burner is 100% (i.e., all electrical power provided to the halogen heating element is transferred to the water) then what is the minimum required electrical power input to the unit in order to meet the design specification?
b) Estimate the temperature of the heating element required.
c) Will the radiant energy from this stove top unit be visible? What is the fraction of the radiation emitted by the element that is visible?

10.2-3 The solar constant, G_{sc}, is the energy from the sun per unit time that would be received on a unit area of surface perpendicular to the direction of the propagation of the radiation at the mean earth-sun distance if there were no atmosphere surrounding earth. We know that the diameter of the sun is approximately D_{sun} = 1.39x10^9 m and that the surface of the sun is at an equivalent temperature of approximately T_{sun} = 5780 K. The diameter of the earth is D_{earth} = 1.276x10^7 m and the mean earth-sun distance is R = 1.497x10^{11} m.

a.) Estimate the value of the solar constant.

b.) In 2003, the amounts of primary energy consumed in the world as a result of combustion of coal, natural gas, and oil was 140x10^9 GJ/yr, 95x10^9 GJ/yr and 190x10^9 GJ/yr, respectively. Compare the amount of energy that is radiated to earth from the sun to the annual energy consumed by combustion of these fossil fuels.

c) The first law of thermodynamics indicates that energy cannot be destroyed. If you answer to part (b) indicated that more energy strikes the planet in year than we use then explain why we are experiencing an energy shortage.

10.2-4 (10-2 in text) Photovoltaic cells convert a portion of the radiation that is incident on their surface into electrical power. The efficiency of the cells is defined as the ratio of the electrical power produced to the incident radiation. The efficiency of solar cells is dependent upon the wavelength distribution of the incident radiation. An explanation for this behavior was originally provided by Einstein and initiated the discovery of quantum theory. Radiation can be considered to consist of flux of photons. The energy per photon (*e*) is: $e = h\,c/\lambda$ where *h* is Planck's constant, c is the speed of light, and λ is the wavelength of the radiation. The number of photons per unit area and time is the ratio of the spectral emissive power, $E_{b,\lambda}$ to the energy of a single photon, *e*. When radiation strikes a material, it may dislodge electrons. However, the electrons are held in place by forces that must be overcome. Only those photons that have energy above a material-specific limit, called the band-gap energy limit (i.e., photons with wavelengths lower than $\lambda_{bandgap}$) are able to dislodge an electron. In addition, photons having energy above the band-gap limit are still only able to dislodge one electron per photon; therefore, only a fraction of their energy, equal to $\lambda/\lambda_{bandgap}$, is useful for providing electrical current. Assuming that there are no imperfections in the material that would prevent dislodging of an electron and that none of the dislodged electrons recombine (i.e, a quantum efficiency of 1), the efficiency of a photovoltaic cell can be expressed as:

$$\eta = \frac{\int_0^{\lambda_{bandgap}} \frac{\lambda}{\lambda_{bandgap}} E_{b,\lambda}\, d\lambda}{\int_0^{\infty} E_{b,\lambda}\, d\lambda}$$

a.) Calculate the maximum efficiency of a silicon solar cell that has a band-gap wavelength of $\lambda_{bandgap}$ = 1.12 μm that is irradiated by solar energy having an equivalent blackbody temperature of 5780 K.

b) Calculate the maximum efficiency of a silicon solar cell that has a band-gap wavelength of $\lambda_{bandgap}$ = 1.12 μm that is irradiated by incandescent light produced by a black tungsten filament at 2700 K.

c) Repeat part (a) for a gallium arsenide cell that has a band-gap wavelength of $\lambda_{bandgap}$ = 0.73 μm, corresponding to a band gap energy of 1.7 ev.

d) Plot the efficiency versus bandgap wavelength for solar irradiation. What bandgap wavelength provides the highest efficiency?

10.2-5 (10-3 in text) A novel hybrid solar lighting system has been proposed in which concentrated solar radiation is collected and then filtered so that only radiation in the visible range (0.38 μm to 0.78 μm) is transferred to luminaires in the building by a fiber optic bundle. The unwanted heating of the building caused by lighting can be reduced in this manner. The non-visible energy at wavelengths greater than 0.78 μm can be used to produce electricity with thermal photovoltaic cells. Solar radiation can be approximated as radiation from a blackbody at 5780 K. See Problem 10.2-4 (10-2 in text) for a discussion of a model of the efficiency of a photovoltaic cell.

a) Determine the maximum theoretical efficiency of silicon photovoltaic cells ($\lambda_{bandgap}$=1.12 μm) if they are illuminated with solar radiation that has been filtered so that only wavelengths greater than 0.78 μm are available.
b) Determine the band-gap wavelength ($\lambda_{bandgap}$) that maximizes the efficiency for this application.

10.2-6 A tungsten filament is placed in an evacuated glass enclosure. Assume that the glass enclosure is completely transparent for wavelengths less than 3 μm but completely opaque for wavelengths greater than 3 μm. The filament is heated to 2550 K.

a) What fraction of the radiant energy emitted by the filament is in the visible region (0.38 – 0.78 μm)?
b) What fraction of the radiant energy emitted by the filament can not be transmitted through the enclosure?

10.2-7 (10-4 in text) Light is "visually evaluated radiant energy", i.e., radiant energy that your eyes are sensitive to (just like sound is pressure waves that your ears are sensitive to). Because light is both radiation and an observer-derived quantity, two different systems of terms and units are used to describe it: radiometric (related to its fundamental electromagnetic character) and photometric (related to the visual sensation of light). The radiant power ($\dot{q}$) is the total amount of radiation emitted from a source and is a radiometric quantity (with units W). The radiant energy emitted by a blackbody at a certain temperature is the product of the blackbody emissive power (E_b, which is the integration of blackbody spectral emissive power over all wavelengths) and the surface area of the object (A).

$$\dot{q} = A E_b = A \int_{\lambda=0}^{\infty} E_{\lambda,b}\, d\lambda = A \sigma T^4$$

On the other hand, luminous power (F) is the amount of "light" emitted from a source and is a photometric quantity (with units of lumen which are abbreviated lm). The radiant and luminous powers are related by:

$$F = A K_m \int_0^{\infty} E_{\lambda,b}(\lambda) V(\lambda)\, d\lambda$$

where K_m is a constant (683 lm/W photopic) and $V(\lambda)$ is the relative spectral luminous efficiency curve. Notice that without the constant K_m, the luminous power is just the radiant power filtered by the function $V(\lambda)$ and has units of W; the constant K_m can be interpreted as converting W to lumen, the photometric unit of light. The filtering function $V(\lambda)$ is derived based on the sensitivity of the human eye to different wavelengths (in much the same way that sound meters use a scale based on the sensitivity of your ear in order to define the acoustic unit, decibel or dB). The function $V(\lambda)$ is defined as the ratio of the sensitivity of the human eye to radiation at a particular wavelength to the sensitivity of your eye at 0.555 µm; 0.555 µm was selected because your eye is most sensitive to this wavelength (which corresponds to green). An approximate equation for $V(\lambda)$ is: $V(\lambda) = \exp\left[-285.4(\lambda - 0.555)^2\right]$ where λ is the wavelength in micron. The luminous efficiency of a light source (η_l) is defined as the number of lumens produced per watt of radiant power:

$$\eta_l = \frac{F}{\dot{q}} = \frac{K_m \int_0^{\infty} E_{b,\lambda}(\lambda) V(\lambda)\, d\lambda}{\sigma T^4}$$

The conversion factor from W to lumen, K_m, is defined so that the luminous efficiency of sunlight is 100 lm/W; most other, artificial light sources will be less than this value. The most commonly used filament in an incandescent light bulb is tungsten; tungsten will melt around 3650 K. An incandescent light bulb with a tungsten filament is typically operated at 2770 K in order to extend the life of the bulb. Determine the luminous efficiency of an incandescent light bulb with a tungsten filament.

Section 10.3: Radiation Exchange between Black Surfaces

10.3-1 Two identical parallel plates, each of size W = 2 m by L = 1.5 m are spaced H = 2 m apart as shown in Figure P10.3-1.

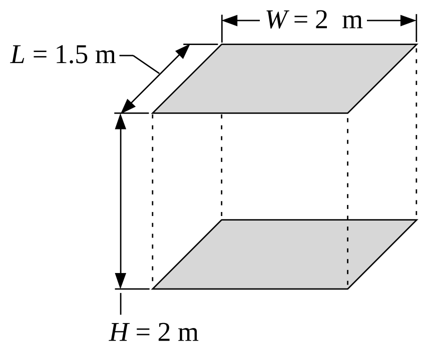

Figure P10.3-1: Two parallel plates.

a.) Calculate the view factor between the two plates by integrating the differential view factor provided in EES library routine FDiff_1.

b.) Compare your result from (a) with the view factor provided for two parallel plates by the function F3D_1.

10.3-2 (10-5 in text) Find the view factor $F_{1,2}$ for the geometry shown in Figure P10.3.2 in the following two ways and compare the results.

a) Use the view factor function F3D_2 in EES (you will need to call the function more than once).

b) Use the differential view factor relation FDiff_4 and do the necessary integration.

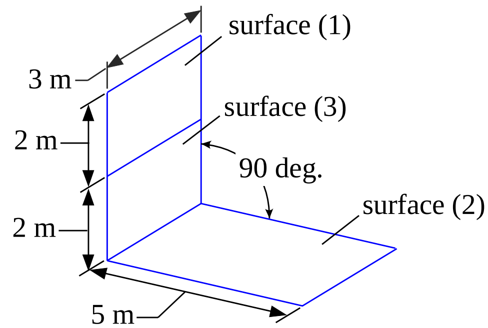

Figure P10.3-2: Determine the view factor $F_{1,2}$.

10.3-3 A room in a building has a floor area of 4 m by 3 m and a ceiling height of 3 m. There is a single door to the room that is 1 m wide, as shown in Figure P10.3-3.

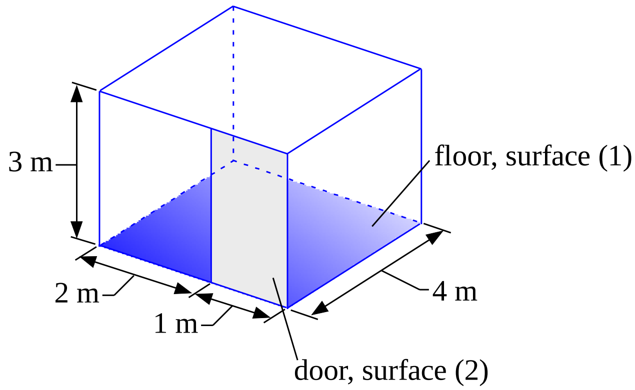

Figure P10.3-3: Room with a door.

a.) Determine the view factor between the door (surface 2) to the floor (surface 1).

10.3-4 A cylindrical thermos bottle is made of a two stainless steel cylinders having the dimensions shown in Figure P10.3-4. Except for a few non-conductive struts, the space between the cylinders is filled with air at atmospheric pressure. The wall thickness of the metal is *th* = 0.7 mm. The thermos is filled with coffee at T_H = 95°C and surrounded by air at T_C = 25°C. Assume that the inner wall of the thermos is at T_H and the outer wall is at T_C. Neglect heat loss from the bottom or top.

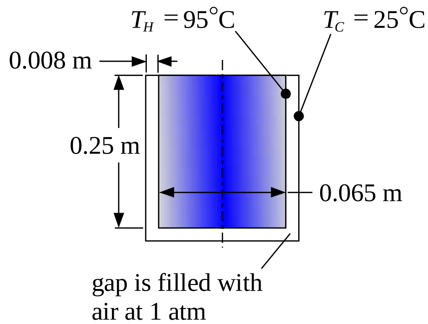

Figure P10.3-4: Thermos

a.) Estimate the rate of heat loss by radiation assuming that the stainless steel surfaces are black.

b.) Is the radiative heat loss significant compared to the convective heat loss due to natural convection in the gap?

10.3-5 (10-6 in text) A rectangular building warehouse has dimensions of 50 m by 30 m with a ceiling height of 10 m. The floor of this building is heated. On a cold day, the inside surface temperature of the walls are found to be 16°C, the ceiling surface is 12°C, and the heated floor is at a temperature of 32°C. Estimate the radiant heat transfer from the floor to walls and the ceiling assuming that all surfaces are black. What fraction of the heat transfer is radiated to the ceiling?

10.3-6 (10-7 in text) A furnace wall has a 4 cm hole in the insulated wall for visual access. The wall is 8 cm wide. The temperature inside the furnace is 1900 C and it is 25°C on the outside of the furnace. Assuming that the insulation acts as a black surface at a uniform temperature, estimate the radiative heat transfer through the hole.

10.3-7 (10-8 in text) A homeowner has installed a skylight in a room that measures 6 m x 4 m with a 2.5 m ceiling height, as shown in Figure P10.3-7. The skylight is located in the center of the ceiling and it is square, 2 m on each side. A desk is to be located in a corner of the room. The surface of the desk is 0.9 m high and the desk surface is 0.5 by 1 m in area. The skylight has a diffusing glass so that the visible light that enters the skylight should be uniformly distributed.

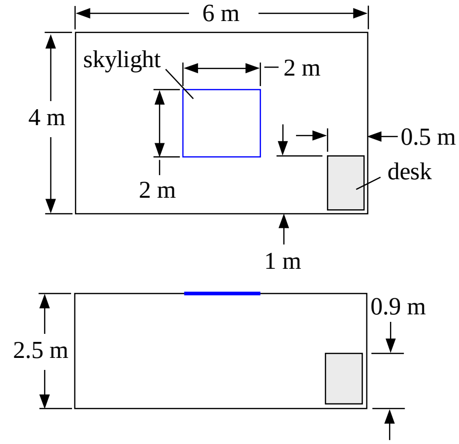

Figure P10.3-7: Desk and skylight in a room.

a.) Determine the fraction of the light emanating from skylight that will directly illuminate the desktop. Does it matter which wall the desk is positioned against (i.e., if you turned the desk 90° would the result be different)?

10.3-8 A cylindrical heating element has a length of L = 15 cm and a diameter of D_1 = 0.5 cm. It is surrounded by a cylindrical enclosure having a diameter of D_2 = 2 cm that is open at the ends, as shown in Figure P10.3-8. The surface of the enclosure is at T_2 = 240°C and the electrical dissipation of the heating element is $\dot{q}_h$ = 70 W. The surroundings are at T_3 = 20°C.

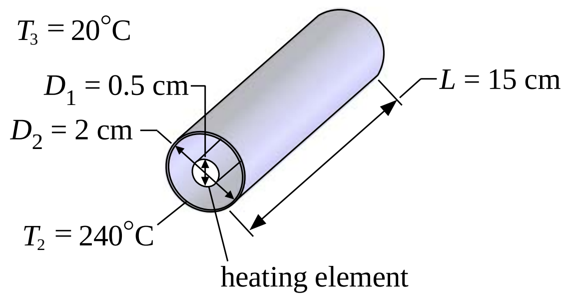

Figure P10.3-8: Cylindrical heating element.

a.) Determine the temperature of the heating element assuming that radiation is the only mechanism for heat transfer. The ends of the heating element may be assumed to be insulated.

b.) How much error would result if the geometry were approximated to be two-dimensional?

10.3-9 (10-9 in text) The bottom surface of the cylindrical cavity shown in Fig. P10.3-9 is heated to T_{bottom} = 750°C while the top surface is maintained at T_{top} = 100°C. The sides of the cavity are insulated externally and isothermal (i.e., the sides are made of a conductive material and therefore come to a single temperature).

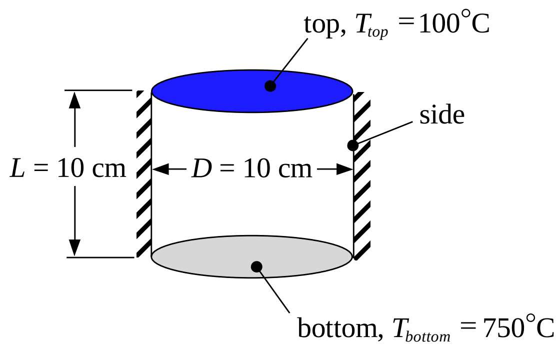

Figure P10.3-9: Cylindrical cavity heated from the bottom and cooled on top.

The diameter of the cylinder is D = 10 cm and its length is L = 10 cm. Assume that the cylinder is evacuated so that the only mechanism for heat transfer is radiation. All surfaces are black (ε = 1.0).

a.) Calculate the net rate of heat transfer from the bottom to the top surface. How much of this energy is radiated directly from the bottom surface to the top and how much is transferred indirectly (from the bottom to the sides to the top)?

b.) What is the temperature of the sides?

c.) If the sides were not insulated but rather also cooled to T_{side} = 100°C then what would be the total heat transfer from the bottom surface?

10.3-10 (10-10 in text) A homeowner inadvertently left a spray can near the barbeque grill, as shown in Figure P10.3-10. The spray can is H = 8 inch high with a diameter of D = 2.25 inch. The side of the barbeque grill is H = 8 inch high and W = 18 inch wide. The spray can is located with its center aligned with the center of the grill wall and it is a = 6 inch from the wall, as shown in Figure P10.3-10. Assume the can to be insulated on its top and bottom.

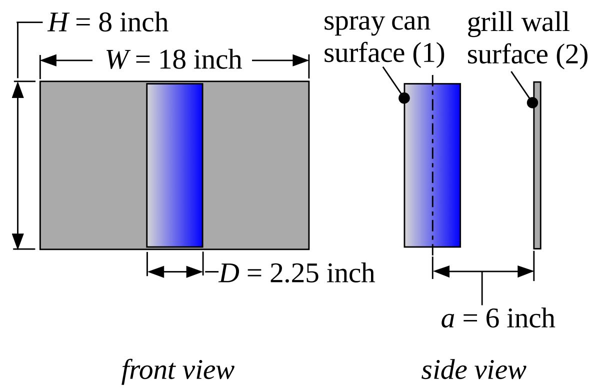

Figure P10.3-10: Spray can near a grill.

a.) What is the view factor between the spray can, surface (1), and the grill wall, surface (2)?
b.) Assuming both surfaces to be black, what is the heat transfer rate to the spray can when the grill wall is at T_2 = 350°F and the spray can exterior is T_1 = 75°F?
c.) The surroundings, surface (3) are at 75°F. What is the equilibrium temperature of the spray can if it can be assumed to be isothermal and radiation is the only heat transfer mechanism?

10.3-11 Figure P10.3.11 illustrates a furnace in a power plant. Just inside the furnace wall is a series of regularly spaced pipes containing water that is being heated by combustion flames at T_f = 870°C. Because of the high temperatures involved, you may assume that all of the heat transfer within the furnace occurs by radiation.

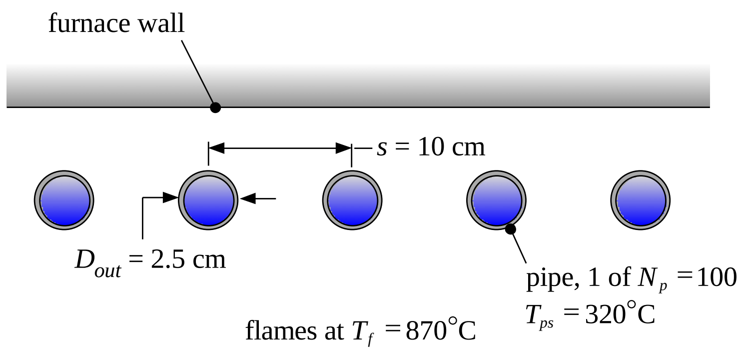

Figure P10.3-11: Furnace in a power plant.

The pipes are spaced s = 10 cm (center to center distance) apart and traverse the entire outer extent of the furnace; there are a total of N_p = 100 pipes although only five are shown in Figure P10.3-11. The pipes have outer diameter D_{out} = 2.5 cm. The surface temperature of the pipes is T_{ps} = 320°C. All surfaces can be assumed to be black. For the purposes of this problem you may treat the flame as a black surface that extends parallel to the furnace wall on the other side of the pipes. End effects can be neglected.

a.) If the furnace wall is perfectly insulated, estimate the total rate of heat transfer to the water (i.e., to the pipe surface) per unit length. What is the wall temperature in this limit?

b.) Assume that the furnace wall is not insulated but rather it is cooled to a temperature, T_w = 800 K. Compute the net heat transferred to the furnace wall (this is the heat that would have to be conducted through the wall and transferred to the ambient air outside of the furnace in order to maintain the temperature of the wall at T_w).

c.) Use your model from (b) to prepare a plot that shows the amount of heat transferred to the wall as a function of the wall temperature; does your plot make sense? Is it consistent with your answer from parts (a) and (b)?

d.) The wall has an area specific resistance (that includes both conduction through the wall and convection from its outer surface) of $R''_w = 0.2\ \text{K-m}^2/\text{W}$ that characterizes the heat transfer from the wall's internal surface to the ambient air outside of the furnace at T_{amb} = 20°C. Overlay a plot of the heat transferred through the wall as a function of the wall temperature on your result from part (c); there should be a location where the two lines intersect so that the heat transfer into the wall predicted using your radiation solution matches the heat transfer through the wall based on the wall resistance.

e.) What is the wall temperature and furnace efficiency (defined as the ratio of the heat transfer to the water to the heat transfer from the flame)?

10.3-12 The incident solar flux on the earth at the earth's mean orbital radius (i.e., the mean distance from the earth to the sun) is approximately equal to $\dot{q}''_{s-e}$ = 1350 W/m^2. The earth's mean orbital radius is $R_{o,e}$ = 149.6 million km.

a.) Based on these facts, what is the rate of energy generated by the sun?

b.) Using the answer from (a), determine the incident solar flux on the planet Mercury. The mean orbital radius of Mercury is $R_{o,m}$ = 57.9 million km. Note that you do not need to know the diameter of Mercury in order to answer this question.

c.) Estimate the equilibrium temperature on Mercury based on an energy balance on the planet (assume that Mercury behaves as a black body and has no atmosphere which would cause a greenhouse effect). You do not need to know the diameter of Mercury to solve this problem.

10.3-13 (10-11 in text) You are working on an advanced detector for biological agents; the first step in the process is to ablate (i.e., vaporize) individual particles in an air stream so that their constituent molecules can be identified through mass spectrometry. There are various methods available for providing the energy to the particle required for ablation; for example using multiple pulses of a high power laser. You are analyzing a less expensive technique for vaporization that utilizes radiation energy. A very high temperature element is located at the bottom of a cylinder, as shown in Figure P10.3-13.

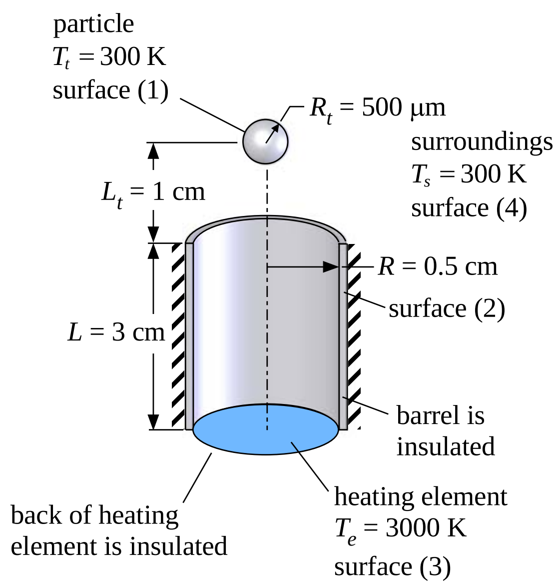

Figure 10.3-13: Radiation vaporization technique.

The length of the cylinder which is the "barrel" of the heat source is L = 3.0 cm and the radius of the cylinder and the heating element is R = 0.5 cm. The heating element is maintained at a very high temperature, T_e = 3000 K. The back side of the heating element and the external surfaces of the barrel of the heat source are insulated. The particle that is being ablated may be modeled as a sphere with radius R_s = 500 μm and is located L_t = 1.0 cm from the mouth of the barrel and is on the centerline of the barrel. The particle is at T_t = 300 K and the surroundings are at T_s = 300 K. All surfaces are black. For this problem, the particle is surface (1), the cylindrical barrel is surface (2), the disk shaped heating element is surface (3), and the surroundings is surface (4).

a.) Determine the areas of all surfaces and the view factors between each surface. This should result in an array A and matrix F that are both completely filled.

b.) Determine the net radiation heat transferred to the target.

c.) What is the efficiency of the ablation system? (i.e., what is the ratio of the energy delivered to the particle to the energy required by the element?)

d.) The particle has density ρ_t = 7000 kg/m^3 and specific heat capacity c_t = 300 J/kg-K. Use your radiation model as the basis of a transient, lumped capacitance numerical model of the particle that can predict the temperature of the particle as a function of time. Assume that the particle is initially at $T_{t,in}$ = 300 K. Use the Integral function in EES and prepare a plot showing the particle temperature as a function of time.

10.3-14 Figure P10.3-14 shows two plates that are parallel and aligned at their center lines.

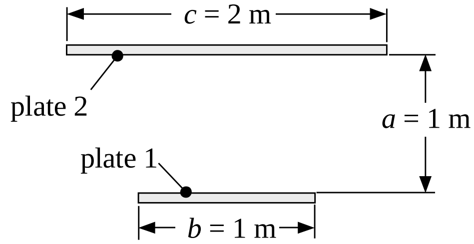

Figure P10.3-14: Plates 1 and 2.

Plate 1 has width b = 1 m and plate 2 has width c = 2 m. The plates are separated by an amount a = 1 m. Assume that the plates extend a long way into the page so that the situation is 2-D.

a.) Determine the view factor $F_{1,2}$ using the crossed and uncrossed strings method.

b.) Check your result from (a) against the value obtained using the EES function F2D_10.

10.3-15 A braze oven is made by heating the bottom surface of a cylindrical enclosure as shown in Figure P10.3-15.

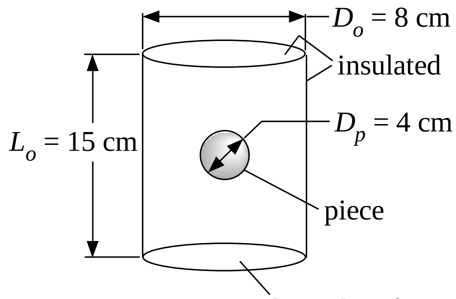

Figure P10.3-15: Braze oven.

The sides and top of the enclosure are insulated. The piece to be heated is suspended at the center of the oven. All surfaces are black. The diameter of the piece is D_p = 4 cm and the piece is made of material with density ρ_p = 7500 kg/m^3 and specific heat capacity c_p = 510 J/kg-K. The diameter of the oven is D_o = 8 cm and the length of the oven is L_o = 15 cm. The temperature of the heater and the piece is initially T_{ini} = 300 K. The heater temperature is ramped linearly from T_{ini} to T_{max} = 1000 K over t_{ramp} = 10 min.

a.) Develop a numerical model using the Integral command in EES that can predict the temperature of the piece as a function of time for 30 minutes after the heater is activated.

b.) Plot the temperature of the piece and the heater as a function of time.

10.3-16 A transfer line is used to provide liquid nitrogen to an experiment, as shown in Figure P10.3-16.

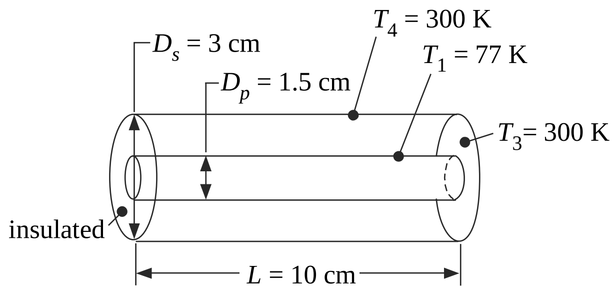

Figure P10.3-16: Transfer line.

The pipe is L = 10 cm long with outer diameter D_p = 1.5 cm. The surface of the pipe is T_1 = 77 K. The space between the pipe and the outer shield is evacuated. The diameter of the outer shield is D_s = 3 cm and the temperature of the shield is T_4 = 300 K. One end is insulated and the other end has temperature T_3 = 100 K. All surfaces are black.

a.) Determine the rate of heat transfer to the pipe.

10.3-17 Droplets of molten metal are injected in a vacuum environment, as shown in Figure P10.3-17.

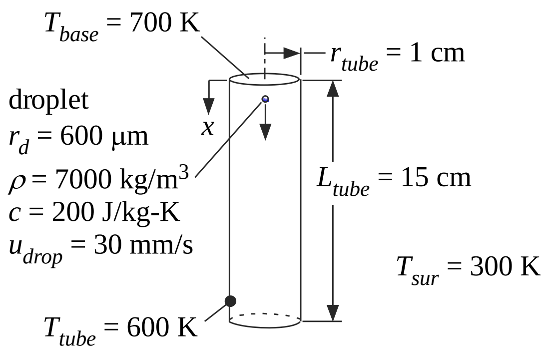

Figure P10.3-17: Molten metal droplet injection system.

The droplets are injected at T_{ini} = 700 K into a tube that is maintained at T_{tube} = 600 K. The base of the tube at x = 0 is kept at T_{base} = 700 K. The droplets have radius r_d = 600 μm and have density ρ = 7000 kg/m^3 and heat capacity c = 200 J/kg-K. The tube radius is r_{tube} = 1 cm and the tube length is L_{tube} = 15 cm. The surroundings are at T_{sur} = 300 K. The droplet velocity is constant and equal to u_{drop} = 30 mm/s. All surfaces are black and the droplet travels along the center line of the tube.

a.) Develop an EES function that can provide the view factor between the droplet and the tube as it moves from $x = r_d$ to $x = 2\,L_{tube}$. Plot the view factor between the droplet and the tube as a function of x. Explain the shape of the curve.

b.) Given an arbitrary value of the time relative to the start of the injection (t) and the droplet temperature (T_d), develop an EES model that can provide the rate of change of the droplet temperature.

c.) Use the EES Integral command to determine the temperature as a function of position of the droplet. Plot the temperature as a function of position for $r_d < x < 2\,L_{tube}$.

d.) Overlay on your plot from (c) the solution for various values of T_{tube} ranging from 300 K to 700 K.

10.3-18 Figure P10.3-18 illustrates a metal plate that is radiatively heated from above.

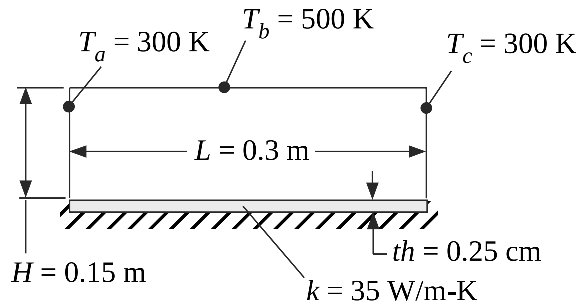

Figure P10.3-18: Radiatively heated plate.

The plate is th = 0.25 cm thick and has conductivity k = 35 W/m-K. The plate is L = 0.3 m long and extends infinitely into the page. The heated surface is located H = 0.15 m from the plate and kept at T_b = 500 K. The sides of the enclosure are maintained at $T_a = T_c$ = 300 K. All surfaces are black.

a.) Plot the temperature distribution in the plate, $T(x)$.

Section 10.4: Radiation Characteristics of Real Surfaces

10.4-1 Radiation that passes through the atmosphere surrounding our planet is absorbed to an extent that depends on its wavelength due to the presence of gases such as water vapor, oxygen, carbon dioxide and methane. However, there is a relatively large range of wavelengths between 8 and 13 microns (see Figure P10.4-1) for which there is relatively little absorption in the atmosphere and thus, the transmittance of atmosphere is high. This wavelength band is called the atmospheric window. Infrared detectors on satellites measure the relative amount of infrared radiation emitted from the ground in this wavelength band in order provide an indication of the ground temperature.

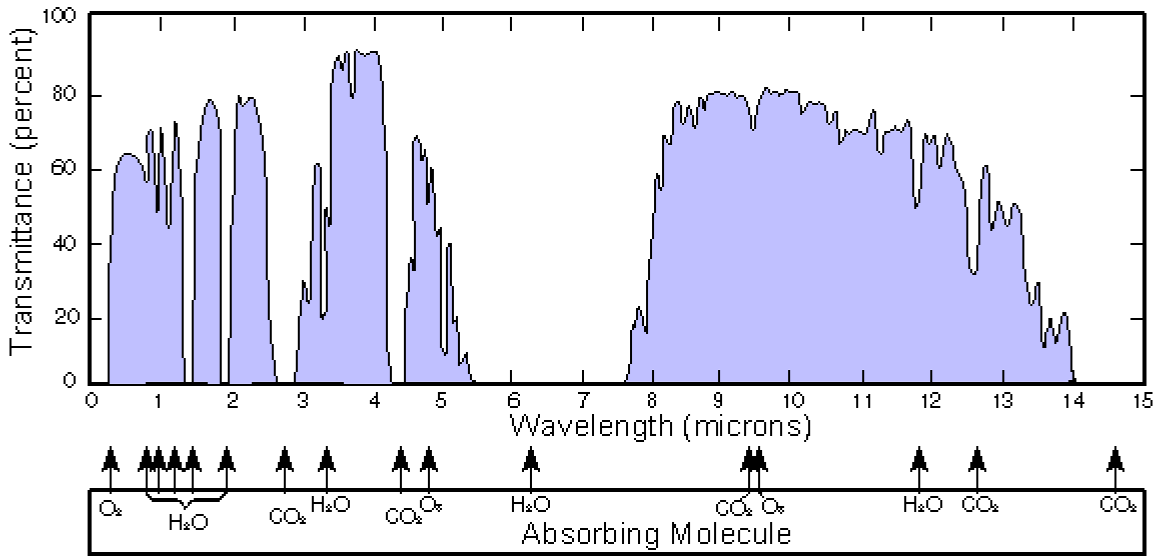

Figure P10.4-1: Spectral transmittance of the atmosphere (figure from http://en.wikipedia.org/)

The transmittance as a function of wavelength data is provided on the text website (www.cambridge.org/nellisandklein) in files atmosphericWindow.csv (EXCEL comma-separated value format) and atmosphericWindow.lkt (EES Lookup table format). A plot of the data in this file is shown in Figure P10.4-1. Using these transmittance data determine and plot the amount of energy received by a satellite detector between wavelengths 8 to 13 microns as a function of ground for temperatures between -10°C to 30°C.

10.4-2 (10-12 in text) A 10,000 sq. ft. office building requires approximately $\dot{q}''_v$ = 1.0 W/ft^2 of visible radiant energy for lighting; this is energy emitted between the wavelengths $\lambda_{v,low}$ = 0.38 μm and $\lambda_{v,high}$ = 0.78 μm. The efficiency of a lighting system (η_v) can be calculated as the ratio of the visible radiant energy that is emitted to the total amount of energy emitted.

a.) Compute the efficiency of a light source that consists of a black body at T = 2800 K.

b.) Plot the efficiency of a black body lighting system as a function of temperature.

There are two costs associated with providing the lighting that is required by the office. The electricity required to heat the black body to its temperature and the electricity that is required to run the cooling system that must remove the energy provided by the light source (note that both the visible and the invisible radiation is deposited as thermal energy in the building). Assume that the building cooling system has an average coefficient of performance of COP = 3.0 and the building is occupied for 5 days per week and 12 hours per day. Assume that the cost of electricity is $0.12/kW-hr.

c.) What is the total cost associated with providing lighting to the office building for one year? How much of this cost is direct (that is, associated with buying electricity to run the light bulbs) versus indirect (that is, associated with running air conditioning equipment in order to remove the energy dumped into the building by the light bulbs). Assume that you are using a light bulb that is a black body with a temperature of 2800 K.

An advanced light bulb has been developed that is not a black body but rather has an emittance that is a function of wavelength. The temperature of the advanced light bulb remains 2800 K, but the filament can be modeled as being semi-gray; the emittance is equal to ε_{low} = 0.80 for wavelengths from 0 to λ_c = 1.0 μm and ε_{high} = 0.25 for wavelengths above 1.0 μm.

d.) What is the efficiency of the new light bulb?

e.) What is the yearly savings in electricity that can be realized by replacing your old light bulbs (the black body at 2800 K) with the advanced light bulbs?

10.4-3 (10-13 in text) The intensity of a surface has been measured as a function of the elevation angle and correlated with the following relation:

$$I = I_{b,\lambda}\left(1-\exp\left(-0.0225-6.683\cos(\theta)+5.947\cos^2(\theta)-2.484\cos^3(\theta)\right)\right)$$

where $I_{b,\lambda}$ is the intensity of a blackbody at wavelength λ.

a) Determine the maximum hemispherical spectral emissive power for this surface if it is maintained at 1200 K.

b) What is the spectral emittance of this surface?

10.4-4 (10-14 in text) A surface has wavelength-dependent properties as listed in Table P10.4-4. The surface is maintained at 500 K.

Table P10.4-4: Wavelength-dependent absorptivity.

Wavelength Range (μm)	α_λ
0-0.6	0.8
0.6-2.6	0.25
2.6-100	0.10

a.) Determine the total hemispherical absorptance of this surface for solar radiation.

b.) Determine the total hemispherical emissivity of this 500 K surface.

10.4-5 The spectral reflectance of a solar collector plate is shown in the plot as a function of wavelength. The collector plate is made of copper and coated with black chrome. (These data were obtained using a Gier-Dunkle IR reflectometer.) Assume that the spectral distribution of energy from the sun can be approximated as that from a black body at 5780 K.

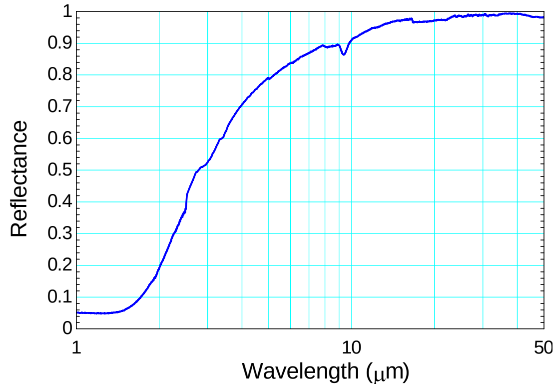

Figure 10.4-5: Reflectance as a function of wavelength.

Note: Tabular data representing the data in this plot are available in two formats on the text web site (www.cambridge.org/nellisandklein). The file reflectance.csv can be read into EXCEL. The file reflectance.lkt can be read into an EES Lookup table using the Open Lookup command in the Table menu.

Using these data:

a.) Estimate the total hemispherical absorptivity of the black chrome plate for solar radiation.

b.) Calculate the total hemispherical emissivity of the plate at 50°C.

c.) Explain the implications of your results.

10.4-6 (10-15 in text) Calculate and plot the total reflectance of polished aluminum at 697 K for radiation emitted from sources between 300 K and 6000 K. The spectral emittance of polished aluminum is provided in the EES Radiation Properties folder as the table Aluminum-Spectral.lkt.

10.4-7 A solar collector is used to absorb energy from the sun. The solar collector losses are based in part on how much energy it emits to its surroundings. Figures P10.4-1 illustrates the variation of emissivity with wavelength for semi-gray surfaces that are referred to as surfaces A, B, and C.

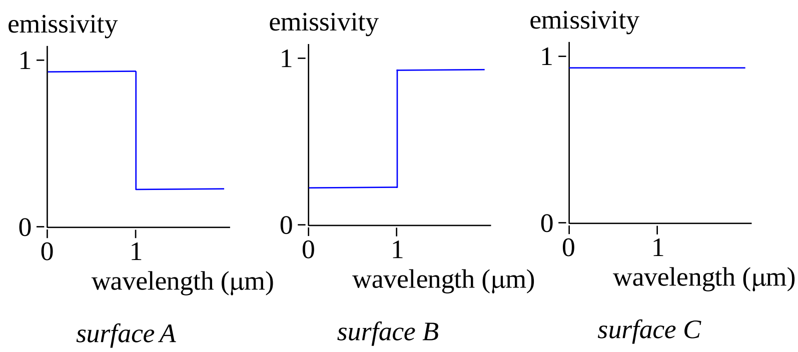

Figure P10.4-7: Variation of emissivity with wavelength for three surfaces

a.) Which of the three surfaces shown in Fig. 10.4-1 is a better choice for your solar collector surface? Justify your answer.

10.4-8 Figure P10.4-8 shows the hemispherical emittance of tungsten as a function of wavelength for various temperatures; these data are provided in an EES Lookup table (Tungsten_spectral.lkt in the Userlib/Heat Transfer/Radiation Properties). The emission properties of tungsten are of particular engineering interest because tungsten is used as a filament for incandescent light bulbs.

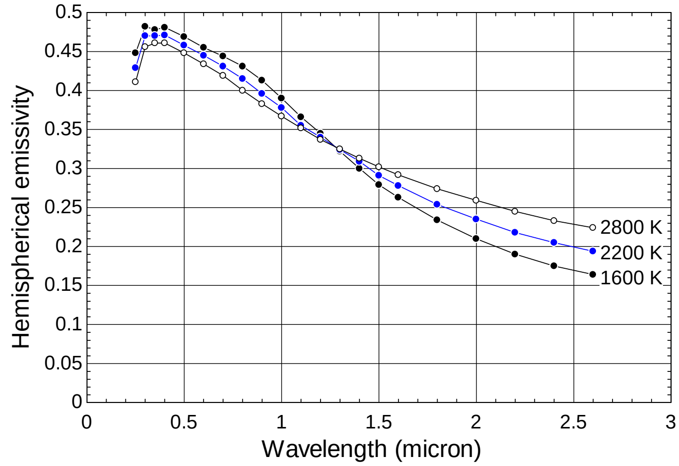

Figure P10.4-8: **Hemispherical emittance of tungsten (data from CRC Handbook)**

a.) Calculate the total hemispherical emissivity for tungsten at 2800 K.

Section 10.5: Diffuse Gray Surface Radiation Exchange

10.5-1 (10-16 in text) Three metal plates, each W = 40 cm by L = 60 cm, are parallel and centered as shown in Figure P10.5-1. Each of the plates have an emissivity of ε = 0.15. The top and bottom plates (surfaces 1 and 3) are separated by a vertical distance of H = 50 cm. The bottom and middle plates (surfaces 1 and 2) are separated by a vertical distance a. The temperature of the bottom plate is maintained at T_1 = 584°C. The plates radiatively interact with the surroundings at T_4 = 25°C. The underside of the bottom plate is insulated.

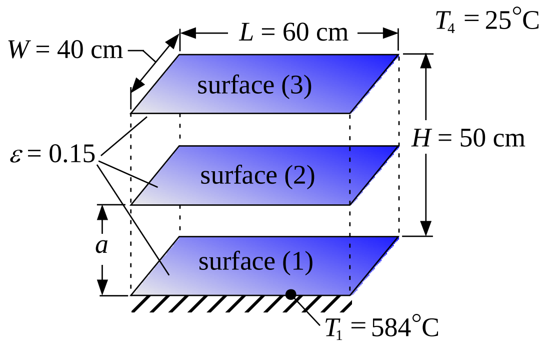

Figure P10.5-1: Three metal plates.

Calculate and plot the temperature of upper plate and the net rate of radiative heat transfer from the lower plate as a function of a for 1 cm < a < 49 cm.

10.5-2 A cylindrical heating element has length L = 15 cm and diameter D_1 = 0.5 cm. The emissivity of the heating element is ε_1 = 0.22. It is surrounded by a cylindrical enclosure having a diameter D_2 = 2 cm that is open at the ends, as shown in Figure P10.5-2. The emissivity of the enclosure is ε_2 = 0.9. The heater and enclosure surroundings are at T_3 = 25°C. The electrical dissipation of the heating element is $\dot{q}_{he}$ = 70 W. Assume that radiation is the only heat transfer mechanism and the ends of the heating element are insulated.

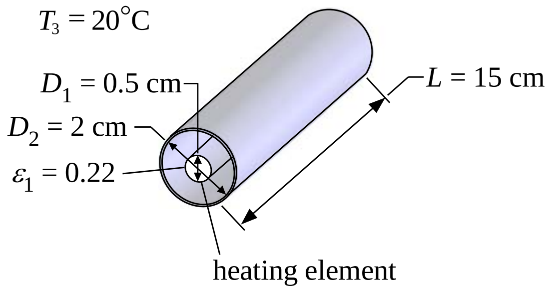

Figure P10.5-2: Heating element.

a.) Calculate and plot the temperature of the heating element and the enclosure as a function of the emissivity of the enclosure.

10.5-3 A long rectangular duct has dimensions H = 1 m by W = 2 m, as shown in Figure P10.5-3. The bottom of the duct is maintained at T_1 = 1200 K, the top is maintained at T_2 = 1000 K and the sides are both at T_3 = 1100 K. A small spherical thermocouple is placed within the duct at a location that is a = 0.25 m from the bottom and b = 1 m from the side. The walls of the duct have an emissivity of ε_d. The thermocouple emissivity is ε_{tc} = 0.5. Assume radiation to be the only heat transfer mechanism.

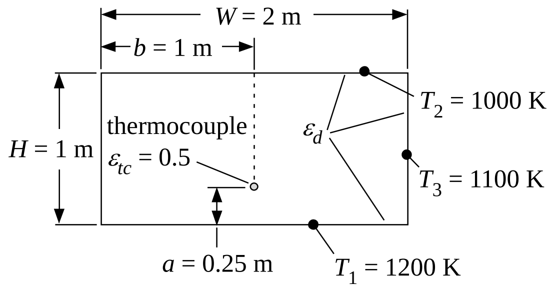

Figure P10.5-3: Thermocouple in a duct

a.) Plot the temperature that the thermocouple will measure as a function of the emissivity of the duct walls, ε_d.

10.5-4 A pipe carrying cryogenic fuel for a spacecraft is shown in Figure P10.5-4. The pipe has diameter, D_1 = 5.0 cm and surface temperature T_1 = 110 K. The emissivity of the pipe surface is ε_1 = 0.2. This pipe is placed s = 15 cm away from another pipe with diameter D_2 = 10 cm, surface temperature T_2 = 320 K, and emissivity ε_2 = 0.5 that carries hot gas. These pipes run parallel to one another and are exposed to space, which can be approximated as having a temperature of T_3 = 4 K.

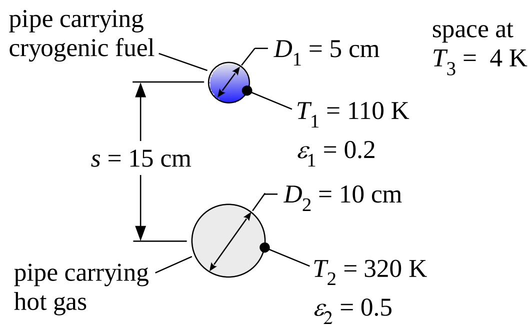

Figure P10.5-4: Pipes running parallel to one another in space

a.) Draw a resistance network to represent this problem. Clearly label what each node and resistor represents.

b.) Calculate the values for each of the resistances in your network (on a per unit length basis, L = 1 m).

c.) Calculate the net radiation heat transfer per unit length to the pipe carrying the cryogenic fluid.

10.5-5 (10-17 in text) Consider two parallel plates that are separated by a distance of H = 0.5 m. The plates are each L = 1 m by W = 2 m. The lower plate (surface 1) is maintained at T_1 = 400 K and has emissivity ε_1 = 0.4. The surroundings (surface 2) are at T_2 = 4 K. The upper plate has a temperature profile that varies linearly in the x-direction from T_C = 500 K at one edge (x = 0) to T_H = 1000 K at the other edge (x = W). The temperature is uniform in the y-direction. The emissivity of the upper plate is ε_3 = 0.6. This problem can be solved numerically by discretizing the upper plate into N equal area segments, each at the constant temperature equal to the temperature of upper plate at the center of the segment. Assume that the upper surface of the upper plate and the lower surface of the lower plate are both insulated.

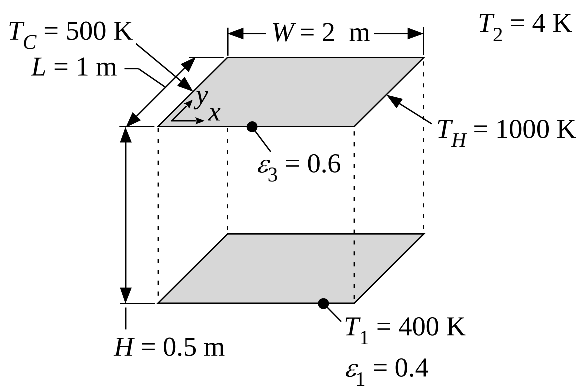

Figure P10.5-5: Two plates.

a.) Calculate the total energy that must be provided to the upper plate.

b.) Plot the total energy provided to the upper plate as a function of N for N = 1 to 10. From your results, how many segments do you believe are needed to represent the effect of the temperature distribution in the upper plate?

10.5-6 (10-18 in text) A cylindrical heating element is used to heat a flow of water to an appliance. Typically, the element is exposed to water and therefore it is well cooled. However, you have been asked to assess the fire hazard associated with a scenario in which the appliance is suddenly drained (i.e., the water is removed) but the heat to the heating element is not deactivated. You want to determine the maximum temperature that the element will reach under this condition.

The heating element and passage wall are shown in Figure P10.5-6. The length of the element is L = 9.0 cm and its diameter is D_e = 0.5 cm. The element is concentric to a passage wall with diameter D_o = 2.0 cm. The emissivity of the element is ε_e = 0.5 and the emissivity of the passage wall is ε_o = 0.9. The surroundings are at T_{sur} = 25°C. The worst case situation occurs if the outer passage wall is assumed to be insulated externally (i.e., there is no conduction or convection from the passage). The heating element dissipates $\dot{q}_e = 60\text{ W}$.

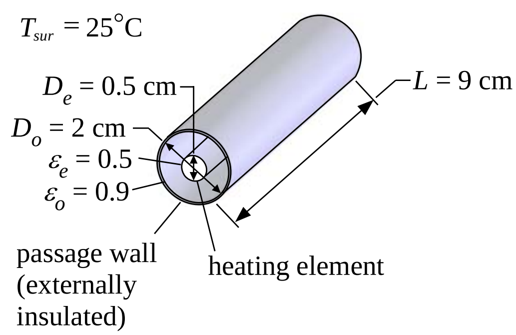

Figure P10.5-6: Heating element.

a.) What is the temperature of the element? Assume that radiation is the only important heat transfer for this problem. Note that your problem should include three surfaces (the element, the passage, and the surroundings); that is, you should not neglect the radiation exchange between the element and passage and the surroundings. However, you may assume that the edges of the element (the top and bottom surfaces) are adiabatic.

b.) What is the temperature of the passage wall?

c.) Other calculations have shown that the passage wall will not reach temperatures greater than 80°C because it is thermally communicating with surroundings. If the passage wall is maintained at T_o = 80°C then what is the maximum temperature that the heating element will reach?

10.5-7 A cylinder is placed at the center of a square enclosure, as shown in Figure P10.5-7.

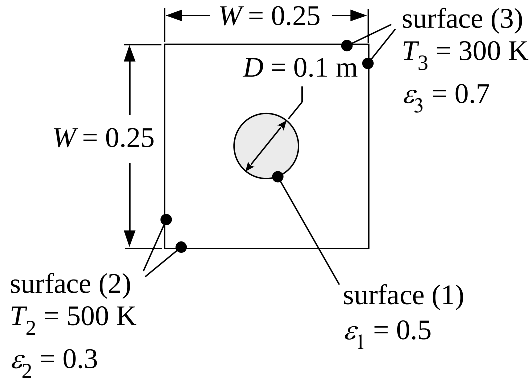

Figure P10.5.7: Cylinder in a square enclosure.

The cylinder is not being heated or cooled and it is at steady state. The surface of the cylinder is surface (1) and the diameter of the cylinder is D = 0.1 m. The emissivity of the surface of the cylinder is ε_1 = 0.5. The enclosure is square and W = 0.25 m on each side. Two of the sides of the enclosure are surface (2) and are maintained at T_2 = 500 K. The emissivity of surface (2) is ε_2 = 0.3. The other two sides of the enclosure are surface (3) and are maintained at T_3 = 300 K. The emissivity of surface (3) is ε_3 = 0.7. The problem is two-dimensional and the view factor between surface 2 and itself and surface 3 and itself are $F_{2,2} = F_{3,3}$ = 0.25.

a.) What is the temperature of the cylinder?

10.5-8 (10-19 in text) This problem considers a (fictitious) power generation system for a spacecraft orbiting the planet Mercury. The surface of Mercury can reach 700 K and therefore you are considering the possibility of collecting radiation emitted from Mercury in order to operate a heat engine. The details of the collector are shown schematically in Figure P10.5-8(a).

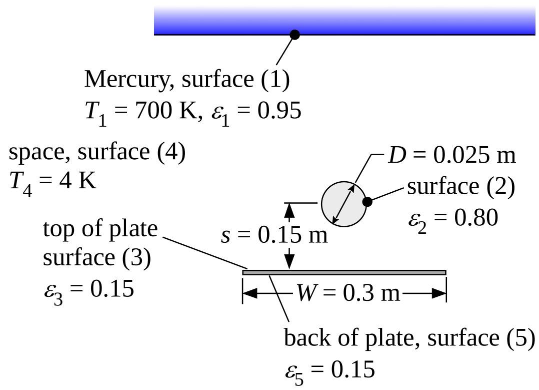

Figure P10.5-8(a): Energy collection system

The collector geometry consists of a pipe and a backing plate; this geometry is 2-D, so the problem will be solved on a per unit length basis, L = 1 m, into the page. The diameter of the pipe is D = 0.025 m. The pipe surface (surface 2) is maintained at a constant temperature (T_2) and has emissivity ε_2 = 0.8. Energy that is transferred to the pipe is provided to the power generation system. The pipe is oriented so that it is parallel to the surface of the planet (surface 1) which is at T_1 = 700 K and has an emissivity of ε_1 = 0.95. You may assume that the surface of the planet extends infinitely in all directions. There is a back plate positioned s = 0.15 m away from the centerline of the collector pipe. The back plate is W = 0.30 m wide and is centered with respect to the pipe. The top surface of the back plate (the surface oriented towards the collector pipe, surface 3) has emissivity ε_3 = 0.15. The bottom surface of the back plate (the surface oriented towards space, surface 5) also has emissivity ε_5 = 0.15. The collector and back plate are surrounded by outer space, which has an effective temperature T_4 = 4 K; assume that the collector is shielded from the sun. Assume that the back plate is isothermal.

a) Prepare a plot showing the net rate of radiation heat transfer to the collector from Mercury as a function of the collector temperature, T_2.

The energy transferred to the collector pipe is provided to the hot end of a heat engine that operates between T_2 and $T_{radiator}$, where T_2 is the collector temperature and $T_{radiator}$ is the temperature of a radiator panel that is used to reject heat, as shown in Figure P10.5-8(b). The heat engine has a 2nd law efficiency η_2 = 0.30; that is, the heat engine produces 30% of the power that a reversible heat engine would produce operating between the same temperature limits (T_2 and $T_{radiator}$). The heat engine radiator rejects heat to space; assume that the radiator panel has an emissivity $\varepsilon_{radiator}$ = 0.90 and a surface area $A_{radiator}$ = 10 m^2. Also, assume that the radiator only sees space at T_4 = 4 K.

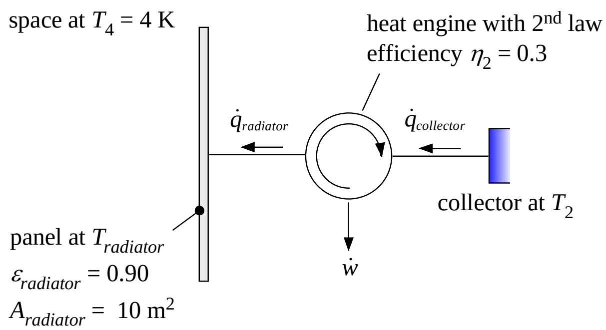

Figure P10.5-8(b): Schematic of the power generation system

b) Prepare a plot showing the amount of power generated by the heat engine ($\dot{w}$) and the radiator temperature (T_6) as a function of the collector temperature, T_2.

10.5-9 A satellite orbits the earth at a height (above the earth) of H_{orbit} = 3.5x10^5 m. The satellite can be modeled as a sphere of diameter D_{sat} = 1 m. The emissivity of the satellite surface is ε_{sat} = 0.5. There is an internal dissipation of energy within the satellite of $\dot{q}_{sat}$ = 100 W. The diameter of the earth is D_{earth} = 1.29x10^7 m and the temperature of the earth is T_{earth} = 300 K and the surface of the earth can be considered to be black. The temperature of space is T_{space} = 3 K. Depending on the position in the orbit, the solar flux ranges from G = 0 W/m^2 (on the night-side of earth) to G = 1350 W/m^2 (on the day-side).

a.) Develop a model that can predict the temperature of the satellite as a function of the solar flux. What is the temperature of the satellite on the night-side of the earth? What is the temperature on the day-side?

b.) Plot the temperature of the satellite as a function of G for various values of the satellite surface emissivity. Is there a value of the emissivity that keeps the satellite temperature within the acceptable range of 280 K < T_{sat} < 400 K during its entire orbit?

10.5-10 Figure P10.5-10 illustrates (in cross-section) a spherical cryogenic experiment that is placed at the center of a cubical enclosure (a box).

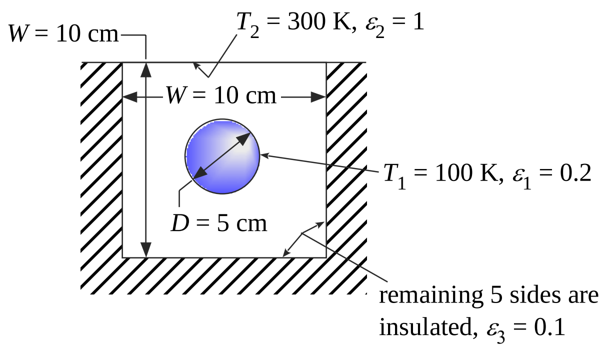

Figure P10.5-10: Spherical cryogenic experiment in a cubical enclosure.

The spherical experiment (surface 1) has diameter D = 5.0 cm and emissivity ε_1 = 0.5. The temperature of the experiment is maintained at T_1 = 100 K. Each face of the cubical enclosure is W = 10 cm x W = 10 cm. The top surface of the enclosure (surface 2) is maintained at T_2 = 300 K and is black. The other five sides (surface 3) are insulated externally and have emissivity ε_3 = 0.1.

a.) What is the view factor between the experiment and the top surface ($F_{1,2}$)?
b.) What is the view factor between the experiment and the 5 insulated sides ($F_{1,3}$)?
c.) What is the view factor between the top surface and the experiment ($F_{2,1}$)?
d.) Draw and clearly label a resistance network that represents the radiation heat transfer problem.
e.) Calculate the values of all of the resistances in your diagram from (d). You may assume that the view factor between the insulated sides and the top ($F_{3,2}$) is 0.70.
f.) What is the net rate of heat transfer to the experiment?
g.) How would your answer to (f) change if the emissivity of the experiment were reduced (would the heat transfer to the experiment increase, decrease, or stay the same)?
h.) How would your answer to (f) change if the emissivity of the insulated sides were reduced (would the heat transfer to the experiment increase, decrease, or stay the same)?

10.5-11 Figure P10.5-11 illustrates an air-cooled heating system.

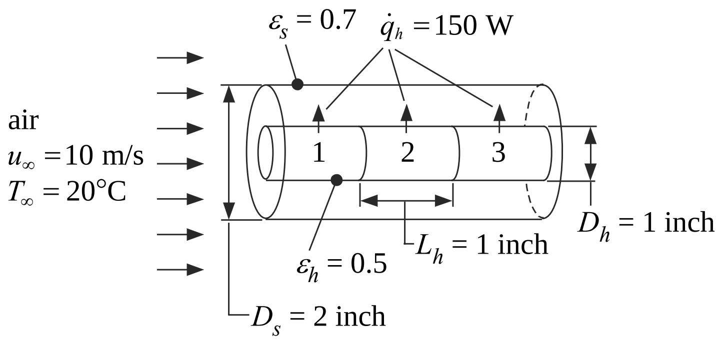

Figure P10.5-11: Air-cooled heating system.

The heater consists of three rods in a row, each rod is isothermal (although the heaters may have different temperatures) and each heater rod experiences ohmic heating at a rate of $\dot{q}_h = 150$ W. The heater rods have diameter $D_h = 1$ inch and length $L_h = 1$ inch. The ends of the rod may be considered to be adiabatic. The surface of the heater rods have emissivity $\varepsilon_h = 0.5$. There is a thin metallic shield the surrounds the rods. The shield can be assumed to be isothermal and is centered over the heaters. The length of the shield is $3L_h$ and the diameter is $D_s = 2$ inch. The surface of the shield (inside and outside) has emissivity $\varepsilon_s = 0.7$. Air at $T_\infty = 20°C$ is blown over the rods and the shield with velocity $u_\infty = 10$ m/s. The heaters and the shield radiate to surroundings at $T_{sur} = T_\infty$.

a.) What are the temperature of each of the heaters and the shield if convection is neglected?

b.) What are the temperature of each of the heaters and the shield if convection is included? You may model the convection on the heaters and shield as external flow over a flat plate.

c.) If the heaters cannot be independently controlled (i.e., the ohmic heating applied to each heater must be the same) and the heater temperature cannot go above 850°C then what is the maximum total ohmic heating that can be achieved (i.e., the sum of the heating applied to all three heaters)?

d.) Plot the maximum total ohmic heating as a function of the air velocity.

e.) Overlay on your plot from (d) the maximum ohmic heating that can be achieved if the heaters can be independently controlled so that the ohmic dissipation in each heater rod can be different.

10.5-12 A satellite orbits the earth at a height (above the surface of the earth) of H_{orbit} = 3.5x10^5 m. The diameter of the earth is D_{earth} = 1.29x10^7 m and the temperature of the earth is T_{earth} = 300 K. The distance between the earth and the sun is approximately R = 1.497x10^{11} m. The sun has diameter D_{sun} = 1.39x10^9 m and the surface temperature of the sun is approximately T_{sun} = 5780 K. The earth and the sun can be considered black. The satellite is spherical with diameter D_{sat} = 1 m. The emissivity of the satellite surface is ε_{sat} = 0.5. There is $\dot{q}_{sat}$ = 100 W of power dissipation within the satellite that must be rejected from its surface through radiation.

a.) Estimate the steady state temperature of the satellite when it is on the day-side of the earth.

b.) Estimate the steady state temperature of the satellite when it is on the night-side of the earth.

c.) Plot the steady-state day-side and night-side temperature as a function of the satellite emissivity. Explain the shape of your plot.

d.) Overlay on your plot from (c) the steady-state day-side and night-side temperature as a function of the satellite emissivity if the satellite power dissipation were $\dot{q}_{sat}$ = 0 W. Explain the shape of your plot.

10.5-13 Figure P10.5-13 illustrates a heater plate used to heat a pipe that has a shield.

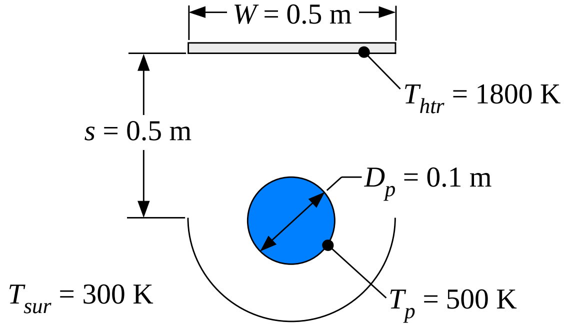

Figure P10.5-13: Heater plate heating a pipe.

The heater plate is W = 0.2 m wide and is heated to T_{htr}= 1800 K. The heater plate is a diffuse gray surface with an emissivity of ε_{htr} = 0.7. The pipe center is s = 0.5 m from the plate and the pipe diameter is D_p = 0.1 m. The pipe temperature is T_p = 500 K. The pipe is a semi-gray surface. The emissivity of the pipe surface from 0 μm to λ_c = 5 μm is $\varepsilon_{p,low}$ = 0.9 while the emissivity above λ_c is $\varepsilon_{p,high}$ = 0.1. The shield is a half-circle centered on the pipe with diameter W. The shield is a diffuse gray surface with emissivity is ε_s = 0.3. The surroundings are at T_{sur} = 300 K. The problem can be considered 2-D.

a.) What is the rate of heat transfer to the pipe per unit length?

10.5-14 A pipe carrying fluid to be heated at T_f = 400 K runs down the center of a rectangular enclosure, as shown in Figure P10.5-14.

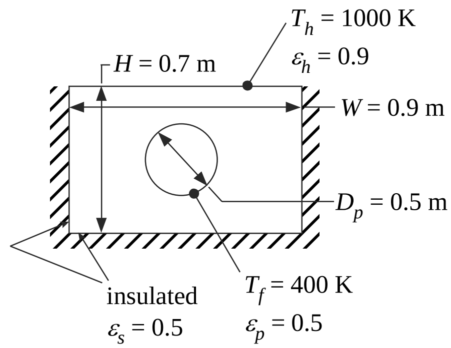

Figure P10.5-14: Pipe heated radiatively.

The top surface of enclosure is heated to T_h = 1000 K and the emissivity of the surface is ε_h = 0.9. The other three surfaces are insulated and have emissivity ε_s = 0.5. Assume that the pipe surface is at T_f and the emissivity of the pipe is ε_p = 0.5. Assume that the problem is 2-D.

a.) Determine the rate of heat transfer to the pipe per unit length.
b.) What is the temperature of the insulated sides?
c.) Plot the heat transfer rate as a function of the heater emissivity.
d.) If the shield was cooled to T_s = 600 K rather than adiabatic then what would the heat transfer to the pipe be? How much cooling is required to keep T_s = 600 K?

10.5-15 A spherical temperature sensor is installed in a combustion chamber in order to measure the temperature of the flame. The diameter of the sensor is D_1 = 0.01 m and the emissivity of the sensor is ε_1 = 0.5. The temperature of the flame is T_2 = 1150 K and the view factor from the sensor to the flame is $F_{1,2}$ = 0.85. The sensor has two sources of error. First, there is a conduction heat transfer from the sensor to its leads of $\dot{q}_{lead}$ = 0.5 W. Second, in addition to experiencing radiation with the flame, the sensor also experiences radiation with the surroundings at T_3 = 300 K. Both the flame and the surroundings can be assumed to be black. Neglect convection from the sensor.

a.) Determine the temperature of the sensor and therefore the error in the flame temperature measurement.

b.) Is the temperature measurement error primarily attributed to conduction to the leads or radiation exchange with the surroundings? Justify your answer with a calculation.

c.) Assume that your analysis in (b) found that conduction to the leads was the primary source of error. (Note that this may or may not be the correct answer.) Would you increase or decrease the emissivity of the sensor in order to minimize this error? Justify your answer.

Section 10.6: Radiation with other Heat Transfer Mechanisms

10.6-1 Consider the turkey that you likely ate for Thanksgiving dinner. The turkey is placed in a cubical oven that is 0.7 m in each dimension. The oven has been preheated to 180°C and the oven walls can be considered as black surfaces. The turkey is approximately spherical with a mass of 4.2 kg and thermal properties that are approximately the same as those of liquid water. It is at a uniform temperature of 10°C when it is placed in the oven and it has an effective emissivity of 0.82. Neglect the effects of the baking pan and the oven rack. The air is still within the oven and free convective heat transfer occurs between the air in the oven and the turkey.

a.) Determine the initial rate of radiative heat transfer to the turkey.

b.) Determine the initial rate of convective heat transfer to the turkey.

c.) Estimate the time required for the center of the turkey to be heated to 50°C.

10.6-2 A solar collector has a selective surface absorber that has an absorptivity of 0.95 for radiation between wavelengths of 0.2 and 4 μm. The emissivity for thermal radiation at wavelengths greater than 4 μm is unknown and the value of the emissivity in this wavelength band is to be estimated from the following experimental data. A square sample of the absorber plate 0.3 m on a side and a blackened copper plate of the same were both exposed to a light from a lamp that has approximately the same spectral distribution as solar radiation. The exact magnitude of the illumination is not known, but it did not vary during the test. Both samples were horizontal and well-insulated on face opposite of the illumination. The room temperature was constant at 25.55°C and there was no detectable forced air motion around the samples during the test. The blackened copper plate has an absorptivity of 0.95 that is not spectrally dependent. A plot of the temperature of the plates as a function of time is shown in Figure P10.6-2. Note that the selective surface attains a steady-state temperature of 85°C whereas the blackened copper plate reaches 63.6°C under identical operating conditions. Estimate the emissivity of the selective surface relative to near room temperature radiation based on these data.

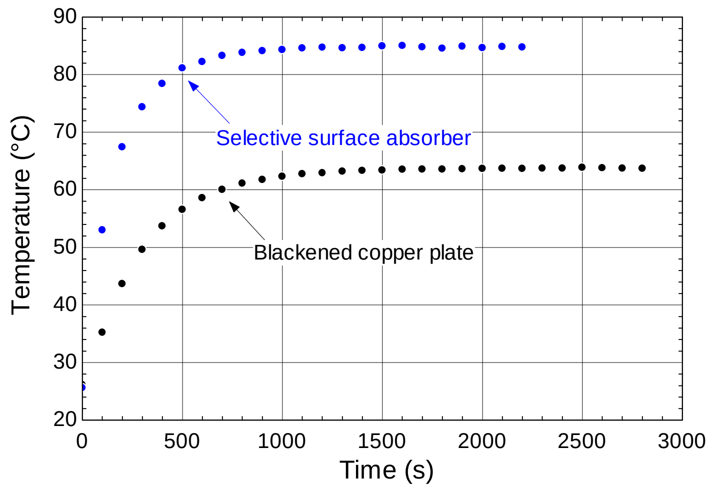

Figure P10.6-2: Variation of temperature with time for selective and non-selective surfaces

10.6-3 A thermometer is mounted within a spherical enclosure in the exact center of a room. The sphere has a diameter of 6 cm and it has a surface emissivity of 0.95. The air in the room is maintained at 25°C, but there is no forced air circulation during the period of this test. The room dimensions are 5 m by 4 m with a ceiling height of 2.5 m. The walls and ceiling have an emissivity of 0.95. The emissivity of the floor is also estimated to be 0.95. Measurements indicate that the surface temperature of the walls is 21.3°C. The ceiling temperature is 23.6°C and floor temperature is 19.8°C. What temperature should the thermometer read?

10.6-4 (10-20 in text) A photovoltaic panel having dimensions of 1 m by 2 m is oriented directly towards the sun (i.e., south) at a 45° angle. The panel is exposed to solar radiation at 720 W/m^2. The efficiency of the panel defined as the electrical power produced divided by the incident solar radiation, is 11.2%. The back side of the photovoltaic panel is well-insulated. The emissivity of the photovoltaic material is estimated to be 0.90. The ambient and ground temperature during the test is 22°C and there is no measurable wind. The sky is clear and the equivalent temperature of the sky for radiation is 7°C. Estimate the steady-state surface temperature of the photovoltaic panel assuming that all of the radiation that strikes the panel is absorbed. What fraction of the thermal energy transfer to the air is due to radiation?

10.6-5 A large double-pane window assembly that is H = 1.5 m in height and W = 1 m in width is being studied in order to determine possible improvements to its design. The air on one side of the window is at T_{in} = 25°C. On the other side, the air is at T_{out} = -10°C. There is no forced air flow on either side, so heat transfer to or from the glazings occurs by free convection. The space between the glazings is th = 1 cm. The glass is thin so conduction through the glass can be neglected in this analysis. Assume that the glass is completely opaque to radiation emitted at high wavelengths (i.e, radiation emitted by all of the surfaces involved in this problem) and that the emissivity of the glass is ε = 0.88. Calculate the rate of heat transfer through the double-pane window assembly if:

a.) the space between the glazings is evacuated.

b.) the space between the glazings is filled with dry air at atmospheric pressure.

10.6-6 (10-21 in text) A thermocouple has a diameter D_{tc} = 0.02 m. The thermocouple is made of a material with density ρ = 8000 kg/m^3 and specific heat capacity c = 450 J/kg-K. The temperature of the thermocouple (you may assume that the thermocouple is at a uniform temperature) is T_{tc} = 320 K and the emissivity of the thermocouple's surface is ε_{tc} = 0.50. The thermocouple is placed between two very large (assume infinite in all directions) black plates. One plate is at T_1 = 300 K and the other is at T_2 = 500 K. The thermocouple is also exposed to a flow of air at T_a = 300 K. The het transfer coefficient between the air and thermocouple is $\bar{h}$ = 50 W/m^2-K. The situation is shown in Figure P10.6-6.

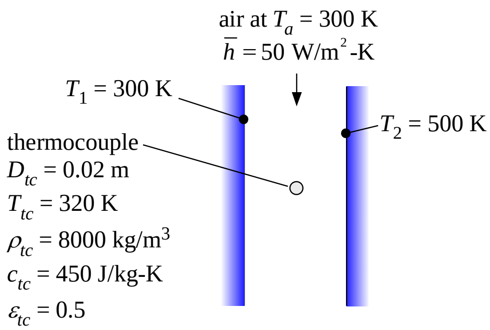

Figure P10.6-6: Thermocouple placed between two plates.

a.) What is the rate of convective heat transfer from the thermocouple?
b.) What is the net rate of radiative heat transfer to the thermocouple?
c.) What is the rate of temperature change of the thermocouple?
d.) If you want the thermocouple to accurately measure the temperature of the air (and therefore be unaffected by radiation), would you try to increase or decrease its emissivity? Justify your answer.

10.6-7 A cylindrical container made of th = 0.4 mm thick aluminum has a diameter of D = 6 cm and a height of H = 20 cm. The emissivity of the surface is ε = 0.7. The top and bottom of the cylinder are insulated. Air is contained within the cylinder. Initially, the cylinder wall and the air are at T_{ini} = 25°C and the absolute pressure of the air in the cylinder is p_{ini} = 100 kPa. The cylinder is now placed W = 15 cm from a wall that is much larger than the container. The surface of the wall is black and maintained at T_{wall} = 180°C. The convection coefficient between the T_{∞} = 25°C surroundings and the external surface of the can is $\overline{h}$ = 8 W/m^2-K. Plot the temperature and pressure of the air in the cylinder as a function of time for a 5 minute period. Assume that the air in the cylinder is at the same temperature as the cylinder wall at all times.

10.6-8 It has been proposed that considerable energy for air conditioning could be saved if the roofs of buildings were made of reflective material. The purpose of this problem is to investigate this claim. Consider a building having a flat roof that is W = 12 m on each side with the interior air maintained at a uniform temperature of T_{in} = 25°C. The heat transfer coefficient between the inside of the roof and the internal air is $\overline{h}_{in}$ = 5 W/m^2-K. Fiberglass insulation is provided between the ceiling of the building the roof surface; the thickness of the fiberglass is th_{ins} = 15 cm. It is T_{∞} = 35°C outdoors with solar radiation at G = 800 W/m^2 and a windspeed of u_{∞} = 5 m/s. Assume that the absorptivity for solar radiation is equal to the emissivity.

a.) Compare the rate of heat gain per unit area for roof surfaces having emissivity values of ε = 0.1 and ε = 0.9.

b.) Plot the rate of heat gain per unit area for ε = 0.1 and ε = 0.9 as a function of the fiberglass insulation thickness from th_{ins} ranging from 2 to 20 cm.

c.) What is your conclusion regarding the merit of using a reflective roof surface?

10.6-9 (10-22 in text) Figure P10.6-9 illustrates a set of three reactor beds that are heated radiantly by three heating elements.

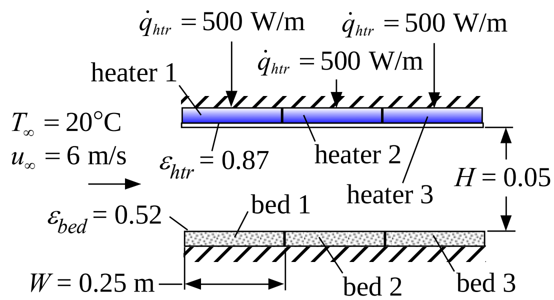

Figure P10.6-9: Reactor beds with heaters.

The reactants are provided as a flow over the beds. The temperature of the reactant flow is T_∞ = 20°C and the free stream velocity is u_∞ = 6 m/s; you may assume that the properties of the reactant flow are consistent with those of air at atmospheric pressure. All of the heaters and beds are each W= 0.25 m wide and very long (the problem is two-dimensional). The heaters and beds are separated by H = 0.05 m. The beds are insulated on their back-sides but transfer heat to the free stream by convection. The surface of the beds has emissivity, ε_{bed} = 0.52. The heaters are each provided with $\dot{q}_{htr}$ = 500 W/m; there is a piece of glass that protects the heaters from the reactants and prevents convective heat loss from the heaters. The upper surfaces of the heaters are insulated. You may assume that the 3 heaters and 3 beds are all isothermal (i.e., they are each at a unique but uniform temperature). The surface of the heaters has emissivity, ε_{htr} = 0.87. The surroundings are at T_{sur} = 20°C.

a.) Determine the temperature of each of the beds.

b.) What is the efficiency of the heating system?

c.) Determine the heater power that should be applied to each of the 3 heaters in order to keep each of the 3 beds at T_{bed} = 65°C.

10.6-10 Figure P10.6-10 illustrates an ice skating rink that can be modeled as a large rectangular building with a floor space that is L = 50 m x W = 20 m and a ceiling that H = 5.0 m high.

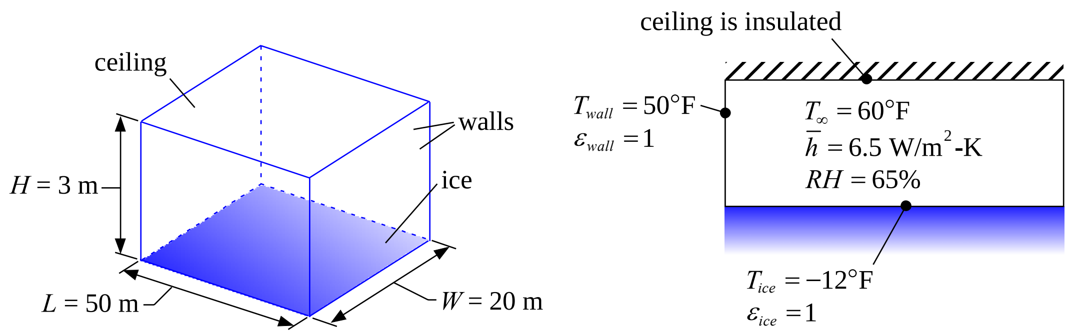

Figure P10.6-10: (a) A rectangular ice skating rink and b) details about the ice, walls and celing.

The air in the rink is maintained at T_∞ = 60°F with a relative humidity of RH = 65%. The heat transfer coefficient between the air and the ceiling, ice surface, and walls is h = 6.5 W/m^2-K. The ceiling is insulated from the external air, as shown in Fig. P10.7-10b. The walls (all 4 of them) are black at T_{wall} = 50°F. The ice is maintained at T_{ice} = -12°F and can also be considered black. This problem deals with the selection of the ceiling surface; specifically, is it best to make the ceiling have a high or low emissivity (ε_c)? The issue is condensation; if the ceiling surface temperature is too low then water will condense out of the air onto the ceiling and drip onto the ice surface, ruining it. Therefore, it is necessary to keep the ceiling surface above the dew point temperature of the air. This is a multimode problem because the ceiling experiences both convection (with the internal air) and radiation (with the walls and the ice). We will solve this problem by separately considering the radiation and convection aspects of the problem and then finally forcing these two components to be consistent.

a.) Draw a resistance network that represents the radiation heat transfer between the ceiling, ice, and the walls. Clearly label what each node and resistance represents.

b.) Calculate the values of each of your resistances from (a). Assume that the emissivity of the ceiling is ε_c = 0.5 for this question.

c.) If the temperature of the ceiling is T_c = 40°F then what is the net rate of radiation heat transfer from the ceiling?

d.) If the temperature of the ceiling is T_c = 40°F then what is the net rate of convection heat transfer to the ceiling?

e.) Adjust the value of T_c so that your answers from (c) and (d) match; that is, determine the value of T_c where the rate of convection to the ceiling matches the rate of radiation from the ceiling.

f.) What is the dew point temperature of the air in the ice rink? You may find the function DewPoint for the fluid AirH2O (an ideal gas mixture of air and water vapor) to be useful for this calculation.

g.) Prepare a plot of the ceiling surface temperature and the dew point temperature as a function of the emissivity of the ceiling. Note that the dew point temperature is not affected by the emissivity (it should be a horizontal line); what range of emissivity will prevent condensation? In general, should architects provide ice rink ceilings with high or low emissivity?

h.) Prepare a plot showing the refrigeration load on the ice rink (i.e., the total rate of heat transfer to the ice) as a function of the emissivity of the ceiling.

10.6-11 (10-23 in text) The earth radiates to space, which has an effective temperature of about 4 K. However, the earth is surrounded by an atmosphere consisting of gases that absorb radiation in specific wavelength bands. For this reason, the equivalent blackbody temperature of the sky is greater than 4 K but generally lower than the ambient temperature by 5 to 30°C, depending on the extent of cloud cover and amount of moisture in the air. The largest difference between the ambient and equivalent blackbody sky temperature occurs during nights in which there is no cloud cover and low humidity. An important multimode heat transfer problem is related to determining the nighttime temperature at which there is a danger that citrus fruit will freeze. Consider the following situation. During a clear calm night, an orange with diameter D = 6.5 cm experiences radiation heat transfer with the sky and the ground as well as convection to the ambient air. The ground temperature is approximately T_{ground} =10°C, regardless of the ambient temperature and is constant during the night. The equivalent blackbody temperature of the sky, T_{sky}, is ΔT_{sky} = 15°C lower than the ambient temperature, T_{∞}. The emissivity of the ground is ε_{ground} = 0.8 and the sky can be considered to be black. The emissivity of the orange is ε_{orange} = 0.5. Estimate the ambient temperature, T_{∞}, at which the orange will freeze; assume that the orange achieves a steady-state condition. Oranges consist of mostly water and therefore they freeze at about 0°C.

10.6-12 Reconsider Problem 10.3-16. Rather than setting the temperature of the shield to T_4 = 300 K, assume that the shield experiences natural convection from its external surface to atmospheric air at T_∞ = 300 K. Gravity is perpendicular to the transfer line. The shield is thin and conductive.

10.6-13 Figure P10.6-13 illustrates a pipe that is being radiatively heated by two plates.

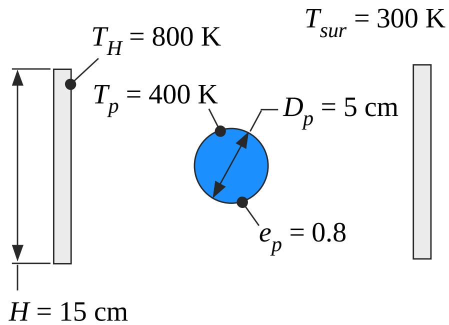

Figure P10.6-13: Pipe being radiatively heated.

The pipe is centered between the two plates. The pipe has diameter D = 5 cm and the surface of the pipe has emissivity ε_p = 0.8. The temperature of the pipe surface is T_p = 400 K. The heater plates are black and have surface temperature T_H = 800 K. The height of the plates is H = 15 cm. The surroundings are at T_{sur} = 300 K. You may assume that this is a 2-D problem. The view factor from the pipe to the heater plates (both of them) is $F_{p,H}$ = 0.5.

a.) Determine the rate of heat transfer to the pipe per unit length.

b.) The pipe contains liquid metal with conductivity k = 50 W/m-K. The flow is laminar and fully developed. Estimate the mean temperature of the fluid in the pipe.

10.7 The Monte Carlo Method

10.7-1 Consider two parallel plates that are separated by a distance of H = 0.5 m. The plates are each L = 1 m by W = 2 m. The lower plate (surface 1) is maintained at T_1 = 400 K and has emissivity ε_1 = 0.4. The upper plate (surface 2) has a temperature profile that varies linearly in the x-direction from T_C = 500 K at one edge (x = 0) to T_H = 1000 K at the other edge (x = W). The temperature is uniform in the y-direction. The emissivity of the upper plate is ε_3 = 0.6. Assume that the upper surface of the upper plate and the lower surface of the lower plate are both insulated.

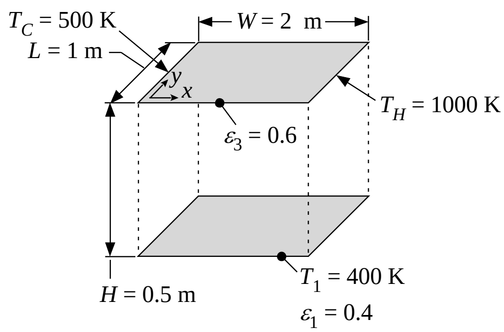

Figure P10.7-1: Two plates.

a.) Calculate the net rate of energy transfer from the upper plate (plate 2) to the lower plate (plate 1) using the Monte Carlo technique.
b.) Estimate the uncertainty in your answer when 10,000 rays are used.
c.) Verify that your answer is consistent with an analytical solution in the limit that ε_1 = ε_2 = 1.0 and surface 2 is isothermal at T_2 = 1000 K.

10.7-2 (10-24 in text) Two parallel rectangular surfaces, each 2 m by 3 m are aligned with one another and separated by a distance of 1 m. Surface 2 has a 1 m diameter hole in it. The center of the hole is located at the center of the rectangle.

a) Determine the view factor of surface 1 to surface 2 using the Monte Carlo method.

b) Compare the value obtained in (a) to the value obtained from the view factor library.

c) Determine the view factor between the surfaces if both surfaces have a 1 m diameter at their centers.

10.7-3 (10-25 in text) Two parallel rectangular surfaces, each 2 m by 3 m are separated by a distance of 1 m and aligned with one another. Each surface has a hole with a diameter of 1 m located at their center. The emissivity of surfaces 1 and 2 are 0.8 and 0.6, respectively. Surface 1 is at 700 K and surface 2 is at 300 K.

a) Determine the net rate of heat transfer from surface 1 to surface 2 using the Monte Carlo method.

b) Using the view factor determined for this geometry in Problem 10.7-2, calculate the net rate of heat transfer between surfaces 1 and 2 using the $\hat{F}$ method and compare your answer to the result from part (a).

10.7-4 Calculate the view factor between perpendicular surfaces 1 and 2 for the geometry shown in Figure P10.7-4 where a = 2 m, b = 1 m and c = 1.5 m. Use the Monte Carlo method.

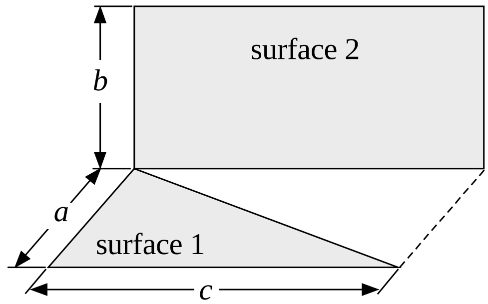

Figure P10.7-4: Perpendicular surfaces

10.7-5 Develop a function that will return the view factor between parallel surfaces 1 and 2 for the geometry shown in Figure P10.7-5. Use the Monte Carlo method.

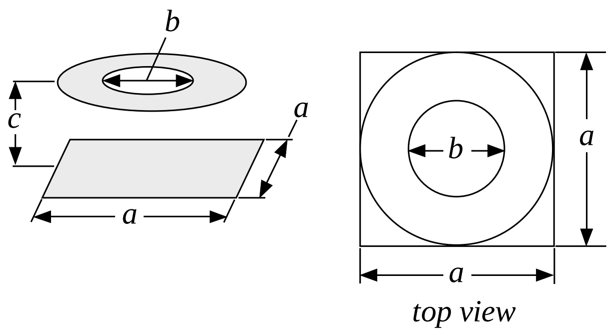

Figure P10.7-5: Parallel surfaces

a.) Determine the view factor when a = 1 m, b = 0.5 m and c = 1 m.
b.) Verify your answer using the EES function F3D_21.
c.) Plot the average value of the view factor associated with 25 calls to your Monte Carlo function as a function of the number of rays used in the calculation. Put uncertainty bars on your plot associated with the standard deviation in the 25 results. Your plot should resemble Figure 10-31 from the text.

Chapter 10: Radiation

Section 10.2: Emission of Radiation by a Blackbody

10.2-1 (10-1 in text) Radiation that passes through the atmosphere surrounding our planet is absorbed to an extent that depends on its wavelength due to the presence of gases such as water vapor, oxygen, carbon dioxide and methane. However, there is a relatively large range of wavelengths between 8 and 13 microns for which there is relatively little absorption in the atmosphere and thus, the transmittance of atmosphere is high. This wavelength band is called the atmospheric window. Infrared detectors on satellites measure the relative amount of infrared radiation emitted from the ground in this wavelength band in order provide an indication of the ground temperature.

a) What fraction of the radiation from sun is in the atmospheric window? The sun can be approximated as a blackbody source at 5780 K.

b) Prepare a plot of the fraction of the thermal radiation emitted between 8 and 13 microns to the total radiation emitted by the ground for temperatures between -10°C to 30°C.

c) Based on your answers to a) and b), indicate whether radiation in the atmospheric window can provides a clear indication of surface temperature to satellite detectors.

10.2-4 (10-2 in text) Photovoltaic cells convert a portion of the radiation that is incident on their surface into electrical power. The efficiency of the cells is defined as the ratio of the electrical power produced to the incident radiation. The efficiency of solar cells is dependent upon the wavelength distribution of the incident radiation. An explanation for this behavior was originally provided by Einstein and initiated the discovery of quantum theory. Radiation can be considered to consist of flux of photons. The energy per photon (e) is: $e = h\,c/\lambda$ where h is Planck's constant, c is the speed of light, and λ is the wavelength of the radiation. The number of photons per unit area and time is the ratio of the spectral emissive power, $E_{b,\lambda}$ to the energy of a single photon, e. When radiation strikes a material, it may dislodge electrons. However, the electrons are held in place by forces that must be overcome. Only those photons that have energy above a material-specific limit, called the band-gap energy limit (i.e., photons with wavelengths lower than $\lambda_{bandgap}$) are able to dislodge an electron. In addition, photons having energy above the band-gap limit are still only able to dislodge one electron per photon; therefore, only a fraction of their energy, equal to $\lambda/\lambda_{bandgap}$, is useful for providing electrical current. Assuming that there are no imperfections in the material that would prevent dislodging of an electron and that none of the dislodged electrons recombine (i.e, a quantum efficiency of 1), the efficiency of a photovoltaic cell can be expressed as:

$$\eta = \frac{\int_0^{\lambda_{bandgap}} \frac{\lambda}{\lambda_{bandgap}} E_{b,\lambda}\, d\lambda}{\int_0^{\infty} E_{b,\lambda}\, d\lambda}$$

a.) Calculate the maximum efficiency of a silicon solar cell that has a band-gap wavelength of $\lambda_{bandgap}$ = 1.12 μm that is irradiated by solar energy having an equivalent blackbody temperature of 5780 K.

b) Calculate the maximum efficiency of a silicon solar cell that has a band-gap wavelength of $\lambda_{bandgap}$ = 1.12 μm that is irradiated by incandescent light produced by a black tungsten filament at 2700 K.

c) Repeat part (a) for a gallium arsenide cell that has a band-gap wavelength of $\lambda_{bandgap}$ = 0.73 μm, corresponding to a band gap energy of 1.7 ev.

d) Plot the efficiency versus bandgap wavelength for solar irradiation. What bandgap wavelength provides the highest efficiency?

10.2-5 (10-3 in text) A novel hybrid solar lighting system has been proposed in which concentrated solar radiation is collected and then filtered so that only radiation in the visible range (0.38 μm to 0.78 μm) is transferred to luminaires in the building by a fiber optic bundle. The unwanted heating of the building caused by lighting can be reduced in this manner. The non-visible energy at wavelengths greater than 0.78 μm can be used to produce electricity with thermal photovoltaic cells. Solar radiation can be approximated as radiation from a blackbody at 5780 K. See Problem 10.2-4 (10-2 in text) for a discussion of a model of the efficiency of a photovoltaic cell.

a) Determine the maximum theoretical efficiency of silicon photovoltaic cells ($\lambda_{bandgap}$=1.12 μm) if they are illuminated with solar radiation that has been filtered so that only wavelengths greater than 0.78 μm are available.
b) Determine the band-gap wavelength ($\lambda_{bandgap}$) that maximizes the efficiency for this application.

10.2-7 (10-4 in text) Light is "visually evaluated radiant energy", i.e., radiant energy that your eyes are sensitive to (just like sound is pressure waves that your ears are sensitive to). Because light is both radiation and an observer-derived quantity, two different systems of terms and units are used to describe it: radiometric (related to its fundamental electromagnetic character) and photometric (related to the visual sensation of light). The radiant power ($\dot{q}$) is the total amount of radiation emitted from a source and is a radiometric quantity (with units W). The radiant energy emitted by a blackbody at a certain temperature is the product of the blackbody emissive power (E_b, which is the integration of blackbody spectral emissive power over all wavelengths) and the surface area of the object (A).

$$\dot{q} = A E_b = A \int_{\lambda=0}^{\infty} E_{\lambda,b}\, d\lambda = A \sigma T^4$$

On the other hand, luminous power (F) is the amount of "light" emitted from a source and is a photometric quantity (with units of lumen which are abbreviated lm). The radiant and luminous powers are related by:

$$F = A K_m \int_0^{\infty} E_{\lambda,b}(\lambda) V(\lambda)\, d\lambda$$

where K_m is a constant (683 lm/W photopic) and $V(\lambda)$ is the relative spectral luminous efficiency curve. Notice that without the constant K_m, the luminous power is just the radiant power filtered by the function $V(\lambda)$ and has units of W; the constant K_m can be interpreted as converting W to lumen, the photometric unit of light. The filtering function $V(\lambda)$ is derived based on the sensitivity of the human eye to different wavelengths (in much the same way that sound meters use a scale based on the sensitivity of your ear in order to define the acoustic unit, decibel or dB). The function $V(\lambda)$ is defined as the ratio of the sensitivity of the human eye to radiation at a particular wavelength to the sensitivity of your eye at 0.555 µm; 0.555 µm was selected because your eye is most sensitive to this wavelength (which corresponds to green). An approximate equation for $V(\lambda)$ is: $V(\lambda) = \exp\left[-285.4(\lambda - 0.555)^2\right]$ where λ is the wavelength in micron. The luminous efficiency of a light source (η_l) is defined as the number of lumens produced per watt of radiant power:

$$\eta_l = \frac{F}{\dot{q}} = \frac{K_m \int_0^{\infty} E_{b,\lambda}(\lambda) V(\lambda)\, d\lambda}{\sigma T^4}$$

The conversion factor from W to lumen, K_m, is defined so that the luminous efficiency of sunlight is 100 lm/W; most other, artificial light sources will be less than this value. The most commonly used filament in an incandescent light bulb is tungsten; tungsten will melt around 3650 K. An incandescent light bulb with a tungsten filament is typically operated at 2770 K in order to extend the life of the bulb. Determine the luminous efficiency of an incandescent light bulb with a tungsten filament.

10.3-2 (10-5 in text) Find the view factor $F_{1,2}$ for the geometry shown in Figure P10.3.2 in the following two ways and compare the results.

a) Use the view factor function F3D_2 in EES (you will need to call the function more than once).

b) Use the differential view factor relation FDiff_4 and do the necessary integration.

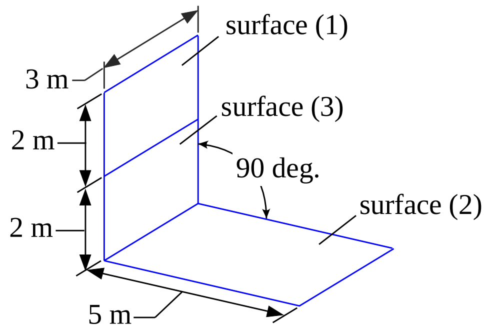

Figure P10.3-2: Determine the view factor $F_{1,2}$.

10.3-5 (10-6 in text) A rectangular building warehouse has dimensions of 50 m by 30 m with a ceiling height of 10 m. The floor of this building is heated. On a cold day, the inside surface temperature of the walls are found to be 16°C, the ceiling surface is 12°C, and the heated floor is at a temperature of 32°C. Estimate the radiant heat transfer from the floor to walls and the ceiling assuming that all surfaces are black. What fraction of the heat transfer is radiated to the ceiling?

10.3-6 (10-7 in text) A furnace wall has a 4 cm hole in the insulated wall for visual access. The wall is 8 cm wide. The temperature inside the furnace is 1900 C and it is 25°C on the outside of the furnace. Assuming that the insulation acts as a black surface at a uniform temperature, estimate the radiative heat transfer through the hole.

10.3-7 (10-8 in text) A homeowner has installed a skylight in a room that measures 6 m x 4 m with a 2.5 m ceiling height, as shown in Figure P10.3-7. The skylight is located in the center of the ceiling and it is square, 2 m on each side. A desk is to be located in a corner of the room. The surface of the desk is 0.9 m high and the desk surface is 0.5 by 1 m in area. The skylight has a diffusing glass so that the visible light that enters the skylight should be uniformly distributed.

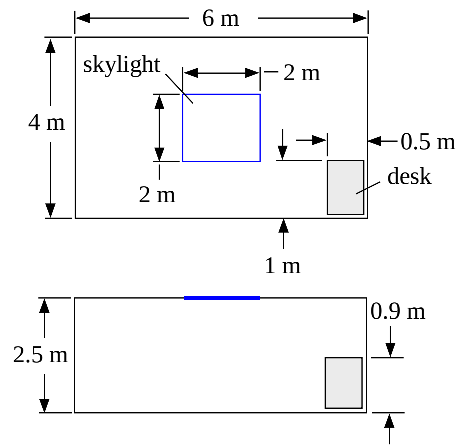

Figure P10.3-7: Desk and skylight in a room.

a.) Determine the fraction of the light emanating from skylight that will directly illuminate the desktop. Does it matter which wall the desk is positioned against (i.e., if you turned the desk 90° would the result be different)?

10.3-9 (10-9 in text) The bottom surface of the cylindrical cavity shown in Fig. P10.3-9 is heated to T_{bottom} = 750°C while the top surface is maintained at T_{top} = 100°C. The sides of the cavity are insulated externally and isothermal (i.e., the sides are made of a conductive material and therefore come to a single temperature).

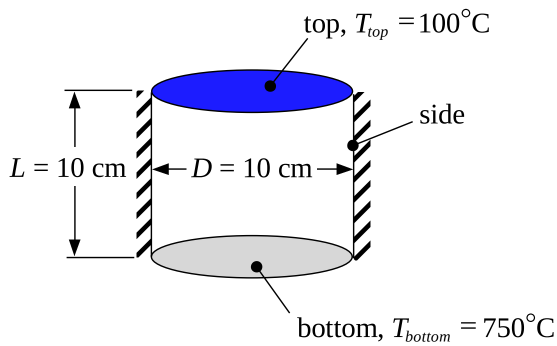

Figure P10.3-9: Cylindrical cavity heated from the bottom and cooled on top.

The diameter of the cylinder is D = 10 cm and its length is L = 10 cm. Assume that the cylinder is evacuated so that the only mechanism for heat transfer is radiation. All surfaces are black (ε = 1.0).

a.) Calculate the net rate of heat transfer from the bottom to the top surface. How much of this energy is radiated directly from the bottom surface to the top and how much is transferred indirectly (from the bottom to the sides to the top)?

b.) What is the temperature of the sides?

c.) If the sides were not insulated but rather also cooled to T_{side} = 100°C then what would be the total heat transfer from the bottom surface?

10.3-10 (10-10 in text) A homeowner inadvertently left a spray can near the barbeque grill, as shown in Figure P10.3-10. The spray can is H = 8 inch high with a diameter of D = 2.25 inch. The side of the barbeque grill is H = 8 inch high and W = 18 inch wide. The spray can is located with its center aligned with the center of the grill wall and it is a = 6 inch from the wall, as shown in Figure P10.3-10. Assume the can to be insulated on its top and bottom.

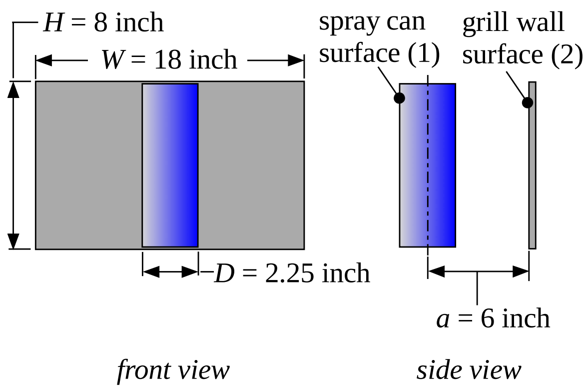

Figure P10.3-10: Spray can near a grill.

a.) What is the view factor between the spray can, surface (1), and the grill wall, surface (2)?

b.) Assuming both surfaces to be black, what is the heat transfer rate to the spray can when the grill wall is at T_2 = 350°F and the spray can exterior is T_1 = 75°F?

c.) The surroundings, surface (3) are at 75°F. What is the equilibrium temperature of the spray can if it can be assumed to be isothermal and radiation is the only heat transfer mechanism?

10.3-13 (10-11 in text) You are working on an advanced detector for biological agents; the first step in the process is to ablate (i.e., vaporize) individual particles in an air stream so that their constituent molecules can be identified through mass spectrometry. There are various methods available for providing the energy to the particle required for ablation; for example using multiple pulses of a high power laser. You are analyzing a less expensive technique for vaporization that utilizes radiation energy. A very high temperature element is located at the bottom of a cylinder, as shown in Figure P10.3-13.

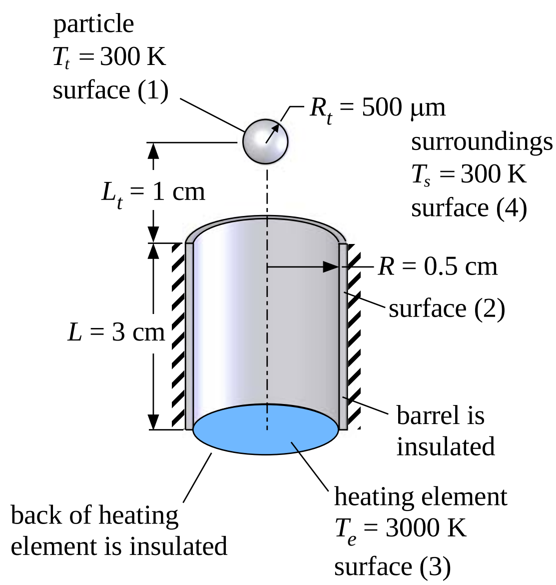

Figure 10.3-13: Radiation vaporization technique.

The length of the cylinder which is the "barrel" of the heat source is L = 3.0 cm and the radius of the cylinder and the heating element is R = 0.5 cm. The heating element is maintained at a very high temperature, T_e = 3000 K. The back side of the heating element and the external surfaces of the barrel of the heat source are insulated. The particle that is being ablated may be modeled as a sphere with radius R_s = 500 μm and is located L_t = 1.0 cm from the mouth of the barrel and is on the centerline of the barrel. The particle is at T_t = 300 K and the surroundings are at T_s = 300 K. All surfaces are black. For this problem, the particle is surface (1), the cylindrical barrel is surface (2), the disk shaped heating element is surface (3), and the surroundings is surface (4).

a.) Determine the areas of all surfaces and the view factors between each surface. This should result in an array A and matrix F that are both completely filled.

b.) Determine the net radiation heat transferred to the target.

c.) What is the efficiency of the ablation system? (i.e., what is the ratio of the energy delivered to the particle to the energy required by the element?)

d.) The particle has density ρ_t = 7000 kg/m^3 and specific heat capacity c_t = 300 J/kg-K. Use your radiation model as the basis of a transient, lumped capacitance numerical model of the particle that can predict the temperature of the particle as a function of time. Assume that the particle is initially at $T_{t,in}$ = 300 K. Use the Integral function in EES and prepare a plot showing the particle temperature as a function of time.

10.4-2 (10-12 in text) A 10,000 sq. ft. office building requires approximately $\dot{q}''_v$ = 1.0 W/ft^2 of visible radiant energy for lighting; this is energy emitted between the wavelengths $\lambda_{v,low}$ = 0.38 μm and $\lambda_{v,high}$ = 0.78 μm. The efficiency of a lighting system (η_v) can be calculated as the ratio of the visible radiant energy that is emitted to the total amount of energy emitted.

a.) Compute the efficiency of a light source that consists of a black body at T = 2800 K.

b.) Plot the efficiency of a black body lighting system as a function of temperature.

There are two costs associated with providing the lighting that is required by the office. The electricity required to heat the black body to its temperature and the electricity that is required to run the cooling system that must remove the energy provided by the light source (note that both the visible and the invisible radiation is deposited as thermal energy in the building). Assume that the building cooling system has an average coefficient of performance of COP = 3.0 and the building is occupied for 5 days per week and 12 hours per day. Assume that the cost of electricity is $0.12/kW-hr.

c.) What is the total cost associated with providing lighting to the office building for one year? How much of this cost is direct (that is, associated with buying electricity to run the light bulbs) versus indirect (that is, associated with running air conditioning equipment in order to remove the energy dumped into the building by the light bulbs). Assume that you are using a light bulb that is a black body with a temperature of 2800 K.

An advanced light bulb has been developed that is not a black body but rather has an emittance that is a function of wavelength. The temperature of the advanced light bulb remains 2800 K, but the filament can be modeled as being semi-gray; the emittance is equal to ε_{low} = 0.80 for wavelengths from 0 to λ_c = 1.0 μm and ε_{high} = 0.25 for wavelengths above 1.0 μm.

d.) What is the efficiency of the new light bulb?

e.) What is the yearly savings in electricity that can be realized by replacing your old light bulbs (the black body at 2800 K) with the advanced light bulbs?

10.4-3 (10-13 in text) The intensity of a surface has been measured as a function of the elevation angle and correlated with the following relation:

$$I = I_{b,\lambda}\left(1 - \exp\left(-0.0225 - 6.683\cos(\theta) + 5.947\cos^2(\theta) - 2.484\cos^3(\theta)\right)\right)$$

where $I_{b,\lambda}$ is the intensity of a blackbody at wavelength λ.

a) Determine the maximum hemispherical spectral emissive power for this surface if it is maintained at 1200 K.

b) What is the spectral emittance of this surface?

10.4-4 (10-14 in text) A surface has wavelength-dependent properties as listed in Table P10.4-4. The surface is maintained at 500 K.

Table P10.4-4: Wavelength-dependent absorptivity.

Wavelength Range (μm)	α_λ
0-0.6	0.8
0.6-2.6	0.25
2.6-100	0.10

a.) Determine the total hemispherical absorptance of this surface for solar radiation.
b.) Determine the total hemispherical emissivity of this 500 K surface.

10.4-6 (10-15 in text) Calculate and plot the total reflectance of polished aluminum at 697 K for radiation emitted from sources between 300 K and 6000 K. The spectral emittance of polished aluminum is provided in the EES Radiation Properties folder as the table Aluminum-Spectral.lkt.

Section 10.5: Diffuse Gray Surface Radiation Exchange

10.5-1 (10-16 in text) Three metal plates, each W = 40 cm by L = 60 cm, are parallel and centered as shown in Figure P10.5-1. Each of the plates have an emissivity of ε = 0.15. The top and bottom plates (surfaces 1 and 3) are separated by a vertical distance of H = 50 cm. The bottom and middle plates (surfaces 1 and 2) are separated by a vertical distance a. The temperature of the bottom plate is maintained at T_1 = 584°C. The plates radiatively interact with the surroundings at T_4 = 25°C. The underside of the bottom plate is insulated.

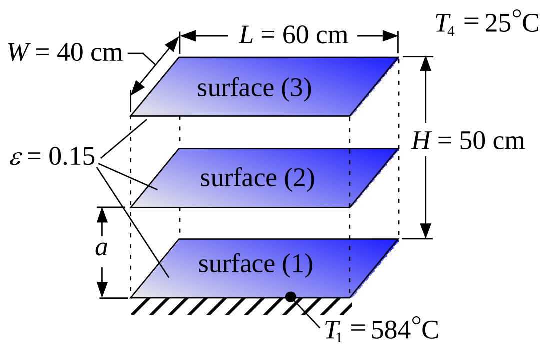

Figure P10.5-1: Three metal plates.

Calculate and plot the temperature of upper plate and the net rate of radiative heat transfer from the lower plate as a function of a for 1 cm < a < 49 cm.

10.5-5 (10-17 in text) Consider two parallel plates that are separated by a distance of H = 0.5 m. The plates are each L = 1 m by W = 2 m. The lower plate (surface 1) is maintained at T_1 = 400 K and has emissivity ε_1 = 0.4. The surroundings (surface 2) are at T_2 = 4 K. The upper plate has a temperature profile that varies linearly in the x-direction from T_C = 500 K at one edge (x = 0) to T_H = 1000 K at the other edge (x = W). The temperature is uniform in the y-direction. The emissivity of the upper plate is ε_3 = 0.6. This problem can be solved numerically by discretizing the upper plate into N equal area segments, each at the constant temperature equal to the temperature of upper plate at the center of the segment. Assume that the upper surface of the upper plate and the lower surface of the lower plate are both insulated.

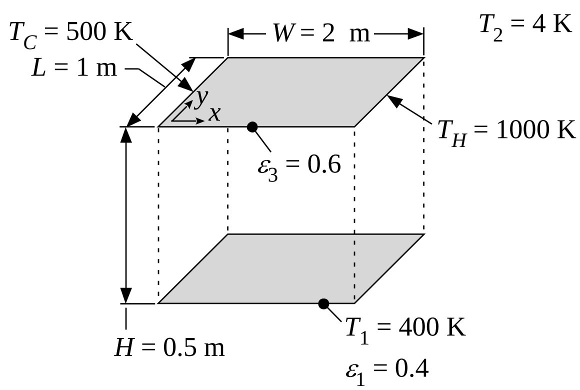

Figure P10.5-5: Two plates.

a.) Calculate the total energy that must be provided to the upper plate.

b.) Plot the total energy provided to the upper plate as a function of N for N = 1 to 10. From your results, how many segments do you believe are needed to represent the effect of the temperature distribution in the upper plate?

10.5-6 (10-18 in text) A cylindrical heating element is used to heat a flow of water to an appliance. Typically, the element is exposed to water and therefore it is well cooled. However, you have been asked to assess the fire hazard associated with a scenario in which the appliance is suddenly drained (i.e., the water is removed) but the heat to the heating element is not deactivated. You want to determine the maximum temperature that the element will reach under this condition.

The heating element and passage wall are shown in Figure P10.5-6. The length of the element is L = 9.0 cm and its diameter is D_e = 0.5 cm. The element is concentric to a passage wall with diameter D_o = 2.0 cm. The emissivity of the element is ε_e = 0.5 and the emissivity of the passage wall is ε_o = 0.9. The surroundings are at T_{sur} = 25°C. The worst case situation occurs if the outer passage wall is assumed to be insulated externally (i.e., there is no conduction or convection from the passage). The heating element dissipates $\dot{q}_e = 60\text{ W}$.

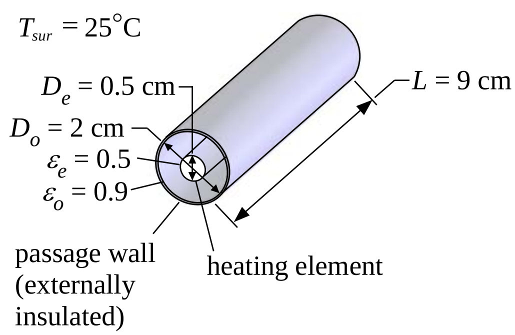

Figure P10.5-6: Heating element.

a.) What is the temperature of the element? Assume that radiation is the only important heat transfer for this problem. Note that your problem should include three surfaces (the element, the passage, and the surroundings); that is, you should not neglect the radiation exchange between the element and passage and the surroundings. However, you may assume that the edges of the element (the top and bottom surfaces) are adiabatic.

b.) What is the temperature of the passage wall?

c.) Other calculations have shown that the passage wall will not reach temperatures greater than 80°C because it is thermally communicating with surroundings. If the passage wall is maintained at T_o = 80°C then what is the maximum temperature that the heating element will reach?

10.5-8 (10-19 in text) This problem considers a (fictitious) power generation system for a spacecraft orbiting the planet Mercury. The surface of Mercury can reach 700 K and therefore you are considering the possibility of collecting radiation emitted from Mercury in order to operate a heat engine. The details of the collector are shown schematically in Figure P10.5-8(a).

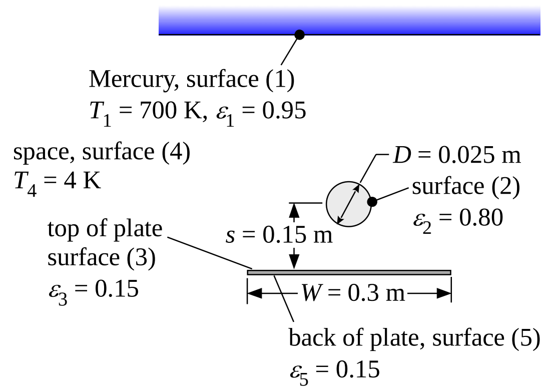

Figure P10.5-8(a): Energy collection system

The collector geometry consists of a pipe and a backing plate; this geometry is 2-D, so the problem will be solved on a per unit length basis, L = 1 m, into the page. The diameter of the pipe is D = 0.025 m. The pipe surface (surface 2) is maintained at a constant temperature (T_2) and has emissivity ε_2 = 0.8. Energy that is transferred to the pipe is provided to the power generation system. The pipe is oriented so that it is parallel to the surface of the planet (surface 1) which is at T_1 = 700 K and has an emissivity of ε_1 = 0.95. You may assume that the surface of the planet extends infinitely in all directions. There is a back plate positioned s = 0.15 m away from the centerline of the collector pipe. The back plate is W = 0.30 m wide and is centered with respect to the pipe. The top surface of the back plate (the surface oriented towards the collector pipe, surface 3) has emissivity ε_3 = 0.15. The bottom surface of the back plate (the surface oriented towards space, surface 5) also has emissivity ε_5 = 0.15. The collector and back plate are surrounded by outer space, which has an effective temperature T_4 = 4 K; assume that the collector is shielded from the sun. Assume that the back plate is isothermal.

a) Prepare a plot showing the net rate of radiation heat transfer to the collector from Mercury as a function of the collector temperature, T_2.

The energy transferred to the collector pipe is provided to the hot end of a heat engine that operates between T_2 and $T_{radiator}$, where T_2 is the collector temperature and $T_{radiator}$ is the temperature of a radiator panel that is used to reject heat, as shown in Figure P10.5-8(b). The heat engine has a 2nd law efficiency η_2 = 0.30; that is, the heat engine produces 30% of the power that a reversible heat engine would produce operating between the same temperature limits (T_2 and $T_{radiator}$). The heat engine radiator rejects heat to space; assume that the radiator panel has an emissivity $\varepsilon_{radiator}$ = 0.90 and a surface area $A_{radiator}$ = 10 m^2. Also, assume that the radiator only sees space at T_4 = 4 K.

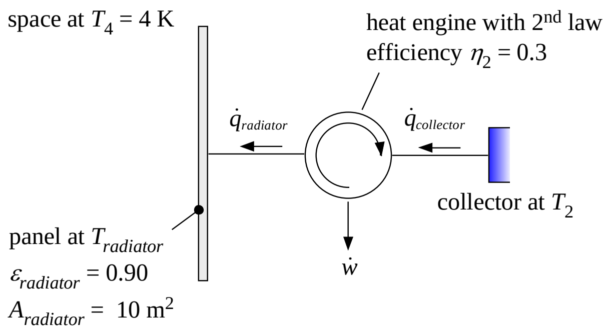

Figure P10.5-8(b): Schematic of the power generation system

b) Prepare a plot showing the amount of power generated by the heat engine ($\dot{w}$) and the radiator temperature (T_6) as a function of the collector temperature, T_2.

10.6-4 (10-20 in text) A photovoltaic panel having dimensions of 1 m by 2 m is oriented directly towards the sun (i.e., south) at a 45° angle. The panel is exposed to solar radiation at 720 W/m^2. The efficiency of the panel defined as the electrical power produced divided by the incident solar radiation, is 11.2%. The back side of the photovoltaic panel is well-insulated. The emissivity of the photovoltaic material is estimated to be 0.90. The ambient and ground temperature during the test is 22°C and there is no measurable wind. The sky is clear and the equivalent temperature of the sky for radiation is 7°C. Estimate the steady-state surface temperature of the photovoltaic panel assuming that all of the radiation that strikes the panel is absorbed. What fraction of the thermal energy transfer to the air is due to radiation?

10.6-6 (10-21 in text) A thermocouple has a diameter D_{tc} = 0.02 m. The thermocouple is made of a material with density ρ = 8000 kg/m^3 and specific heat capacity c = 450 J/kg-K. The temperature of the thermocouple (you may assume that the thermocouple is at a uniform temperature) is T_{tc} = 320 K and the emissivity of the thermocouple's surface is ε_{tc} = 0.50. The thermocouple is placed between two very large (assume infinite in all directions) black plates. One plate is at T_1 = 300 K and the other is at T_2 = 500 K. The thermocouple is also exposed to a flow of air at T_a = 300 K. The het transfer coefficient between the air and thermocouple is $\overline{h}$ = 50 W/m^2-K. The situation is shown in Figure P10.6-6.

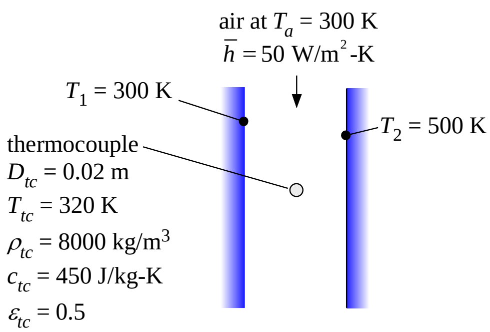

Figure P10.6-6: Thermocouple placed between two plates.

a.) What is the rate of convective heat transfer from the thermocouple?
b.) What is the net rate of radiative heat transfer to the thermocouple?
c.) What is the rate of temperature change of the thermocouple?
d.) If you want the thermocouple to accurately measure the temperature of the air (and therefore be unaffected by radiation), would you try to increase or decrease its emissivity? Justify your answer.

10.6-9 (10-22 in text) Figure P10.6-9 illustrates a set of three reactor beds that are heated radiantly by three heating elements.

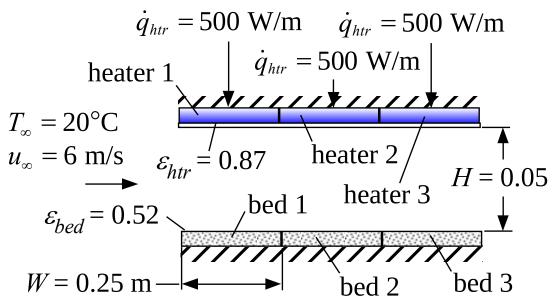

Figure P10.6-9: Reactor beds with heaters.

The reactants are provided as a flow over the beds. The temperature of the reactant flow is T_∞ = 20°C and the free stream velocity is u_∞ = 6 m/s; you may assume that the properties of the reactant flow are consistent with those of air at atmospheric pressure. All of the heaters and beds are each W= 0.25 m wide and very long (the problem is two-dimensional). The heaters and beds are separated by H = 0.05 m. The beds are insulated on their back-sides but transfer heat to the free stream by convection. The surface of the beds has emissivity, ε_{bed} = 0.52. The heaters are each provided with $\dot{q}_{htr}$ = 500 W/m; there is a piece of glass that protects the heaters from the reactants and prevents convective heat loss from the heaters. The upper surfaces of the heaters are insulated. You may assume that the 3 heaters and 3 beds are all isothermal (i.e., they are each at a unique but uniform temperature). The surface of the heaters has emissivity, ε_{htr} = 0.87. The surroundings are at T_{sur} = 20°C.

a.) Determine the temperature of each of the beds.
b.) What is the efficiency of the heating system?
c.) Determine the heater power that should be applied to each of the 3 heaters in order to keep each of the 3 beds at T_{bed} = 65°C.

10.6-11 (10-23 in text) The earth radiates to space, which has an effective temperature of about 4 K. However, the earth is surrounded by an atmosphere consisting of gases that absorb radiation in specific wavelength bands. For this reason, the equivalent blackbody temperature of the sky is greater than 4 K but generally lower than the ambient temperature by 5 to 30°C, depending on the extent of cloud cover and amount of moisture in the air. The largest difference between the ambient and equivalent blackbody sky temperature occurs during nights in which there is no cloud cover and low humidity. An important multimode heat transfer problem is related to determining the nighttime temperature at which there is a danger that citrus fruit will freeze. Consider the following situation. During a clear calm night, an orange with diameter D = 6.5 cm experiences radiation heat transfer with the sky and the ground as well as convection to the ambient air. The ground temperature is approximately T_{ground} =10°C, regardless of the ambient temperature and is constant during the night. The equivalent blackbody temperature of the sky, T_{sky}, is ΔT_{sky} = 15°C lower than the ambient temperature, T_{∞}. The emissivity of the ground is ε_{ground} = 0.8 and the sky can be considered to be black. The emissivity of the orange is ε_{orange} = 0.5. Estimate the ambient temperature, T_{∞}, at which the orange will freeze; assume that the orange achieves a steady-state condition. Oranges consist of mostly water and therefore they freeze at about 0°C.

10.7-2 (10-24 in text) Two parallel rectangular surfaces, each 2 m by 3 m are aligned with one another and separated by a distance of 1 m. Surface 2 has a 1 m diameter hole in it. The center of the hole is located at the center of the rectangle.

a) Determine the view factor of surface 1 to surface 2 using the Monte Carlo method.

b) Compare the value obtained in (a) to the value obtained from the view factor library.

c) Determine the view factor between the surfaces if both surfaces have a 1 m diameter at their centers.

10.7-3 (10-25 in text) Two parallel rectangular surfaces, each 2 m by 3 m are separated by a distance of 1 m and aligned with one another. Each surface has a hole with a diameter of 1 m located at their center. The emissivity of surfaces 1 and 2 are 0.8 and 0.6, respectively. Surface 1 is at 700 K and surface 2 is at 300 K.

a) Determine the net rate of heat transfer from surface 1 to surface 2 using the Monte Carlo method.

b) Using the view factor determined for this geometry in Problem 10.7-2, calculate the net rate of heat transfer between surfaces 1 and 2 using the $\hat{F}$ method and compare your answer to the result from part (a).