SOLAR ENERGY

Problem 1

A solar collector is designed to track the sun so that the collector surface is always perpendicular to the sun's rays. The collector is located at 50 °N and 88 °W.

(a) Determine the tilt and azimuth angles of the collector necessary for proper tracking at 9:00 am, local time on May 10th.

(b) Determine the combined beam (direct) and diffuse-scattered solar insolation if the sky is clear at the same time and date.

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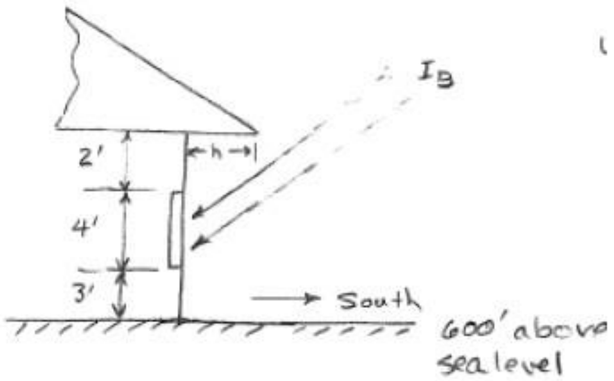
Problem 2

What should the overhang h be so that the south-facing window is shaded at solar noon on June 21? The house is located in Houghton, Michigan at an elevation of 600 feet above sea level.



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Problem 3

A 550 nm, monochromatic 1 mW light source is incident on a silicon wafer.

(a) Determine the number of photons per second impinging on the wafer.

(b) Determine the maximum possible efficiency of conversion to electricity.

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Problem 4

A 7.5-cm-diameter circular photovoltaic solar cell is exposed to a solar energy flux of 2.5 10^{17} photons/cm^2.s at an average photon wavelength of 0.0868 µm. Calculate the solar insolation on the cell in W/m^2.

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Problem 5

A manufacturer provides the following “name plate" data for a silicon solar cell at 27 °C:

- short-circuit current density, j_s = 158 A/m^2
- reverse-saturation current density, j_o = 8 10^{-8} A/m^2

(a) For maximum power, determine the solar cell area required to deliver 1 kW_e (DC).

(b) Estimate the conversion efficiency for an incident solar flux of 1200 W/m^2.

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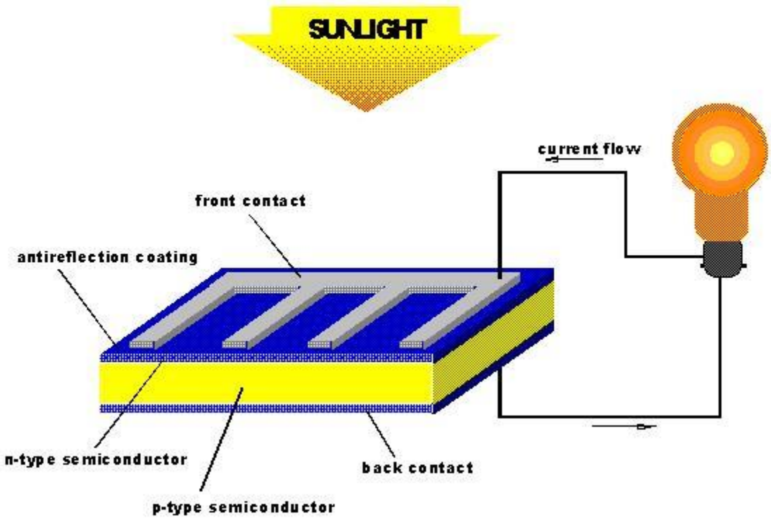
Problem 6

The diagram below shows an actual NP silicon solar cell. Explain the steps by which incident sunlight would provide energy to light the bulb.



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Problem 7 (ME436s15q4)

You are designing a solar car with a total roof area for solar cells of 6.4 m^2. Calculate the electrical power available, assuming total cell efficiency of 17 % and a constant light intensity of 980 W/m^2.

Answer: 1066 W

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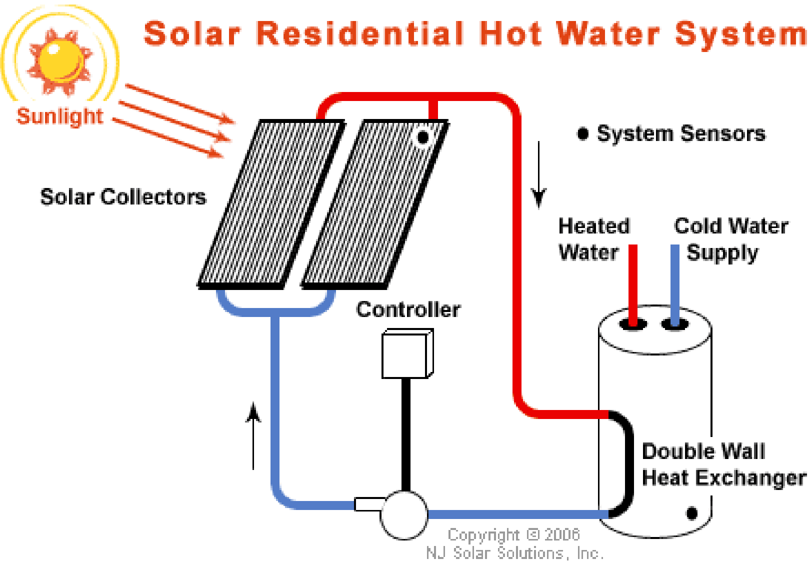
Problem 8 (ME436s15h5 / ME405f15m2-2 / ME436s16m2-2 / ME436s20h7)

A solar hot water system receives solar energy at the rate of 10.5 MJ/m^2 per day. If the collector area is 4.8 m^2, collector efficiency is 0.7 and the water volume is 325 dm^3;

a) Calculate the total water energy gain per day;

b) Estimate the temperature rise of the water in the tank during the day.



Answer: (a) 35300 kJ

(b) 26 ºC

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Problem 9

We can think of the sun's power as it radiates out as being a vector field of power intensity. That is, at each point in space, there is a vector whose magnitude represents the intensity of the sun there (in Watts/m^2) and whose direction represents the direction the solar energy waves are travelling.

Let F(x, y, z) be this vector field of solar power intensity (where we are assuming the sun is at the origin). What is F(x, y, z)? The vector field should be radially symmetric and have the property that the flux over any closed surface surrounding the sun is 4 10^{26} Watts, which is the total power released by the sun.

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Problem 10

Calculate the mean and apparent solar times for Ankara at 12:00 PM on June 21st. Daylight savings time is in effect.

See http://www.mapsofworld.com/lat_long/turkey-lat-long.html for longitude and latitude of Ankara.

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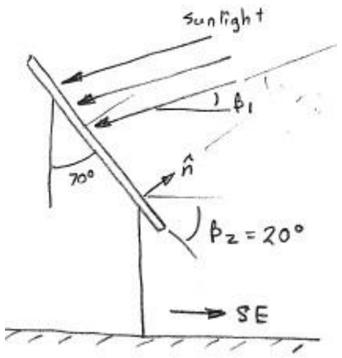
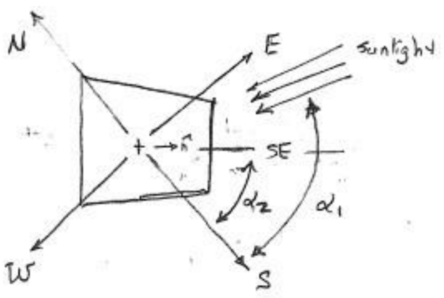
Problem 11

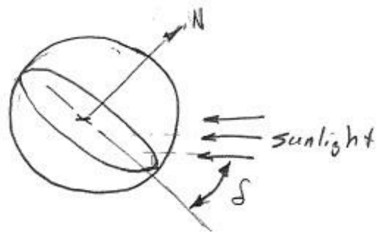
An old galvanized roof (ε = α = 0.9), inclined at 70° from vertical. 38° N latitude, 67° W longitude, 9 AM (local daylight savings time in effect) on July 7.

a) Calculate the incidence angle, θ

b) Determine the absorbed beam and diffuse-scattered solar insolation







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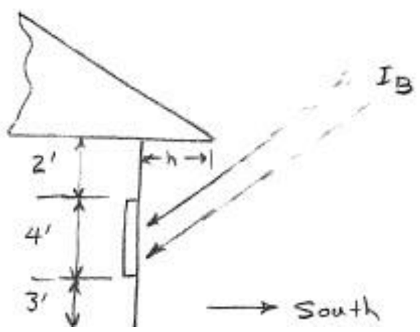
Problem 12



What should the overhang be (h = ?) so that the south-facing window shown in the Figure is shaded at solar noon on June 21st. The house is located in Ankara at an elevation of 800 m above sea level.

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Problem 13

Consider mid-February (day number: N = 45) in a city with 42.3° north latitude. Calculate the expected daily insolation to fall on a south-facing solar collector panel having a tilt angle 45°. The ground reflectance is 0.7 (snow more than 2.5 cm deep). Solar data for the city are H = 8.61 MJ/day (daily integrated insolation) and K_T = 0.435 (average clearness index). These parameters are derived from the analysis of local insolation data given in national weather data Web site. Assume isotropic sky conditions.

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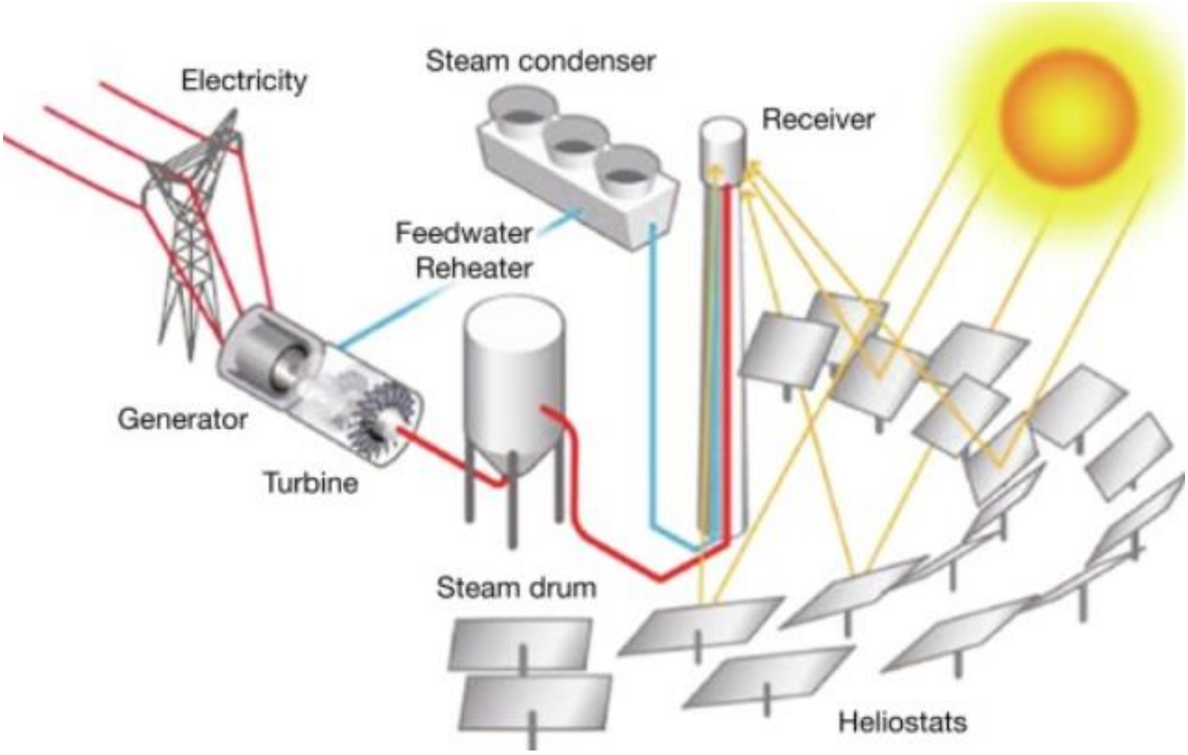
Problem 14 (ME436s15h6 / ME405f15h6 / ME436s16h7 / ME405s23h8)

A rudimentary Solar Electric Generating Station (SEGS) system consists of 2500 heliostats, each of 10 m^2, focusing on a central tower. The tower-heliostat system is able to transfer 50% of the incoming solar energy to incoming water, which then boils and is transferred to the turbine. Ignore other losses between the heliostats and expansion in the turbine. The plant averages 10 h/day of operation year round, and during that time the incoming sun averages 400 W/m^2. Ignore losses of insolation due to the heliostats not facing in a normal direction to the sun. Before entering the tower, the water is compressed to 20 MPa. In the tower it is then heated to 700 °C. The superheated steam is then expanded through the turbine using a basic Rankine cycle, and condensed at 33 °C. Assume that the actual efficiency achieved by this cycle is 85 % of the ideal efficiency. The generator is 98 % efficient. What is the annual electric output in kWh/year?

Typical schematic diagram of a solar electric generating station with heliostats and a central receiver:



Here is a photo of an actual SEG system under construction in Ouarzazate, Morocco. The manufacturer is the Chinese engineering and manufacturing firm named “CASEN Investment Co”.

Most heliostats are usually stowed at night with their mirrors facing the sky. This can cause the mirrors to be soiled by a sticky mix of moisture (dew), dust, and air pollution. They also are subject to adverse weather, including sandstorms and hail. In much of the Middle East, for example, great expense usually is required to clean the hard-to-remove dirt from the mirrors that's been deposited at night.

The innovative mirrors of CASEN, however, include several unique design features:

- The heliostats are stowed at night with their mirrors facing down, avoiding these serious and expensive cleaning problems.
- The tracking of each heliostat is controlled, wirelessly.
- Each heliostat is rotated using its own integrated solar cell and battery.

Answer: 7 245 250 kWh/year

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Problem 15 (ME436s15m2-2)

Consider mid-April (N = 105) in Ankara with L = 40° north latitude. Calculate the expected daily insolation to fall on a south-facing solar collector panel having a tilt angle β = 25°. The ground reflectance is 0.3. Solar data for the city are H = 5 MJ/day (daily integrated insolation) and K_T = 0.5 (average clearness index). Assume isotropic sky conditions.

Related relations:

Declination angle: $\delta = 23.45 \sin\left(\frac{360\,(284 + N)}{365}\right)$ in degrees.

Diffuse component of the daily insolation: $\frac{H_d}{H} = 1.39 - 4.03\,K_T + 5.53\,K_T^2 - 3.11\,K_T^3$

Sunset hour angle (for a south-facing or horizontal surface):

$$w_s = \cos^{-1}\left(-\tan(L)\tan(\delta)\right)$$ for a month between fall and spring equinoxes.

$$w_s' = \mathrm{Min}\left[w_s\ ,\ \cos^{-1}\left(-\tan(L-\beta)\tan(\delta)\right)\right]$$ for a month between spring and fall equinoxes.

The ratio of average direct beam insolation on a tilted surface to that on a horizontal surface:

$$R_{b,\beta} = \frac{\cos(L-\beta)\cos(\delta)\sin(w_s') + w_s'\sin(L-\beta)\sin(\delta)}{\cos(L)\cos(\delta)\sin(w_s) + w_s\sin(L)\sin(\delta)}$$

The ratio of average total insolation on a tilted surface to that on a horizontal surface:

$$R = \left(1 - \frac{H_d}{H}\right) R_{b,\beta} + \left(\frac{H_d}{H}\right)\left(\frac{1+\cos(\beta)}{2}\right) + \frac{\rho\,\left(1-\cos(\beta)\right)}{2}$$

Answer: 5.3 MJ/m^2

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Problem 16 (ME405f15f-2 / ME436s16f-2)

Consider a city with latitude angle L = 35° North in mid-January (day number: N = 15). The ground reflectance is ρ = 0.3. Solar data for January are: H = 8.0 MJ/m^2, and K_T = 0.4. H is daily integrated average insolation on a horizontal surface, and K_T is monthly clearness index which is an average value over a month. These parameters are derived from analysis of local insolation data over time using national data Web sites.

(a) Calculate the expected daily total insolation that falls on the glass cover of a south-facing solar collector panel having a tilt angle of β = 45°. Assume isotropic sky conditions.

(b) What are the direct, diffuse and reflected components of this daily total insolation?

(c) Explain in words (and equations if necessary) the difference(s) between the insolation on the glass cover and the energy that is actually taken up by the working fluid.

Relations:

Declination angle: $\delta = 23.45 \sin\left(\frac{360\,(284 + N)}{365}\right)$

Note that $\frac{360\,(284 + N)}{365}$ is in degrees. So is δ.

Sunset hour angle: $w_s = \cos^{-1}\left(-\tan(L)\tan(\delta)\right)$ (for winter time)

Ratio of diffuse to total daily insolation: $\frac{H_d}{H} = 1.39 - 4.03\,K_T + 5.53\,K_T^2 - 3.11\,K_T^3$

Ratio of average direct beam insolation on a tilted surface to that on a horizontal surface:

$$R_{b,\beta} = \frac{\cos(L-\beta)\cos(\delta)\sin(w_s) + w_s\sin(L-\beta)\sin(\delta)}{\cos(L)\cos(\delta)\sin(w_s) + w_s\sin(L)\sin(\delta)}$$

Note that w_s is in radians.

Ratio of average total insolation on a tilted surface to that on a horizontal surface:

$$R = \left(1 - \frac{H_d}{H}\right) R_{b,\beta} + \left(\frac{H_d}{H}\right)\left(\frac{1+\cos(\beta)}{2}\right) + \frac{\rho\,(1-\cos(\beta))}{2}$$

Answer: (a) H_T = 12.4155 MJ/day

(b) H_{direct} = 8.9 MJ/day ; H_{diff} = 3.17 MJ/day ; H_{ref} = 0.35 MJ/day

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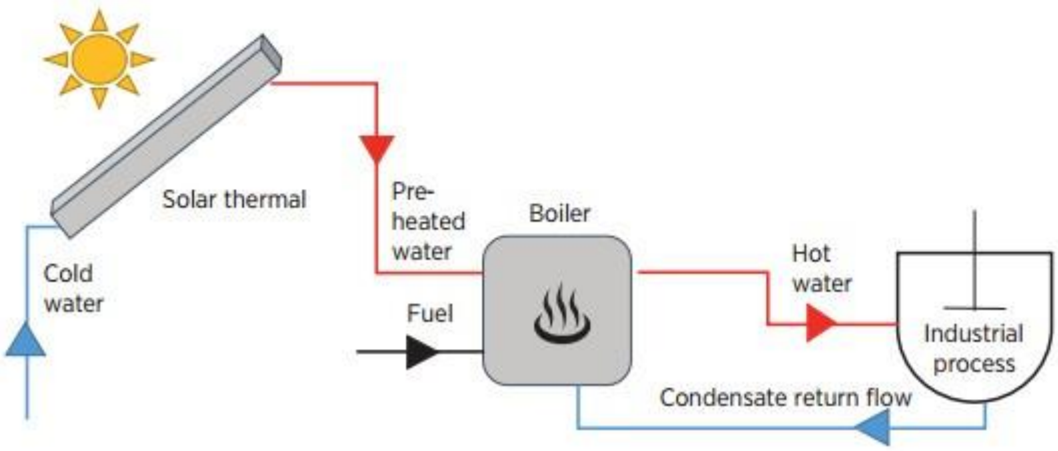
Problem 17 (ME437s17h8)

At a location of latitude 40 °N, a process heating system employing flat plate collectors, facing south with a slope (tilt angle) of 40°, of area 50 m^2 has been installed. The collector parameters are $F_R U_L$ = 2.63 W/m^2.K and F_R ($\tau\alpha$) = 0.72. The system is required to supply energy at a minimum temperature of 60 °C at a rate of 12 kW for 12 hours a day. Assume that the ground reflectance is 0.2. What is the necessary radiation level, I, for the month of January if daily average total insolation is H = 8.6 MJ/m^2.day, and the average ambient temperature is T_a = -5 °C. The inlet temperature of the water circulating in the collector array is T_{in} = 10 °C.

The schematic diagram of the use of solar energy in that industrial process as an auxiliary supply of energy is given below.



Answer: I = 462 W/m^2

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Problem 19 (ME436s16q8 / ME436s17m2-4)

A home in Güzelyurt, Cyprus, requires 62 kWh of thermal energy on a winter day to maintain a constant indoor temperature of 20 °C.

(a) How much collector surface area does it need for an all-solar heating system that has a 20 % efficiency?

(b) How large does the storage tank have to be to provide this much energy?

Güzelyurt is located at about 35° N. The average solar radiation in winter is about 6.5 kWh/m^2/day.

Specific heat of water = 4.2 kJ/kg.K

Assume that the temperature difference between the hot fluid in the secondary loop and the cold water going into the storage tank is 40 °C.

Answer: (a) 48 m^2;

(b) 1328.6 kg

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Problem 20 (ME436s16h6)

Consider a surface exposed to solar radiation. At a given time, the direct component of solar radiation is 400 W/m^2 at a zenith angle of 20˚. The diffuse component of solar radiation is 300 W/m^2. The surface temperature is observed to be 320 K. Assuming an effective sky temperature of 260 K, determine the net rate of radiation heat transfer for these cases:

(a) α_s = 0.9 and ε = 0.9 (gray absorber surface)

(b) α_s = 0.1 and ε = 0.1 (gray reflector surface)

(c) α_s = 0.9 and ε = 0.1 (selective absorber surface, gray for sky irradiation)

(d) α_s = 0.1 and ε = 0.9 (selective reflective surface, gray for sky irradiation)

where α_s is the absorption coefficient of the surface for solar irradiation at short wavelengths and ε is the emissivity of the surface for emission at longer wavelengths.

Assumptions: Given above for each case, find: q_s for cases (a) through (d) above.

Definitions:

- A gray surface is characterized by having properties independent of wavelength.
- A diffuse surface has properties independent of direction.
- The emissivity of a given surface is the measure of its ability to emit radiation energy in comparison to a blackbody at the same temperature.
- If the amounts of radiation energy absorbed, reflected, and transmitted when radiation strikes a surface are measured in percentage of the total energy in the incident electromagnetic waves. The total energy would be divided into three groups, they are called absorptivity (α), reflectivity (ρ) and transmissivity (τ).
- α + ρ + τ = 1

Answer: (a) 306.4 W/m^2

(b) 34 W/m^2

(c) 574.75 W/m^2

(d) - 234.3 W/m^2

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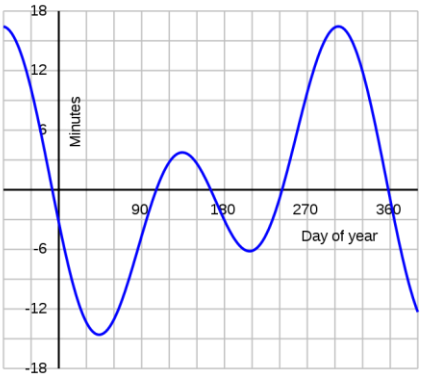
Problem 21 (ME405f16q7)

Calculate the local solar time for Ankara at 4 PM on December 9. Daylight savings time is in effect.

$$\text{LST} = \begin{pmatrix}\text{local}\\ \text{standard}\\ \text{time}\end{pmatrix} + (4)\left[\begin{pmatrix}\text{local}\\ \text{longitude}\end{pmatrix} - \begin{pmatrix}\text{standard}\\ \text{meridian}\\ \text{longitude}\end{pmatrix}\right] + \text{EoT}$$



For Ankara: Latitude: 39° 57’ N

Longitude: 32° 54’ E

December 9 => Day number N = 343

$$\text{EoT} = 9.87\sin(2\,B) - 7.53\cos(B) - 1.5\sin(B)$$

where EoT is in minutes, and

$$B = \frac{360}{365}(N - 81)$$

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Problem 22 (ME405f16q8)

At a location of latitude 40 °N, a process heating system employing flat plate collectors, facing south with a slope (tilt angle) of 40°, of area 50 m^2 has been installed. The collector parameters are $F_R\,U_L$ = 2.63 W/m^2.K and $F_R\,(\tau\alpha)$ = 0.72. The system is required to supply energy at a minimum temperature of 60 °C at a rate of 12 kW for 12 hours a day. Assume that the ground reflectance is 0.2. What is the necessary radiation level, I, for the month of January if daily average total insolation is H = 8.6 MJ/m^2.day, and the average ambient temperature is T_a = -5 °C.

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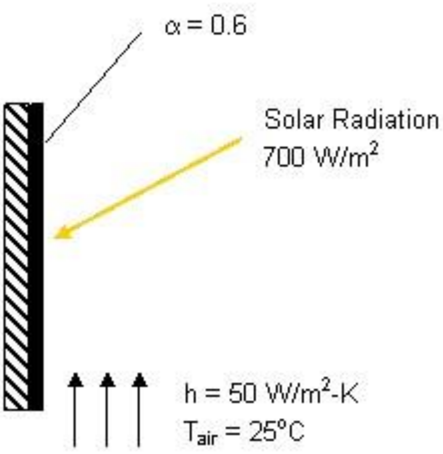
Problem 23 (ME405f16h6 / ME436s17h7 / ME436s18h7 / ME405s18h6)

A thin, metal plate is insulated on the back surface and exposed to solar radiation on the front surface, as shown in the figure. The exposed surface of the plate has an absorptivity of 0.6 for solar radiation. If solar radiation is incident on the plate at a rate of 700 W/m² and the surrounding air temperature is 25°C, determine the temperature of the exposed surface of the plate at steady-state. Assume the convection heat transfer coefficient is 50 W/m².K.



List all the assumptions first and do not neglect heat loss by radiation.

Apply first law and solve for the surface temperature, T_s.

Heat loss by convection: $\frac{\dot{Q}_{conv}}{A} = h\left(T_s - T_{air}\right)$

Heat loss by radiation: $\frac{\dot{Q}_{rad}}{A} = \varepsilon\ \sigma\left(T_s^4 - T_{air}^4\right)$

Answer: T_s = 305.815 = 32.815 °C

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Problem 24 (ME405f16h7 / ME436s17q8)

A home in Lefkosa, Cyprus, requires 62 kWh of heat on a winter day to maintain a constant indoor temperature of 20 °C.

(a) How much collector surface area does it need for an all-solar heating system that has a 20% efficiency?

(b) How large does the storage tank have to be to provide this much energy? The temperature of the hot water obtained from the collector is 60 °C.

The heat capacity of water is 1 kcal/kg.K. The conversion factor is: 1 kcal = 0.00116 kWh.

Variation of solar radiation (in W h/m^2) with time and latitude

Date	Perpendicular	Horizontal	Vertical South	60° South
October 21				
32°N	8,498	5,213		
40 °N	7,735	4,249	5,212	6,536
48 °N	6,789	3,221		
November 21				
32 °N	7,584	4,035		
40 °N	6,707	2,969	5,314	6,013
48 °N	5,257	1,879		
December 21				
32 °N	7,401	3,581		
40 °N	6,235	2,465	5,188	5,660
48 °N	4,551	1,406		
January 21				
32 °N	7,748	4,060		
40 °N	6,878	2,988	5,440	6,127
48 °N	5,390	1,879		
February 21				
32 °N	9,053	5,434		
40 °N	8,321	4,457	5,452	6,858
48 °N	7,344	3,404		
March 21				
32 °N	9,494	6,569		
40 °N	9,191	5,838	4,677	6,852
48 °N	8,763	4,974		

[Sources: Kraushaar and Ristinen, op. cit.; A.W. Culp, Jr., "Principles of Energy Conversion," McGraw-Hill, 1991.]

Answer: Collector surface area = 48 m^2

Mass = 1336 kg

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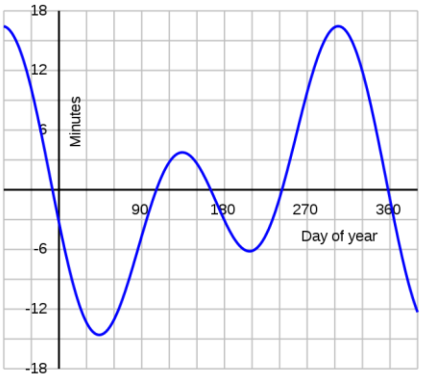
Problem 25 (ME436s18q9 / ME405s18q9)

Calculate the local solar time for Ankara at 11:30 AM on April 11. Daylight savings time is not in effect.

$$\text{LST} = \begin{pmatrix}\text{local}\\ \text{standard}\\ \text{time}\end{pmatrix} + (4)\left[\begin{pmatrix}\text{local}\\ \text{longitude}\end{pmatrix} - \begin{pmatrix}\text{standard}\\ \text{meridian}\\ \text{longitude}\end{pmatrix}\right] + \text{EoT}$$



For Ankara: Latitude: 39° 57' N

Longitude: 32° 54' E

April 11 => Day number N = 111

$$EoT = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B)$$

where EoT is in minutes, and

$$B = \frac{360}{365}(N - 81) \quad \text{in degrees}$$

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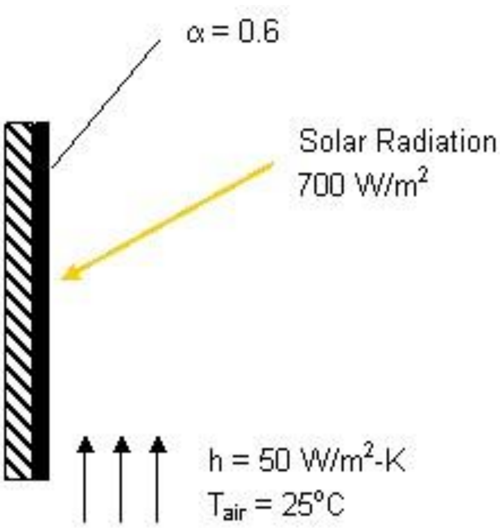
Problem 26 (ME436s18q10)



A thin, metal plate is insulated on the back surface and exposed to solar radiation on the front surface, as shown in the figure. The exposed surface of the plate has an absorptivity of 0.6 for solar radiation. If solar radiation is incident on the plate at a rate of 700 W/m^2 and the surrounding air temperature is 25°C, determine the temperature of the exposed surface of the plate at steady state. Assume the convective heat transfer coefficient is 50 $W/m^2.K$. List all the assumptions first and neglect heat loss by radiation.

Apply first law and solve for the surface temperature, T_s.

Heat loss by convection: $\frac{\dot{Q}_{conv}}{A} = h\left(T_s - T_{air}\right)$ Heat loss by radiation: $\frac{\dot{Q}_{rad}}{A} = \varepsilon\,\sigma\left(T_s^4 - T_{air}^4\right)$

Answer: 33.4 °C

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Problem 27 (ME436s18m2-4 / ME405s18m2-4 / ME436s19q8 / ME405s19q8 / ME436s20q8)

Solar radiation is incident on A = 5 m^2 solar absorber plate surface at a rate of I/A = 800 W/m^2. 93 % of the solar radiation is absorbed by the absorber plate, while remaining 7 % is reflected away. The solar absorber plate has a surface temperarture of T_s = 40 °C with an emissivity of ε = 0.9 that experiences radiation exchange with the surrounding temperature T_{surr} = - 5 °C. In addition, convective heat transfer occurs between the absorber plate surface and the ambient air at T_{air} = 20 °C with a convection heat transfer coefficient of h_c = 7 W/m^2.K. Determine the efficiency of the solar absorber, which is defined as the ratio of the usable heat collected by the absorber to the incident solar radiation on the absorber.
Stephan-Boltzmann constant is: $\sigma = 5.67\ 10^{-8}$ $W/m^2.K^4$

Answer: Efficiency = 47 %

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Problem 28 (ME436s19q7 / ME405s19q7 / ME436s20q6)
The radius of the Sun is $R_s = 6.96\ 10^8$ m, and the distance between the Sun and Earth is D = 1.5 10^{11} m. The solar constant is 1366 W/m^2. Estimate the surface temperature of the Sun. Hint: use the Stefan–Boltzmann law. $\sigma = 5.67\ 10^{-8}$ $W/m^2.K^4$.

Answer: 5784 K

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Problem 29 (ME436s19h6 / ME405s19h6 / ME436s20h6 / ME436s22h9 / ME405s22h8)
Consider mid-April in Antalya. Calculate the expected daily insolation to fall on a south-facing solar collector panel having a tilt angle β = 35°. The ground reflectance is 0.3. Solar data for the city are H = 12 MJ/day (daily integrated insolation) and K_T = 0.65 (average clearness index). These parameters are derived from the analysis of local insolation data given in national weather data Web site. Assume isotropic sky conditions.
Related relations:

Declination angle: $\delta = 23.45 \sin\left(\frac{360\ (284 + N)}{365}\right)$ in degrees.

Solar declination angle is between the solar rays and equator plane of the earth, measured from the plane to the rays, positive to the north. N is the day number.

Diffuse component of the daily insolation: $\frac{H_d}{H} = 1.39 - 4.03\ K_T + 5.53\ K_T^2 - 3.11\ K_T^3$

H is the daily insolation, H_d is its diffuse component, and K_T is the clearness index.

Sunset hour angle (for a south-facing or horizontal surface):

$w_s = \cos^{-1}\left(- \tan(L)\tan(\delta)\right)$ for a month between fall and spring equinoxes.

$w_s' = \mathrm{Min}\left[w_s \text{ , } \cos^{-1}\left(- \tan(L - \beta)\tan(\delta)\right)\right]$ for a month between spring and fall equinoxes.

L is the local latitude, angle north and south of the equator, positive if north.

The ratio of average direct beam insolation on a tilted surface to that on a horizontal surface:

$$R_{b,\beta} = \frac{\cos(L - \beta)\cos(\delta)\sin(w_s') + w_s' \sin(L - \beta)\sin(\delta)}{\cos(L)\cos(\delta)\sin(w_s) + w_s \sin(L)\sin(\delta)}$$

The ratio of average total insolation on a tilted surface to that on a horizontal surface:

$$R = \left(1 - \frac{H_d}{H}\right) R_{b,\beta} + \left(\frac{H_d}{H}\right)\left(\frac{1 + \cos(\beta)}{2}\right) + \frac{\rho\left(1 - \cos(\beta)\right)}{2}$$

ρ is reflectivity of the ground. The three terms on the right are for direct, diffuse, and reflected components.

Average daily total insolation: $H_T = H\,R$

Answer: 12.478 MJ/day

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Problem 30 (ME436s19m2-4 / ME405s19m2-4)

It has been reported that the latest module of the SEGS (Solar Electric Generating System) plant in Kramer Junction, California, USA, generates 80 MW of electricity by using 483 360 square meters of collectors to achieve an annual output of 260 GWh (gigawatthours). Check whether these numbers make sense. What is the efficiency of the collectors?

Answer: Yes, they make sense.

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Problem 31 (ME436s19m2-5 / ME405s19m2-5)

What is the local solar time on 1st of May 2019, in Ankara, at 13:00 clock time?

$$\text{LST} = \begin{pmatrix}\text{local}\\ \text{standard}\\ \text{time}\end{pmatrix} + (4)\left[\begin{pmatrix}\text{local}\\ \text{longitude}\end{pmatrix} - \begin{pmatrix}\text{standard}\\ \text{meridian}\\ \text{longitude}\end{pmatrix}\right] + \text{EoT}$$

For Ankara: Latitude: 39° 57’ N

Longitude: 32° 54' E

Standard meridian: 45° E

$EoT = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B)$ in minutes

$B = \frac{360}{365}(N - 81)$ in degrees, where N is day number

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Problem 32 (ME436s20q7)

A surface tilted 30° from the horizontal (β_2 = 30 deg) and pointed due south is located at 35° N latitude (L = 35°). Calculate the angle of incidence, θ, at 1 hour after local noon (H = 15°) on April 1 (N = 91).

Note the following: The optimum tilt angle is calculated by adding 15 degrees to the latitude during winter, and subtracting 15 degrees from the latitude during summer. For instance, if your latitude is 35°, the optimum tilt angle for your solar panels during winter will be 35 + 15 = 50°. The summer optimum tilt angle on the other hand will be 35 – 15 = 20°.

Answer: θ = 0.0785 rad = 4.5 deg

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Problem 33 (ME436s20f-2)

Find the length of a day in Ankara today, 13th of June.

For Ankara: Latitude: 39° 57' N

Longtitude: 32° 54' E

$w_s = \cos^{-1}[-\tan(L)\tan(\delta)]$ between fall and spring equinoxes

$w'_s = \mathrm{Min}\left[w_s, \cos^{-1}[-\tan(L-\beta)\tan(\delta)]\right]$ between spring and fall equinoxes

$\text{Declination angle} = 23.45 \sin\left(\frac{360\,(284 + N)}{365}\right)$ in degrees

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Problem 34 (ME436s21q8 / ME405s21q8)

Solar radiation is incident on the outer surface of a spaceship at a rate of 1250 W/m^2. The surface has an absorptivity of $\alpha = 0.10$ for solar radiation and an emissivity of $\varepsilon = 0.6$ at room temperature. The outer surface radiates heat into space at 0 K. If there is no net heat transfer into the spaceship, determine the equilibrium temperature of the surface. The equilibrium temperature of the spaceship occurs when the incoming solar radiation absorbed by the surface equals the radiation emitted into space. (There is no convection in the vacuum of outer space.).

Answer: $T_{ship} = 246$ K

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Problem 35 (ME436s21h8 / ME405s21h8 / ME436s22h8 / ME405s22h7)

For a city of your choice in Turkey, report the following solar data for every month

Month	H, Daily integrated average insolation on a horizontal surface in MJ/m^2	K_T, monthly clearness index
January		
February		
…..		

You may refer to the Web site of the national Meteorological Institute of Turkey.

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Problem 36 (ME436s21f-3 / ME405s21f-3)

A home in Antalya requires 62 kWh of heat on a winter day to maintain a constant indoor temperature of 20 °C.

(a) How much collector surface area does it need for an all-solar heating system that has a 20 % efficiency?

(b) How large does the storage tank have to be to provide this much energy? The temperature of the hot water obtained from the collector is 60 °C.

Latitude of Antalya is 37 °N

Assume that the collectors have 50° tilt angle facing due South.

Specific heat of water is 4.18 kJ/kg.K

Variation of solar radiation (in W h/m^2) with time and latitude

Date	Perpendicular	Horizontal	Vertical South	60° South
October 21				
32°N	8,498	5,213		
40 °N	7,735	4,249	5,212	6,536
48 °N	6,789	3,221		
November 21				
32 °N	7,584	4,035		
40 °N	6,707	2,969	5,314	6,013
48 °N	5,257	1,879		
December 21				
32 °N	7,401	3,581		
40 °N	6,235	2,465	5,188	5,660
48 °N	4,551	1,406		
January 21				
32 °N	7,748	4,060		
40 °N	6,878	2,988	5,440	6,127
48 °N	5,390	1,879		
February 21				
32 °N	9,053	5,434		
40 °N	8,321	4,457	5,452	6,858
48 °N	7,344	3,404		
March 21				
32 °N	9,494	6,569		
40 °N	9,191	5,838	4,677	6,852
48 °N	8,763	4,974		

[Sources: Kraushaar and Ristinen, op. cit.; A.W. Culp, Jr., "Principles of Energy Conversion," McGraw-Hill, 1991.]

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Problem 37 (ME436s22q7 / ME405s22q7)

Knowing that the solar radiation just outside of the atmosphere is (about 1360 W/m^2), and assuming that the proportion of radiation reflected on the clouds and the earth's surface is of 30 % (i.e. that 70 % of this radiation is absorbed by the earth), one can deduce a hypothetical equilibrium temperature that would be reached in the absence of atmosphere, considering the earth as a black body. Find that temperature and comment.

Answer: - 20 C

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Problem 38 (ME405s22q8 / ME436s22q9 / ME405f22q9)

The absorber surface of a solar collector is made of aluminum coated with black chrome paint (α_s = 0.87 and ε = 0.09). Solar radiation is incident on the surface at a rate of 600 W/m^2. The air and effective sky temperatures are 25 ^oC and 15 ^oC, respectively, and the convective heat transfer coefficient is 10 $W/m^2.^oC$. For an absorber surface temperature of 70 ^oC, determine the net rate of solar energy delivered by the absorber plate to the water circulating behind it.

Answer: $\dot{q}_{collector} = 36.5\ W/m^2$

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Problem 39 (ME405f22h8)

Using the precise data collected by the Danish astronomer, Tycho Brahe, Johannes Kepler carefully analyzed the positions in the sky of all the known planets and the Moon, plotting their positions at regular intervals of time. From this analysis, he formulated three laws. Briefly explain the first two laws of Kepler.

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Problem 40 (ME405f22h9)

Suppose that a solar PV system is to be installed in the campus of METU.

(a) Estimate the area and electrical energy storage required to power the whole campus purely by sunlight.

(b) If a solar PV system with a capacity factor of 15 % can be installed for $3 per Watt, and the energy storage costs are $200 per kWh, what would be the up-front installation cost of such a system?

(c) If it lasts for 20 years and performs to its ideal specifications year round (i.e. you don't have to consider losses due to bad weather, clouds, fog, etc.) and interest costs for money are zero so that the present value and future value of money is equal (really an ideal world!), how much does the electrical energy cost per kWh?

(d) How does this compare against conventional electrical energy costs?

Make reasonable assumptions for the following:

- The average electricity power usage of the whole campus (10 MW)
- The average hours that the PV system can operate in a day (12 hours)
- The average nightly hours that the energy storage system can support (12 hours)
- The life time of the whole system (20 years); and
- Current price of the conventional electricity in $ per kWh (0.12 $/kWh)

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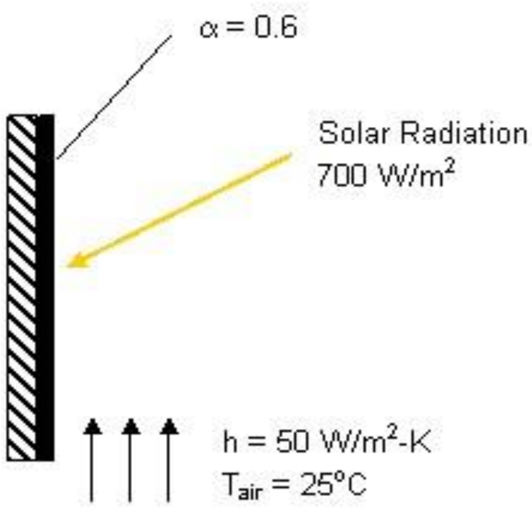
Problem 41 (ME405f22f-2)



A thin, metal plate is insulated on the back surface and exposed to solar radiation on the front surface, as shown in the figure. The exposed surface of the plate has an absorptivity of α = 0.6 for solar radiation. The emissivity of the surface is ε = 0.8. The intensity of the beam solar radiation is 700 W per m^2 surface area. The surrounding air temperature is T_{air} = 25 °C and the sky temperature is T_{sky} = 15 °C. The convective heat transfer coefficient is h = 50 $W/m^2.K$. Stephan-Boltzmann constant is σ = 5.67 10^{-8} $W/m^2.K^4$.

(a) Find the equation where T_s is the only unknown. Substitute numbers for all the known parameters in the equation.

(b) Find T_s by neglecting radiative heat loss.

(c) Is neglecting radiative heat loss a good assumption?

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Problem 42 (ME405s23q7)

A beam radiation has a flux value of I_B = 350 W/m^2. What is the flux, I_{BN}, reaching a surface facing due south and tilted by 25° at 11 AM solar time on the summer solstice in Ankara?

$I_{BN} = I_B \cos(\theta)$

Angle of incidence: $\cos\theta = (\sin\beta_1)\left(\cos\beta_2\right) + (\cos\beta_1)\left(\sin\beta_2\right)\left(\cos\delta\right)$

Declination angle at summer solstice: δ = 23.45 degrees

Tilt angle of the surface: β_2 = 25 degrees

Solar altitude angle: $\sin(\beta_1) = \cos(L)\cos(\delta)\cos(H) + \sin(L)\sin(\delta)$

Latitude angle of Ankara: L = 40°

Hour angle at 11 am solar time: H = - 15°

Answer: I_{BN} = 344.73 W/m^2

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Problem 43 (ME405f23q8)

Define an efficiency for a flat-plate solar collector under steady state conditions. Find the mathematical expression for the efficiency.

$$\dot{Q}_u = F_R \left[I\, A_{ap}\, \tau_c\, \alpha_s - U_L\, A_{ap}\, (T_{in} - T_a) \right] = \dot{m}\, c_p\, (T_{out} - T_{in})$$

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Problem 44 (ME405s23h7)

A beam radiation has a flux value of I_B = 350 W/m^2. What is the flux, I_{BN}, reaching a surface facing due south and tilted by 25° at 11 AM local time on June 15 in Antalya?

$$I_{BN} = I_B \cos(\theta)$$

Angle of incidence: $\cos\theta = (\sin\beta_1)\,(\cos\beta_2) + (\cos\beta_1)\,(\sin\beta_2)\,(\cos\delta)$

Declination angle in degrees: $\delta = (23.45^\circ)\ \sin\left(\frac{360}{365}(284 + N)\right) \quad , \quad 1 \le N \le 365$

Tilt angle of the surface: β_2 = 25 degrees

Solar altitude angle: $\sin(\beta_1) = \cos(L)\cos(\delta)\cos(H) + \sin(L)\sin(\delta)$

Latitude of Antalya: L = 37°

Longitude for Antalya: 30.7°

Standard Meridian Longitude: 45°

$$\text{Local Solar Time: } LST = \begin{pmatrix}\text{local}\\ \text{standard}\\ \text{time}\end{pmatrix} - \left(\frac{4\ \text{min}}{{}^\circ\text{Longitude}}\right)\left[\begin{pmatrix}\text{standard}\\ \text{meridian}\\ \text{longitude}\end{pmatrix} - \begin{pmatrix}\text{local}\\ \text{longitude}\end{pmatrix}\right] - EoT$$

Equation of Time: $EoT = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B)$ in minutes

$$B = \frac{360}{365}(N - 81)$$

Answer: I_{BN} = 343 W/m^2

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Problem 45 (ME405f24h9)

(a) Find the solar altitude angle at 12:00 local clock time in Ankara, on December 21.

(b) Find the sunrise and sunset times in Ankara on that day.

For Ankara: Latitude L = 39.9255°

Longitude = 32.8663°

$I_{BN} = I_B \cos(\theta)$

Angle of incidence: $\cos\theta = (\sin\beta_1)(\cos\beta_2) + (\cos\beta_1)(\sin\beta_2)(\cos\delta)$

Declination angle in degrees: $\delta = (23.45^\circ)\ \sin\left(\frac{360}{365}(284 + N)\right)$, $1 \le N \le 365$

Solar altitude angle: $\sin(\beta_1) = \cos(L)\cos(\delta)\cos(H) + \sin(L)\sin(\delta)$

Standard Meridian Longitude: 45°

$$\text{Local Solar Time: LST} = \begin{pmatrix}\text{local}\\ \text{standard}\\ \text{time}\end{pmatrix} + (4\ \text{min})\left[\begin{pmatrix}\text{local}\\ \text{longitude}\end{pmatrix} - \begin{pmatrix}\text{standard}\\ \text{meridian}\\ \text{longitude}\end{pmatrix}\right] + \text{EoT}$$

Equation of Time: EoT = 9.87 sin(2 B) - 7.53 cos(B) - 1.5 sin(B) in minutes

$$B = \frac{360}{365}(N - 81)$$

Answer: (a) β_1 = 25.68 deg (b) Sunrise time = 4 hours and 35 minutes before solar noon

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Problem 46 (ME405f23h8)

On a spring day (which happens to be the day of the spring equinox) a group of engineering students have gathered for a picnic at solar noon in Eslöv, Sweden (55.83º N, 13.30º E). One of them has brought a home-built electric stove powered by a PV array, but the others are unsure if it will be able to collect enough solar energy. At solar noon on this day, the horizontal plane receives 621 W/m^2 of global radiation, of which 236 W/m^2 are diffuse.

(a) It is decided that the PV array is oriented to collect as much beam radiation as possible at solar noon. Which tilt and azimuth angles should be chosen?

(b) Assuming that the ground has an albedo of 20%, how much diffuse, beam and ground-reflected radiation does the array collect at this orientation?

Answer: $I_{b,tilt}$ = 685.48 W/m^2 $I_{d,tilt}$ = 302.24 W/m^2 $I_{g,tilt}$ = 27.2 W/m^2

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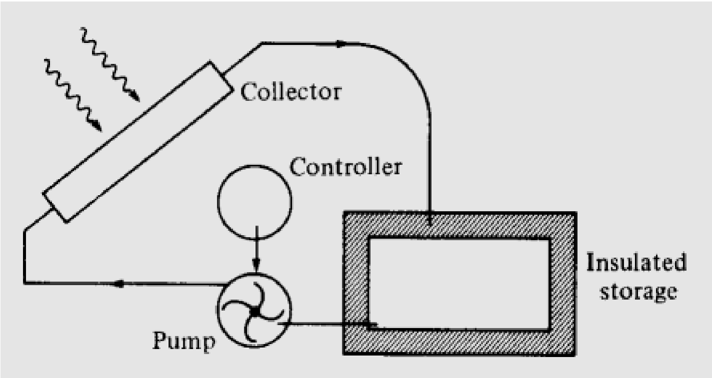
Problem 47 (ME405f23m-2)



A flat plate collector measuring 2 m × 0.8 m has an overall heat-loss resistance R_L = 0.13 m^2.K/W and a plate efficiency η_p = 0.85. The glass cover has transmittance τ = 0.9 and the absorptance of the plate is α = 0.9. Water enters at a temperature T_1 = 40 °C. The ambient temperature is T_a = 20 °C and the irradiance on the collector is I = 750 W/m^2. Assume the plate temperature to be T_p = 42 °C.

(a) Calculate the volumetric flow rate, $\dot{v}$ in m^3/s and L/hour, needed to produce a temperature rise of 4 °C.

(b) Suppose the pump continues to work at night, when I = 0. What will be the temperature fall in each passage through the collector? (Assume that T_p = 38 °C and T_a = 20 °C.)

Density of water = 1000 kg/m^3

Specific heat of water = 4180 J/kg.K

Plate efficiency: $\eta_p = \dfrac{\text{Heat given to the water}}{\text{Heat absorbed by the plate - heat loss to the environment}}$

Answers: (a) $\dot{v}$ = 128.3 L/h (b) $T_2 - T_1$ = - 1.26 °C

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Problem 48

What are the advantages and disadvantages of having a glass cover (glazing) over a flat plate solar collector? Cite three factors for each

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Problem 49

Find the solar data, H (daily integrated insolation in MJ/day) and K_T (average clearness index), for as many cities in Turkey as you can.

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