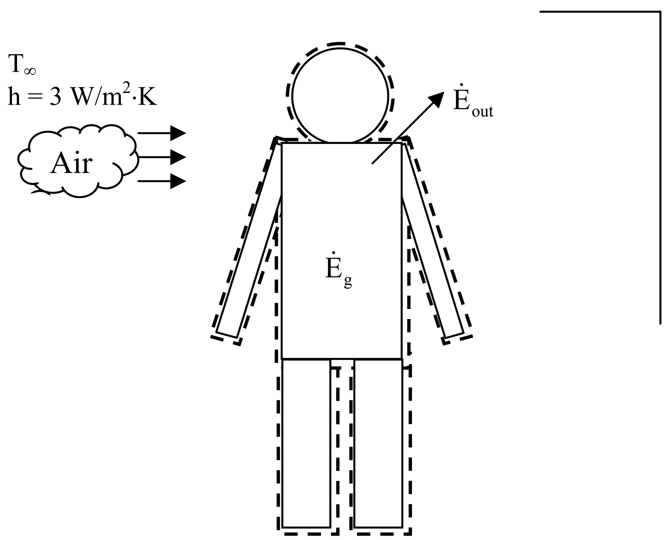
PROBLEM 1.74

KNOWN: Daily thermal energy generation, surface area, temperature of the environment, and heat transfer coefficient.

FIND: (a) Skin temperature when the temperature of the environment is 20ºC, and (b) Rate of perspiration to maintain skin temperature of 33ºC when the temperature of the environment is 33ºC.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state conditions, (2) Thermal energy is generated at a constant rate throughout the day, (3) Air and surrounding walls are at same temperature, (4) Skin temperature is uniform, (5) Bathing suit has no effect on heat loss from body, (6) Heat loss is by convection and radiation to the environment, and by perspiration in Part 2. (Heat loss due to respiration, excretion of waste, etc., is negligible.), (7) Large surroundings.

PROPERTIES: Table A.11, skin: $\varepsilon = 0.95$, Table A.6, water (306 K): $\rho = 994\ kg/m^3$, $h_{fg} = 2421$ kJ/kg.

ANALYSIS:
(a) The rate of energy generation is:

$$\dot{E}_g = 2000 \times 10^3\ \text{cal/day} \big/ (0.239\ \text{cal/J} \times 86{,}400\ \text{s/day}) = 96.9\ \text{W}$$

Under steady-state conditions, an energy balance on the human body yields:

$$\dot{E}_g - \dot{E}_{out} = 0$$

Thus $\dot{E}_{out} = q = 96.9$ W. Energy outflow is due to convection and net radiation from the surface to the environment, Equations 1.3a and 1.7, respectively.

$$\dot{E}_{out} = hA(T_s - T_\infty) + \varepsilon\sigma A(T_s^4 - T_{sur}^4)$$

Substituting numerical values

Continued…

$$96.9\text{ W} = 3\text{ W/m}^2\cdot\text{K}\times 1.8\text{ m}^2 \times (T_s - 293\text{ K})$$
$$+ 0.95 \times 5.67 \times 10^{-8}\text{ W/m}^2\cdot\text{K}^4 \times 1.8\text{ m}^2 \times (T_s^4 - (293\text{ K})^4)$$

and solving either by trial-and-error or using *IHT* or other equation solver, we obtain

$$T_s = 299\text{ K} = 26^\circ\text{C}$$ <

Since the comfortable range of skin temperature is typically 32 – 35ºC, we usually wear clothing warmer than a bathing suit when the temperature of the environment is 20ºC.

(b) If the skin temperature is 33ºC when the temperature of the environment is 33ºC, there will be no heat loss due to convection or radiation. Thus, all the energy generated must be removed due to perspiration:

$$\dot{E}_{out} = \dot{m}h_{fg}$$

We find:

$$\dot{m} = \dot{E}_{out}/h_{fg} = 96.9\text{ W}/2421\text{ kJ/kg} = 4.0\times 10^{-5}\text{ kg/s}$$

This is the perspiration rate in mass per unit time. The volumetric rate is:

$$\dot{\forall} = \dot{m}/\rho = 4.0\times 10^{-5}\text{ kg/s} / 994\text{ kg/m}^3 = 4.0\times 10^{-8}\text{ m}^3\text{/s} = 4.0\times 10^{-5}\ \ell\text{/s}$$ <

COMMENTS: (1) In Part 1, heat losses due to convection and radiation are 32.4 W and 60.4 W, respectively. Thus, it would not have been reasonable to neglect radiation. Care must be taken to include radiation when the heat transfer coefficient is small, even if the problem statement does not give any indication of its importance. (2) The rate of thermal energy generation is not constant throughout the day; it adjusts to maintain a constant core temperature. Thus, the energy generation rate may decrease when the temperature of the environment goes up, or increase (for example, by shivering) when the temperature of the environment is low. (3) The skin temperature is not uniform over the entire body. For example, the extremities are usually cooler. Skin temperature also adjusts in response to changes in the environment. As the temperature of the environment increases, more blood flow will be directed near the surface of the skin to increase its temperature, thereby increasing heat loss. (4) If the perspiration rate found in Part 2 was maintained for eight hours, the person would lose 1.2 liters of liquid. This demonstrates the importance of consuming sufficient amounts of liquid in warm weather.