7.18 Consider the photovoltaic solar panel of Example 3.3. The heat transfer coefficient should no longer be taken to be a specified value.

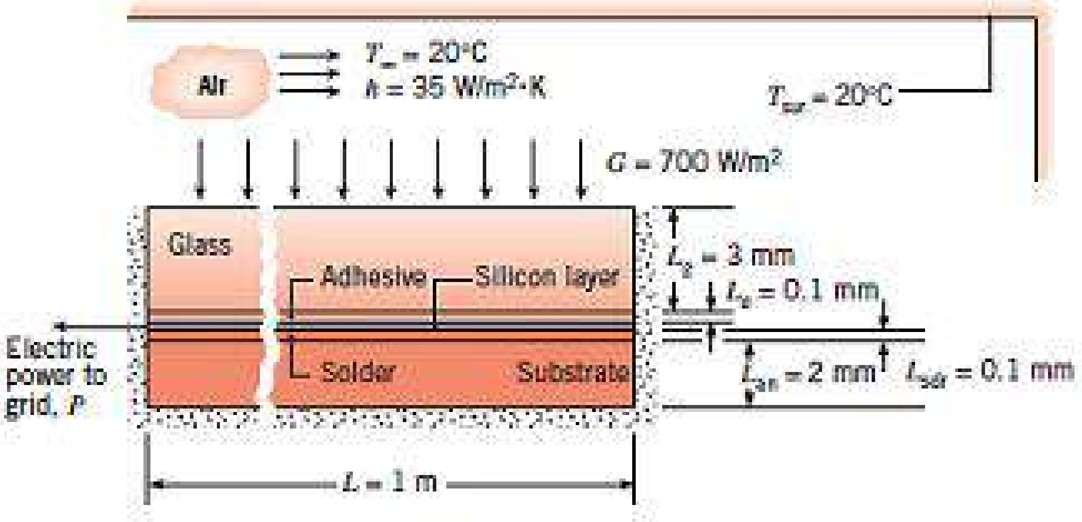
(a) Determine the silicon temperature and the electric power produced by the solar cell for an air velocity of 4 m/s parallel to the long direction, with air and surroundings temperatures of 20°C. The boundary layer is tripped to a turbulent condition at the leading edge of the panel.

(b) Repeat part (a), except now the panel is oriented with its short side parallel to the airflow, that is, $L = 0.1$ m and $w = 1$ m.

(c) Plot the electric power output and the silicon temperature versus air velocity over the range $0 \leq u_\infty \leq 10$ m/s for the $L = 0.1$ m and $w = 1$ m case.

EXAMPLE 3.3

A photovoltaic panel consists of (top to bottom) a 3-mm-thick ceria-doped glass ($k_g = 1.4$ W/m·K), a 0.1-mm-thick optical grade adhesive ($k_a = 145$ W/m·K), a *very thin* layer of silicon within which solar energy is converted to electrical energy, a 0.1-mm-thick solder layer ($k_{sdr} = 50$ W/m·K), and a 2-mm-thick aluminum nitride substrate ($k_{sn} = 120$ W/m·K). The solar-to-electrical conversion efficiency within the silicon layer η decreases with increasing silicon temperature, T_{si}, and is described by the expression $\eta = a - bT_{si}$, where $a = 0.553$ and $b = 0.001\ \mathrm{K}^{-1}$. The temperature T is expressed in kelvins over the range $300\ \mathrm{K} \le T_{si} \le 525\ \mathrm{K}$. Of the incident solar irradiation, $G = 700\ \mathrm{W/m^2}$, 7% is reflected from the top surface of the glass, 10% is absorbed at the top surface of the glass, and 83% is transmitted to and absorbed within the silicon layer. Part of the solar irradiation absorbed in the silicon is converted to thermal energy, and the remainder is converted to electrical energy. The glass has an emissivity of $\varepsilon = 0.90$, and the bottom as well as the sides of the panel are insulated. Determine the electric power P produced by an $L = 1$-m-long, $w = 0.1$-m-wide solar panel for conditions characterized by $h = 35\ \mathrm{W/m^2 \cdot K}$ and $T_\infty = T_{sur} = 20°\mathrm{C}$.

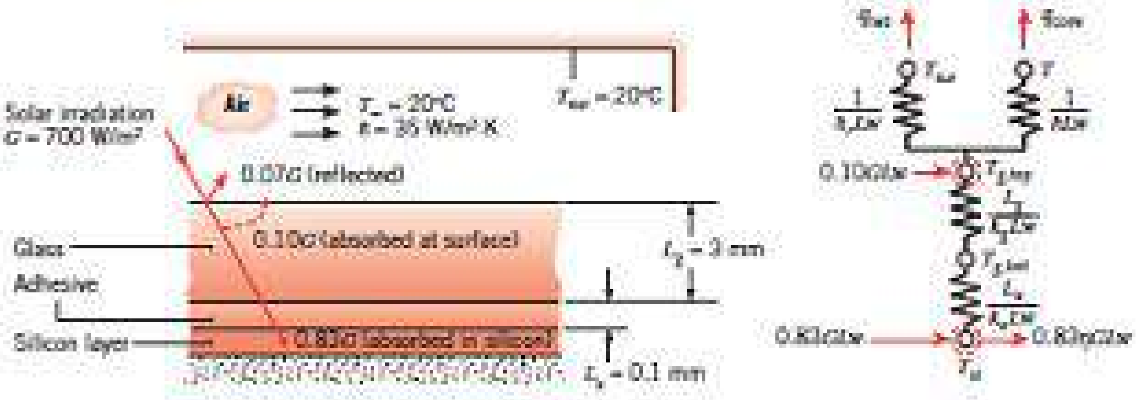


SOLUTION

Known: Dimensions and materials of a photovoltaic solar panel. Material properties, solar irradiation, convection coefficient and ambient temperature, emissivity of top panel surface and surroundings temperature. Partitioning of the solar irradiation, and expression for the solar-to-electrical conversion efficiency.

Find: Electric power produced by the photovoltaic panel.

Schematic:



Assumptions:

1. Steady-state conditions.
2. One-dimensional heat transfer.
3. Constant properties.
4. Negligible thermal contact resistances.
5. Negligible temperature differences within the silicon layer.

Analysis: Recognize that there is no heat transfer to the bottom insulated surface of the solar panel. Hence, the solder layer and aluminum nitride substrate do not affect the solution, and all of the solar energy absorbed by the panel must ultimately leave the panel in the form of radiation and convection heat transfer from the top surface of the glass, and electric power to the grid, $P = \eta 0.83\,GLw$. Performing an energy balance on the node associated with the silicon layer yields

$$0.83\,GLw - \eta 0.83\,GLw = \frac{T_{si} - T_{g,top}}{\dfrac{L_a}{k_a Lw} + \dfrac{L_g}{k_g Lw}}$$

Substituting the expression for the solar-to-electrical conversion efficiency and simplifying leads to

$$0.83\,G(1 - a + bT_{si}) = \frac{T_{si} - T_{g,top}}{\dfrac{L_a}{k_a} + \dfrac{L_g}{k_g}} \qquad (1)$$

Performing a second energy balance on the node associated with the top surface of the glass gives

$$0.83\,GLw(1 - \eta) + 0.1\,GLw = hLw(T_{g,top} - T_\infty) + \varepsilon\sigma Lw(T_{g,top}^4 - T_{sur}^4)$$

Substituting the expression for the solar-to-electrical conversion efficiency into the preceding equation and simplifying provides

$$0.83\,G(1 - a + bT_{si}) + 0.1\,G = h(T_{g,top} - T_\infty) + \varepsilon\sigma(T_{g,top}^4 - T_{sur}^4) \qquad (2)$$

Finally, substituting known values into Equations 1 and 2 and solving simultaneously yields $T_{si} = 307\text{ K} = 34°\text{C}$, providing a solar-to-electrical conversion efficiency of $\eta = 0.553 - 0.001\text{ K}^{-1} \times 307\text{ K} = 0.247$. Hence, the power produced by the photovoltaic panel is

$$P = \eta 0.83\, GLw = 0.247 \times 0.83 \times 700\text{ W/m}^2 \times 1\text{ m} \times 0.1\text{ m} = 14.3\text{ W} \qquad \triangleleft$$

Comments:

1. The correct application of the conservation of energy requirement is crucial to determining the silicon temperature and the electric power. Note that solar energy is converted to *both* thermal and electrical energy, and the thermal circuit is used to quantify *only* the thermal energy transfer.
2. Because of the thermally insulated boundary condition, it is not necessary to include the solder or substrate layers in the analysis. This is because there is no conduction through these materials and, from Fourier's law, there can be no temperature gradients within these materials. At steady state, $T_{sdr} = T_{an} = T_{si}$.
3. As the convection coefficient increases, the temperature of the silicon decreases. This leads to a higher solar-to-electrical conversion efficiency and increased electric power output. Similarly, higher silicon temperatures and less power production are associated with smaller convection coefficients. For example, $P = 13.6\text{ W}$ and 14.6 W for $h = 15\text{ W/m}^2 \cdot \text{K}$ and $55\text{ W/m}^2 \cdot \text{K}$, respectively.
4. The cost of a photovoltaic system can be reduced significantly by *concentrating* the solar energy onto the relatively expensive photovoltaic panel using inexpensive focusing mirrors or lenses. However, good thermal management then becomes even more important. For example, if the irradiation supplied to the panel were increased to $G = 7{,}000\text{ W/m}^2$ through concentration, the conversion efficiency drops to $\eta = 0.160$ as the silicon temperature increases to $T_{si} = 119°\text{C}$, even for $h = 55\text{ W/m}^2 \cdot \text{K}$. A key to reducing the cost of photovoltaic power generation is developing innovative cooling technologies for use in concentrating photovoltaic systems.
5. The simultaneous solution of Equations 1 and 2 may be achieved by using *IHT*, another commercial code, or a handheld calculator. A trial-and-error solution could also be obtained, but with considerable effort. Equations 1 and 2 could be combined to write a single transcendental expression for the silicon temperature, but the equation must still be solved numerically or by trial-and-error.