Thermodynamics I

Lecture 9

Practice Problems (Ch-2)

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(P-1)

Natural gas, which is mostly methane CH_4, is a fuel and a major energy source. Can we say the same about hydrogen gas, H_2?

(P-2)

Calculate the total kinetic energy, in Btu, of an object with a mass of 10 lbm when its velocity is 50 ft/s.

$$\text{KE} = m\frac{V^2}{2}$$

$$\cancel{=(10\ \text{lb}\ldots \frac{\ldots\text{ft/s})^2}{2}}$$

$$=(10\ \text{lbm})\frac{(50\ \text{ft/s})^2}{2}\left(\frac{1\ \text{Btu/lbm}}{25{,}037\ \text{ft}^2/\text{s}^2}\right) = 0.499\ \text{Btu} \cong \mathbf{0.50\ Btu}$$

(P-3)

Calculate the total potential energy, in Btu, of an object with a mass of 200 lbm when it is 10 ft above a datum level at a location where standard gravitational acceleration exists.

$$\mathrm{PE} = mgz$$

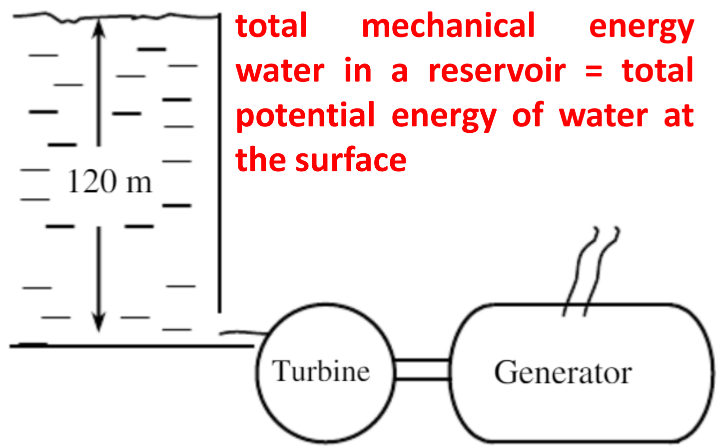
$$(200\ \mathrm{lbm})(32.2\ \mathrm{ft/s^2})(10\ \mathrm{ft})\left(\frac{1\ \mathrm{Btu/lbm}}{25{,}037\ \mathrm{ft^2/s^2}}\right) = \mathbf{2.57\ Btu}$$

What if asked for:

- **Specific Potential Energy**
- **Specific Kinetic Energy**

(P-4)

Electric power is to be generated by installing a hydraulic turbine–generator at a site 120 m below the free surface of a large water reservoir that can supply water at a rate of 2400 kg/s steadily. Determine the power generation potential.



total mechanical energy water in a reservoir = total potential energy of water at the surface

Therefore, the power potential of water is its potential energy, which is gz p[illegible]ss

$$e_{\text{mech}} = pe = gz = (9.81 \ldots)\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 1.177\ \text{kJ/kg}$$

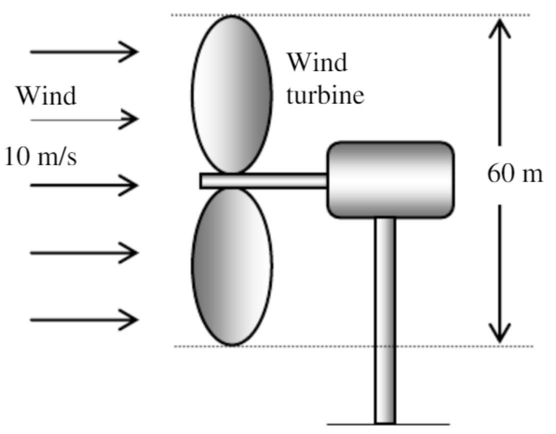
$$\dot{W}_{\text{max}} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}}$$

$$= (2400\ \text{kg/s})(1.177\ \text{kJ/kg})\left(\frac{1\ \text{kW}}{1\ \text{kJ/s}}\right) = \mathbf{2825\ kW}$$

(P-5)

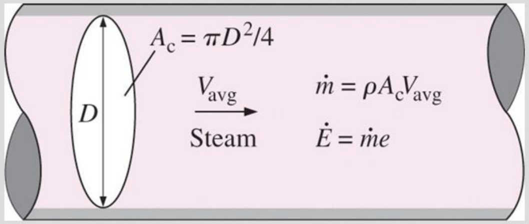
At a certain location, wind is blowing steadily at 10 m/s. Determine the mechanical energy of air per unit mass and the power generation potential of a wind turbine with 60-m-diameter blades at that location. Take the air density to be 1.25 kg/m³.

$$\dot{W}_{max} = \dot{E}_{mech} = \dot{m}e_{mech}$$



$$e_{mech} = ke = \frac{V^2}{2} = \frac{(10\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 0.050\text{ kJ/kg}$$

If you remember



Mass flow rate

$$\dot{m} = \rho\dot{V} = \rho A_c V_{avg} \qquad \text{(kg/s)}$$

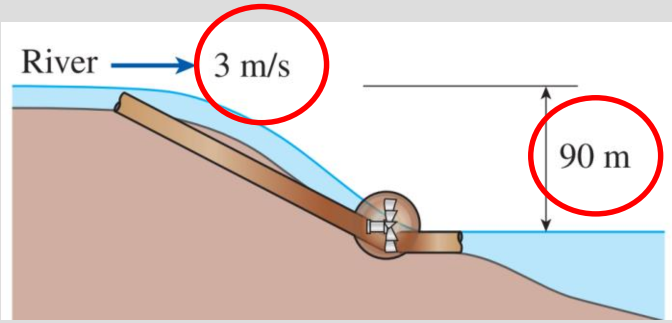
$$= (1.25\text{ kg/m}^3)(10\text{ m/s})\frac{\pi(60\text{ m})^2}{4} = 35{,}340\text{ kg/s}$$

$$\dot{W}_{max} = \dot{E}_{mech} = \dot{m}e_{mech} = (35{,}340\text{ kg/s})(0.050\text{ kJ/kg}) = \mathbf{1770\ kW}$$

(P-6)

Consider a river flowing toward a lake at an average velocity of 3 m/s at a rate of 500 m3/s at a location 90 m above the lake surface. Determine the total mechanical energy of the river water per unit mass and the power generation potential of the entire river at that location.

$$\dot{W}_{max} = \dot{E}_{mech} = \dot{m}e_{mech}$$



$$e_{mech} = pe + ke = gh + \frac{V^2}{2} = \left((9.81\,\text{m/s}^2)(90\,\text{m}) + \frac{(3\,\text{m/s})^2}{2}\right)\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = \mathbf{0.887 kJ/kg}$$

$$\dot{m} = \rho\dot{V} = (1000\,\text{kg/m}^3)(500\,\text{m}^3/\text{s}) = 500{,}000\,\text{kg/s}$$

$$\dot{W}_{max} = \dot{E}_{mech} = \dot{m}e_{mech} = (500{,}000\,\text{kg/s})(0.887\ \text{kJ/kg}) = 444{,}000\,\text{kW} = \mathbf{444\ MW}$$

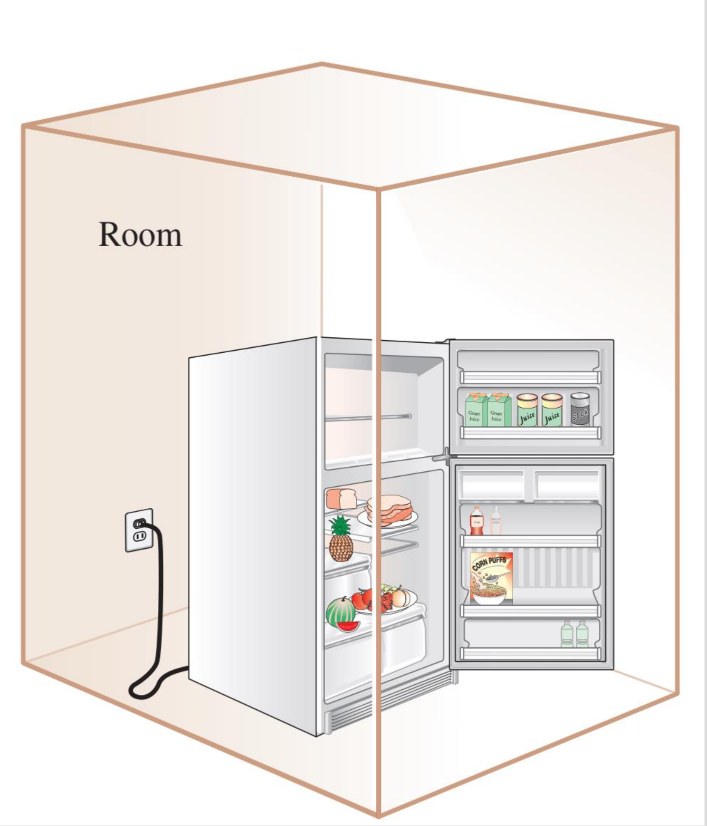
(P-7)

Consider an electric refrigerator located in a room. Determine the direction of the work and heat interactions (in or out) when the following are taken as the system:

(a) the contents of the refrigerator,

(b) all parts of the refrigerator including the contents, and

(c) everything contained within the room during a winter day.



(P-8)

A gas in a piston-cylinder device is compressed, and as a result its temperature rises. Is this a heat or work interaction?

It is a work interaction.

(P-9)

A man weighing 180 lbf is pushing a cart that weighs 100 lbf with its contents up a ramp that is inclined at an angle of 10 from the horizontal. Determine the work needed to move along this ramp a distance of 100 ft considering (a) the man and (b) the cart and its contents as the system. Express your answers in both lbf·ft and Btu.

(a) Considering the man as the system, letting l be the displacement along the ramp, and letting θ be the inclination angle of the ramp,

$$W = Fl\sin\theta$$

$$= (100+180\ \text{lbf})(100\ \text{ft})\sin(10) = \mathbf{4862\,lbf\cdot ft}$$

$$= (4862\ \text{lbf}\cdot\text{ft})\left(\frac{1\ \text{Btu}}{778.169\ \text{lbf}\cdot\text{ft}}\right) = \mathbf{6.248\,Btu}$$

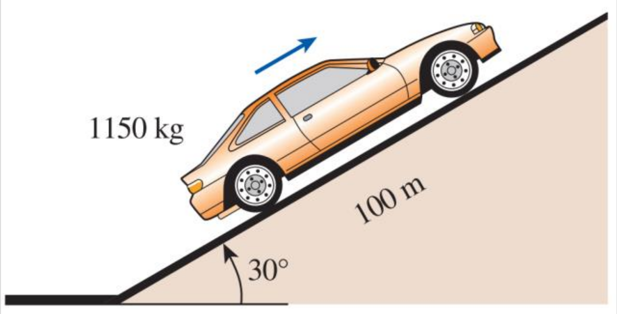
(b) Applying the same logic to the cart and its contents gives

$$W = Fl\sin\theta = (100\ \text{lbf})(100\ \text{ft})\sin(10) = \mathbf{1736\,lbf\cdot ft}$$

$$= (1736\ \text{lbf}\cdot\text{ft})\left(\frac{1\ \text{Btu}}{778.169\ \text{lbf}\cdot\text{ft}}\right) = \mathbf{2.231\,Btu}$$

(P-11)

Determine the power required for a 1150-kg car to climb a 100-m-long uphill road with a slope of 30 degree (from horizontal) in 12 s (a) at a constant velocity, (b) from rest to a final velocity of 30 m/s, and (c) from 35 m/s to a final velocity of 5 m/s. Disregard friction, air drag, and rolling resistance.



The total power required for each case is the sum of the rates of changes in potential and kinetic energies. That is,

$$\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g$$

(a) $\dot{W}_a = 0$ since the velocity is constant. Also, the vertical rise is h = (100 m)(sin 30°) = 50 m. Thus,

$$\dot{W}_g = mg(z_2 - z_1) / \Delta t$$

$$= (1150\text{ kg})(9.81\text{ m/s}^2)(50\text{ m})\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right)/(12\text{ s}) = 47.0\text{ kW}$$

(P-11)

(*b*) The power needed to accelerate is

$$\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g$$

$$\dot{W}_a = \frac{1}{2}m(V_2^2 - V_1^2) / \Delta t$$

$$= \frac{1}{2}(1150 \text{ kg})\left[(30 \text{ m/s})^2 - 0\right]\left(\frac{1 \text{ kJ}}{1000 \text{ kg} \cdot \text{m}^2/\text{s}^2}\right)/(12 \text{ s}) = 43.1 \text{ kW}$$

$$\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = 47.0 + 43.1 = \mathbf{90.1\ kW}$$

(*c*) The power needed to decelerate is

$$\dot{W}_a = \frac{1}{2}m(V_2^2 - V_1^2) / \Delta t$$

$$= \frac{1}{2}(1150 \text{ kg})\left[(5 \text{ m/s})^2 - (35 \text{ m/s})^2\right]\left(\frac{1 \text{ kJ}}{1000 \text{ kg} \cdot \text{m}^2/\text{s}^2}\right)/(12 \text{ s}) = -57.5 \text{ kW}$$

$$\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = -57.5 + 47.1 = \mathbf{-10.5\ kW} \quad \text{(breaking power)}$$

(P-11)

A vertical piston-cylinder device contains water and is being heated on top of a range. During the process, 65 Btu of heat is transferred to the water, and heat losses from the side walls amount to 8 Btu. The piston rises as a result of evaporation, and 5 Btu of work is done by the vapor. Determine the change in the energy of the water for this process.

If you remember

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

$$Q_{in} - W_{out} - Q_{out} = \Delta U = U_2 - U_1$$

$$65\text{ Btu} - 5\text{ Btu} - 8\text{ Btu} = \Delta U$$

$$\Delta U = U_2 - U_1 = \textbf{52 Btu}$$

What is the significance/physical interpretation?

(P-12)

A classroom that normally contains 40 people is to be air-conditioned with window air-conditioning units of 5-kW cooling capacity. A person at rest may be assumed to dissipate heat at a rate of about 360 kJ/h. There are 10 lightbulbs in the room, each with a rating of 100 W. The rate of heat transfer to the classroom through the walls and the windows is estimated to be 15,000 kJ/h. If the room air is to be maintained at a constant temperature of 21 degree, determine the number of window air-conditioning units required.

The total cooling load of the room is determined from

$$\dot{Q}_{\text{cooling}} = \dot{Q}_{\text{lights}} + \dot{Q}_{\text{people}} + \dot{Q}_{\text{heat gain}}$$

$$\dot{Q}_{\text{lights}} = 10 \times 100 \text{ W} = 1 \text{ kW}$$

$$\dot{Q}_{\text{people}} = 40 \times 360 \text{ kJ / h} = 4 \text{ kW}$$

$$\dot{Q}_{\text{heat gain}} = 15{,}000 \text{ kJ / h} = 4.17 \text{ kW}$$

$$= 9.17 \text{ kW}$$

Thus the number of air-conditioning units required is

$$\frac{9.17 \text{ kW}}{5 \text{ kW/unit}} = 1.83 \longrightarrow \textbf{2 units}$$

(P-13)

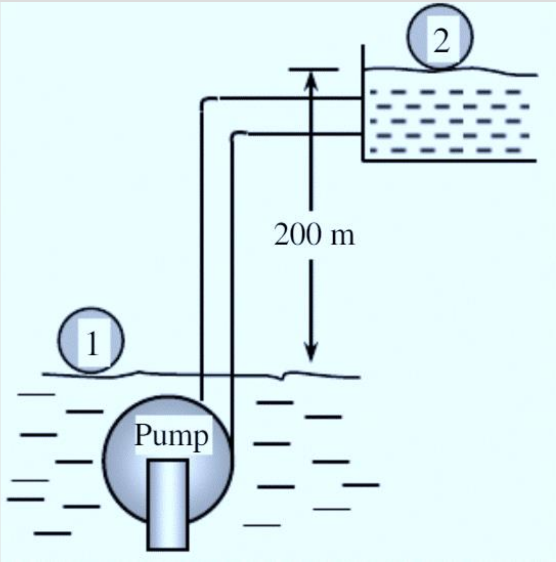
A geothermal pump is used to pump brine whose density is 1050 kg/m3 at a rate of 0.3 m^3/s from a depth of 200 m. For a pump efficiency of 74 percent, determine the required power input to the pump. Disregard frictional losses in the pipes, and assume the geothermal water at 200 m depth to be exposed to the atmosphere.

$$\Delta \dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\Delta pe$$

$$= \dot{m}g\Delta z = \rho \dot{V} g \Delta z$$

$$= (1050\ \text{kg/m}^3)(0.3\ \text{m}^3/\text{s})(9.81\ \text{m/s}^2)(200\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kW}}{1000\ \text{N}\cdot\text{m/s}}\right)$$

$$= 618.0\ \text{kW}$$

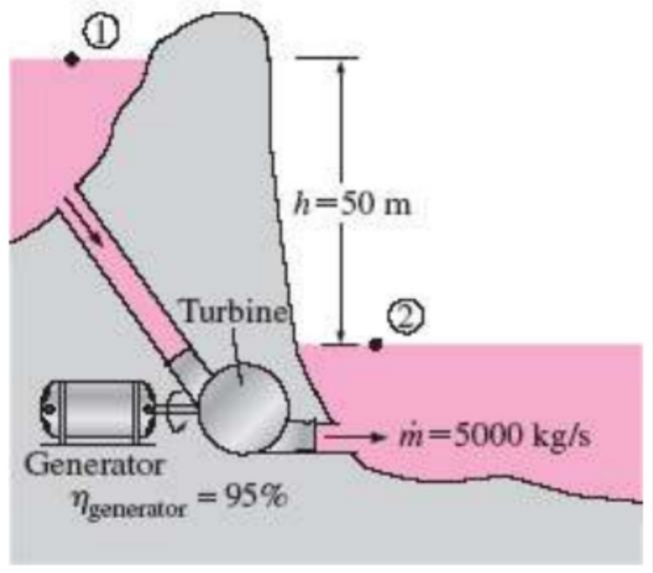


Then the required power input to the pump becomes

$$\dot{W}_{\text{pump,elect}} = \frac{\Delta \dot{E}_{\text{mech}}}{\eta_{\text{pump-motor}}} = \frac{618\ \text{kW}}{0.74} = \mathbf{835kW}$$

(P-14)

The water in a large lake is to be used to generate electricity by the installation of a hydraulic turbine-generator at a location where the depth of the water is 50 m. Water is to be supplied at a rate of 5000 kg/s. If the electric power generated is measured to be 1862 kW and the generator efficiency is 95 percent, determine (a) the overall efficiency of the turbine—generator, (b) the mechanical efficiency of the turbine, and (c) the shaft power supplied by he turbine to the generator.



(a) We take the bottom of the lake as the reference level for convenience. Then kinetic and potential energies of water are zero, and the mechanical energy of water consists of pressure energy only which is

$$e_{\text{mech,in}} - e_{\text{mech,out}} = \frac{P}{\rho} = gh$$

$$= (9.81\,\text{m/s}^2)(50\,\text{m})\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right)$$

$$= 0.491\,\text{kJ/kg}$$

Then the rate at which mechanical energy of fluid supplied to the turbine and the overall efficiency become

$$|\Delta\dot{E}_{\text{mech,fluid}}| = \dot{m}(e_{\text{mech,in}} - e_{\text{mech,in}}) = (5000\,\text{kg/s})(0.491\,\text{kJ/kg}) = 2455\,\text{kW}$$

(P-14)

$$\eta_{\text{overall}} = \eta_{\text{turbine-gen}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta\dot{E}_{\text{mech,fluid}}|} = \frac{1862\text{ kW}}{2455\text{ kW}} = \mathbf{0.760}$$

(b) Knowing the overall and generator efficiencies, the mechanical efficiency of the turbine is determined from

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}}$$

$$\eta_{\text{turbine}} = \frac{\eta_{\text{turbine-gen}}}{\eta_{\text{generator}}} = \frac{0.76}{0.95} = \mathbf{0.800}$$

(c) The shaft power output is determined from the definition of mechanical efficiency,

$$\dot{W}_{\text{shaft,out}} = \eta_{\text{turbine}}|\Delta\dot{E}_{\text{mech,fluid}}|$$

$$= (0.800)(2455\text{ kW}) = 1964\text{ kW} \approx \mathbf{1960kW}$$

(P-15)

A geothermal power plant in Nevada is generating electricity using geothermal water extracted at 180°C, and reinjected back to the ground at 85°C. It is proposed to utilize the reinjected brine for heating the residential and commercial buildings in the area, and calculations show that the geothermal heating system can save 18 million therms of natural gas a year. Determine the amount of NO_x and CO_2 emissions the geothermal system will save a year. Take the average NO_x and CO_2 emissions of gas furnaces to be 0.0047 kg/therm and 6.4 kg/therm, respectively.

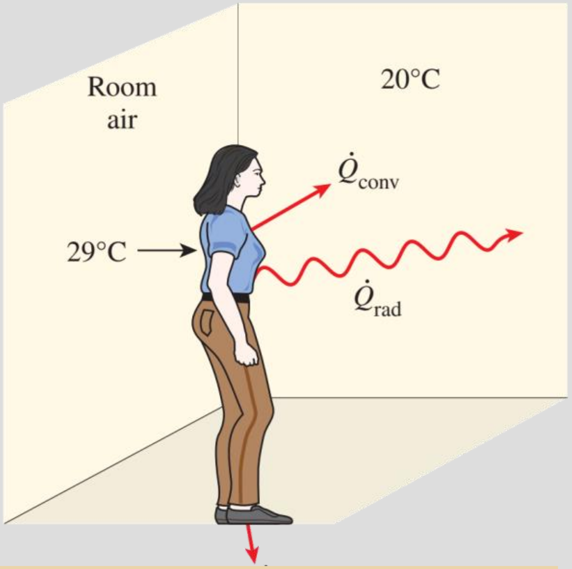
$$
\begin{aligned}
NO_x \text{ savings} &= (NO_x \text{ emission per therm})(\text{No. of therms per year}) \\
&= (0.0047 \text{ kg/therm})(18 \times 10^6 \text{ therm/year}) \\
&= \mathbf{8.5 \times 10^4 \text{ kg/year}}
\end{aligned}
$$

$$
\begin{aligned}
CO_2 \text{ savings} &= (CO_2 \text{ emission per therm})(\text{No. of therms per year}) \\
&= (6.4 \text{ kg/therm})(18 \times 10^6 \text{ therm/year}) \\
&= \mathbf{1.2 \times 10^8 \text{ kg/year}}
\end{aligned}
$$

Discussion A typical car on the road generates about 8.5 kg of NO_x and 6000 kg of CO_2 a year. Therefore the environmental impact of replacing the gas heating systems in the area by the geothermal heating system is equivalent to taking 10,000 cars off the road for NO_x emission and taking 20,000 cars off the road for CO_2 emission. The proposed system should have a significant effect on reducing smog in the area.

EXAMPLE 2–18 Heat Transfer from a Person

Consider a person standing in a breezy room at 20°C. Determine the total rate of heat transfer from this person if the exposed surface area and the average outer surface temperature of the person are 1.6 m^2 and 29°C, respectively, and the convection heat transfer coefficient is 6 $W/m^2{\cdot}°C$ (Fig. 2–75).



$$\begin{aligned}\dot{Q}_{conv} &= hA(T_s - T_f)\\ &= (6\ W/m^2{\cdot}°C)(1.6\ m^2)(29 - 20)°C\\ &= 86.4\ W\end{aligned}$$

$$\begin{aligned}\dot{Q}_{rad} &= \varepsilon\sigma A(T_s^4 - T_{surr}^4)\\ &= (0.95)(5.67 \times 10^{-8}\ W/m^2{\cdot}K^4)(1.6\ m^2) \times [(29 + 273)^4 - (20 + 273)^4]K^4\\ &= 81.7\ W\end{aligned}$$

$$\dot{Q}_{total} = \dot{Q}_{conv} + \dot{Q}_{rad} = 86.4 + 81.7 = \mathbf{168.1\ W}$$