Solutions Manual for

Thermodynamics: An Engineering Approach

Seventh Edition

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Chapter 2

ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS

Forms of Energy

2-1C The *macroscopic* forms of energy are those a system possesses as a whole with respect to some outside reference frame. The *microscopic* forms of energy, on the other hand, are those related to the molecular structure of a system and the degree of the molecular activity, and are independent of outside reference frames.

2-2C The sum of all forms of the energy a system possesses is called *total energy*. In the absence of magnetic, electrical and surface tension effects, the total energy of a system consists of the kinetic, potential, and internal energies.

2-3C Thermal energy is the sensible and latent forms of internal energy, and it is referred to as heat in daily life.

2-4C The *mechanical energy* is the form of energy that can be converted to mechanical work completely and directly by a mechanical device such as a propeller. It differs from thermal energy in that thermal energy cannot be converted to work directly and completely. The forms of mechanical energy of a fluid stream are kinetic, potential, and flow energies.

2-5C Hydrogen is also a fuel, since it can be burned, but it is not an energy source since there are no hydrogen reserves in the world. Hydrogen can be obtained from water by using another energy source, such as solar or nuclear energy, and then the hydrogen obtained can used as a fuel to power cars or generators. Therefore, it is more proper to view hydrogen is an energy carrier than an energy source.

2-6E The total kinetic energy of an object is given is to be determined.

Analysis The total kinetic energy of the object is given by

$$\mathrm{KE} = m\frac{V^2}{2} = (15\ \mathrm{lbm})\frac{(100\ \mathrm{ft/s})^2}{2}\left(\frac{1\ \mathrm{Btu/lbm}}{25{,}037\ \mathrm{ft^2/s^2}}\right) = \mathbf{3.00\ Btu}$$

2-7 The total kinetic energy of an object is given is to be determined.

Analysis The total kinetic energy of the object is given by

$$\mathrm{KE} = m\frac{V^2}{2} = (100\ \mathrm{kg})\frac{(20\ \mathrm{m/s})^2}{2}\left(\frac{1\ \mathrm{kJ/kg}}{1000\ \mathrm{m^2/s^2}}\right) = \mathbf{20.0\ kJ}$$

2-8E The specific potential energy of an object is to be determined.

Analysis In the English unit system, the specific potential energy in Btu is given by

$$\text{pe} = gz = (32.1\,\text{ft/s}^2)(100\,\text{ft})\left(\frac{1\,\text{Btu/lbm}}{25{,}037\,\text{ft}^2/\text{s}^2}\right) = \mathbf{0.128\ Btu/lbm}$$

2-9E The total potential energy of an object is to be determined.

Analysis Substituting the given data into the potential energy expression gives

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

2-10 The total potential energy of an object that is below a reference level is to be determined.

Analysis Substituting the given data into the potential energy expression gives

$$\text{PE} = mgz = (20\,\text{kg})(9.5\,\text{m/s}^2)(-20\,\text{m})\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = \mathbf{-3.8\ kJ}$$

2-11 A person with his suitcase goes up to the 10^{th} floor in an elevator. The part of the energy of the elevator stored in the suitcase is to be determined.

Assumptions **1** The vibrational effects in the elevator are negligible.

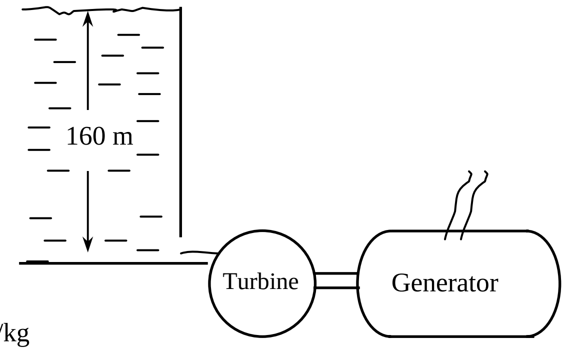
Analysis The energy stored in the suitcase is stored in the form of potential energy, which is *mgz*. Therefore,

$$\Delta E_{\text{suitcase}} = \Delta PE = mg\Delta z = (30\,\text{kg})(9.81\,\text{m/s}^2)(35\,\text{m})\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = \mathbf{10.3\ kJ}$$

Therefore, the suitcase on 10^{th} floor has 10.3 kJ more energy compared to an identical suitcase on the lobby level.

Discussion Noting that 1 kWh = 3600 kJ, the energy transferred to the suitcase is 10.3/3600 = 0.0029 kWh, which is very small.

2-12 A hydraulic turbine-generator is to generate electricity from the water of a large reservoir. The power generation potential is to be determined.



Assumptions **1** The elevation of the reservoir remains constant. **2** The mechanical energy of water at the turbine exit is negligible.

Analysis The total mechanical energy water in a reservoir possesses is equivalent to the potential energy of water at the free surface, and it can be converted to work entirely. Therefore, the power potential of water is its potential energy, which is gz per unit mass, and $\dot{m}gz$ for a given mass flow rate.

$$e_{\text{mech}} = pe = gz = (9.81\ \text{m/s}^2)(160\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 1.574\ \text{kJ/kg}$$

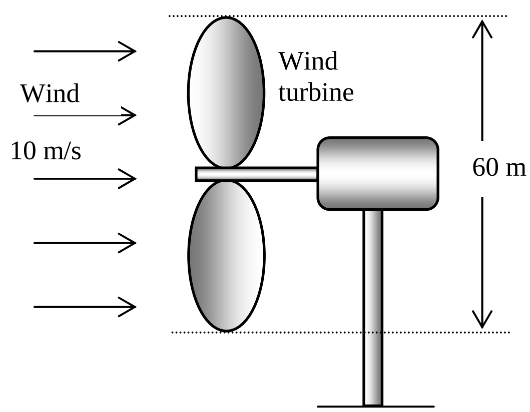
Then the power generation potential becomes

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (3500\ \text{kg/s})(1.574\ \text{kJ/kg})\left(\frac{1\ \text{kW}}{1\ \text{kJ/s}}\right) = \mathbf{5509\ kW}$$

Therefore, the reservoir has the potential to generate 1766 kW of power.

Discussion This problem can also be solved by considering a point at the turbine inlet, and using flow energy instead of potential energy. It would give the same result since the flow energy at the turbine inlet is equal to the potential energy at the free surface of the reservoir.

2-13 Wind is blowing steadily at a certain velocity. The mechanical energy of air per unit mass and the power generation potential are to be determined.



Assumptions The wind is blowing steadily at a constant uniform velocity.

Properties The density of air is given to be $\rho = 1.25\ \text{kg/m}^3$.

Analysis Kinetic energy is the only form of mechanical energy the wind possesses, and it can be converted to work entirely. Therefore, the power potential of the wind is its kinetic energy, which is $V^2/2$ per unit mass, and $\dot{m}V^2/2$ for a given mass flow rate:

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

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

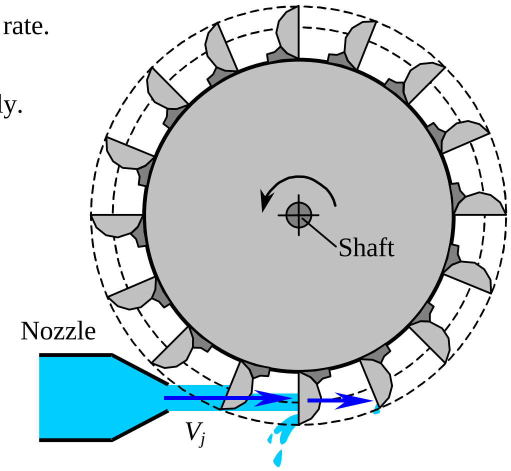
$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (35{,}340\ \text{kg/s})(0.050\ \text{kJ/kg}) = \mathbf{1770\ \ kW}$$

Therefore, 1770 kW of actual power can be generated by this wind turbine at the stated conditions.

Discussion The power generation of a wind turbine is proportional to the cube of the wind velocity, and thus the power generation will change strongly with the wind conditions.

2-14 A water jet strikes the buckets located on the perimeter of a wheel at a specified velocity and flow rate. The power generation potential of this system is to be determined.

Assumptions Water jet flows steadily at the specified speed and flow rate.



Analysis Kinetic energy is the only form of harvestable mechanical energy the water jet possesses, and it can be converted to work entirely. Therefore, the power potential of the water jet is its kinetic energy, which is $V^2/2$ per unit mass, and $\dot{m}V^2/2$ for a given mass flow rate:

$$e_{\text{mech}} = ke = \frac{V^2}{2} = \frac{(60\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 1.8\ \text{kJ/kg}$$

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

$$= (120\ \text{kg/s})(1.8\ \text{kJ/kg})\left(\frac{1\ \text{kW}}{1\ \text{kJ/s}}\right) = \mathbf{216\ kW}$$

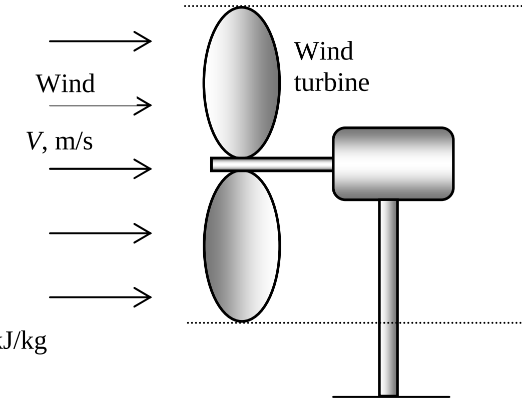
Therefore, 216 kW of power can be generated by this water jet at the stated conditions.

Discussion An actual hydroelectric turbine (such as the Pelton wheel) can convert over 90% of this potential to actual electric power.

2-15 Two sites with specified wind data are being considered for wind power generation. The site better suited for wind power generation is to be determined.

Assumptions **1**The wind is blowing steadily at specified velocity during specified times. **2** The wind power generation is negligible during other times.

Properties We take the density of air to be ρ = 1.25 kg/m^3 (it does not affect the final answer).



Analysis Kinetic energy is the only form of mechanical energy the wind possesses, and it can be converted to work entirely. Therefore, the power potential of the wind is its kinetic energy, which is $V^2/2$ per unit mass, and $\dot{m}V^2/2$ for a given mass flow rate. Considering a unit flow area (A = 1 m^2), the maximum wind power and power generation becomes

$$e_{\text{mech},1} = ke_1 = \frac{V_1^2}{2} = \frac{(7\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 0.0245\text{ kJ/kg}$$

$$e_{\text{mech},2} = ke_2 = \frac{V_2^2}{2} = \frac{(10\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 0.050\text{ kJ/kg}$$

$$\dot{W}_{\text{max},1} = \dot{E}_{\text{mech},1} = \dot{m}_1 e_{\text{mech},1} = \rho V_1 A ke_1 = (1.25\text{ kg/m}^3)(7\text{ m/s})(1\text{ m}^2)(0.0245\text{ kJ/kg}) = 0.2144\text{ kW}$$

$$\dot{W}_{\text{max},2} = \dot{E}_{\text{mech},2} = \dot{m}_2 e_{\text{mech},2} = \rho V_2 A ke_2 = (1.25\text{ kg/m}^3)(10\text{ m/s})(1\text{ m}^2)(0.050\text{ kJ/kg}) = 0.625\text{ kW}$$

since 1 kW = 1 kJ/s. Then the maximum electric power generations per year become

$$E_{\text{max},1} = \dot{W}_{\text{max},1}\Delta t_1 = (0.2144\text{ kW})(3000\text{ h/yr}) = \mathbf{643\ kWh/yr}\ \text{(per m}^2\text{ flow area)}$$

$$E_{\text{max},2} = \dot{W}_{\text{max},2}\Delta t_2 = (0.625\text{ kW})(2000\text{ h/yr}) = \mathbf{1250\ kWh/yr}\ \text{(per m}^2\text{ flow area)}$$

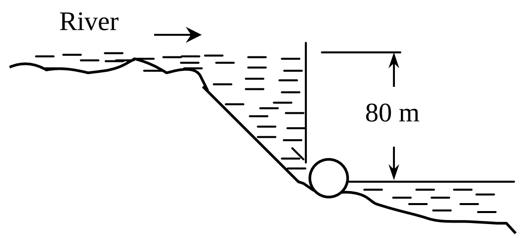
Therefore, **second site** is a better one for wind generation.

Discussion Note the power generation of a wind turbine is proportional to the cube of the wind velocity, and thus the average wind velocity is the primary consideration in wind power generation decisions.

2-16 A river flowing steadily at a specified flow rate is considered for hydroelectric power generation by collecting the water in a dam. For a specified water height, the power generation potential is to be determined.

Assumptions **1** The elevation given is the elevation of the free surface of the river. **2** The mechanical energy of water at the turbine exit is negligible.

Properties We take the density of water to be ρ = 1000 kg/m^3.



Analysis The total mechanical energy the water in a dam possesses is equivalent to the potential energy of water at the free surface of the dam (relative to free surface of discharge water), and it can be converted to work entirely. Therefore, the power potential of water is its potential energy, which is gz per unit mass, and $\dot{m}gz$ for a given mass flow rate.

$$e_{\text{mech}} = pe = gz = (9.81\,\text{m/s}^2)(80\text{ m})\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = 0.7848\text{ kJ/kg}$$

The mass flow rate is

$$\dot{m} = \rho\dot{\boldsymbol{V}} = (1000\,\text{kg/m}^3)(175\,\text{m}^3/\text{s}) = 175{,}000\,\text{kg/s}$$

Then the power generation potential becomes

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (175{,}000\,\text{kg/s})(0.7848\,\text{kJ/kg})\left(\frac{1\,\text{MW}}{1000\,\text{kJ/s}}\right) = \mathbf{137\ MW}$$

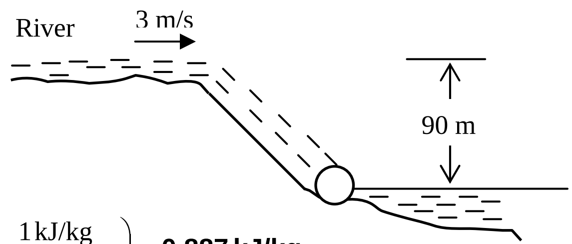
Therefore, 137 MW of power can be generated from this river if its power potential can be recovered completely.

Discussion Note that the power output of an actual turbine will be less than 137 MW because of losses and inefficiencies.

2-17 A river is flowing at a specified velocity, flow rate, and elevation. The total mechanical energy of the river water per unit mass, and the power generation potential of the entire river are to be determined.

Assumptions **1** The elevation given is the elevation of the free surface of the river. **2** The velocity given is the average velocity. **3** The mechanical energy of water at the turbine exit is negligible.

Properties We take the density of water to be ρ = 1000 kg/m^3.



Analysis Noting that the sum of the flow energy and the potential energy is constant for a given fluid body, we can take the elevation of the entire river water to be the elevation of the free surface, and ignore the flow energy. Then the total mechanical energy of the river water per unit mass becomes

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

The power generation potential of the river water is obtained by multiplying the total mechanical energy by the mass flow rate,

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

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

Therefore, 444 MW of power can be generated from this river as it discharges into the lake if its power potential can be recovered completely.

Discussion Note that the kinetic energy of water is negligible compared to the potential energy, and it can be ignored in the analysis. Also, the power output of an actual turbine will be less than 444 MW because of losses and inefficiencies.

Energy Transfer by Heat and Work

2-18C Energy can cross the boundaries of a closed system in two forms: heat and work.

2-19C The form of energy that crosses the boundary of a closed system because of a temperature difference is heat; all other forms are work.

2-20C An adiabatic process is a process during which there is no heat transfer. A system that does not exchange any heat with its surroundings is an adiabatic system.

2-21C Point functions depend on the state only whereas the path functions depend on the path followed during a process. Properties of substances are point functions, heat and work are path functions.

2-22C (*a*) The car's radiator transfers heat from the hot engine cooling fluid to the cooler air. No work interaction occurs in the radiator.

(*b*) The hot engine transfers heat to cooling fluid and ambient air while delivering work to the transmission.

(*c*) The warm tires transfer heat to the cooler air and to some degree to the cooler road while no work is produced. No work is produced since there is no motion of the forces acting at the interface between the tire and road.

(*d*) There is minor amount of heat transfer between the tires and road. Presuming that the tires are hotter than the road, the heat transfer is from the tires to the road. There is no work exchange associated with the road since it cannot move.

(*e*) Heat is being added to the atmospheric air by the hotter components of the car. Work is being done on the air as it passes over and through the car.

2-23C When the length of the spring is changed by applying a force to it, the interaction is a work interaction since it involves a force acting through a displacement. A heat interaction is required to change the temperature (and, hence, length) of the spring.

2-24C (*a*) From the perspective of the contents, heat must be removed in order to reduce and maintain the content's temperature. Heat is also being added to the contents from the room air since the room air is hotter than the contents.

(*b*) Considering the system formed by the refrigerator box when the doors are closed, there are three interactions, electrical work and two heat transfers. There is a transfer of heat from the room air to the refrigerator through its walls. There is also a transfer of heat from the hot portions of the refrigerator (i.e., back of the compressor where condenser is placed) system to the room air. Finally, electrical work is being added to the refrigerator through the refrigeration system.

(*c*) Heat is transferred through the walls of the room from the warm room air to the cold winter air. Electrical work is being done on the room through the electrical wiring leading into the room.

2-25C (*a*) As one types on the keyboard, electrical signals are produced and transmitted to the processing unit. Simultaneously, the temperature of the electrical parts is increased slightly. The work done on the keys when they are depressed is work done on the system (i.e., keyboard). The flow of electrical current (with its voltage drop) does work on the keyboard. Since the temperature of the electrical parts of the keyboard is somewhat higher than that of the surrounding air, there is a transfer of heat from the keyboard to the surrounding air.

(*b*) The monitor is powered by the electrical current supplied to it. This current (and voltage drop) is work done on the system (i.e., monitor). The temperatures of the electrical parts of the monitor are higher than that of the surrounding air. Hence there is a heat transfer to the surroundings.

(*c*) The processing unit is like the monitor in that electrical work is done on it while it transfers heat to the surroundings.

(*d*) The entire unit then has electrical work done on it, and mechanical work done on it to depress the keys. It also transfers heat from all its electrical parts to the surroundings.

2-26 The power produced by an electrical motor is to be expressed in different units.

Analysis Using appropriate conversion factors, we obtain

(*a*) $$\dot{W} = (5\text{ W})\left(\frac{1\text{ J/s}}{1\text{ W}}\right)\left(\frac{1\text{ N}\cdot\text{m}}{1\text{ J}}\right) = \mathbf{5\ N\cdot m/s}$$

(*b*) $$\dot{W} = (5\text{ W})\left(\frac{1\text{ J/s}}{1\text{ W}}\right)\left(\frac{1\text{ N}\cdot\text{m}}{1\text{ J}}\right)\left(\frac{1\text{ kg}\cdot\text{m/s}^2}{1\text{ N}}\right) = \mathbf{5\ kg\cdot m^2/s^3}$$

2-27E The power produced by a model aircraft engine is to be expressed in different units.

Analysis Using appropriate conversion factors, we obtain

(*a*) $$\dot{W} = (10\text{ W})\left(\frac{1\text{ Btu/s}}{1055.056\text{ W}}\right)\left(\frac{778.169\text{ lbf}\cdot\text{ft/s}}{1\text{ Btu/s}}\right) = \mathbf{7.38\ lbf\cdot ft/s}$$

(*b*) $$\dot{W} = (10\text{ W})\left(\frac{1\text{ hp}}{745.7\text{ W}}\right) = \mathbf{0.0134\ hp}$$

Mechanical Forms of Work

2-28C The work done is the same, but the power is different.

2-29 A car is accelerated from rest to 100 km/h. The work needed to achieve this is to be determined.

Analysis The work needed to accelerate a body the change in kinetic energy of the body,

$$W_a = \frac{1}{2}m(V_2^2 - V_1^2) = \frac{1}{2}(800\text{ kg})\left(\left(\frac{100{,}000\text{ m}}{3600\text{ s}}\right)^2 - 0\right)\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right) = \mathbf{309\ kJ}$$

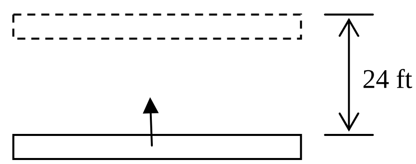
2-30E A construction crane lifting a concrete beam is considered. The amount of work is to be determined considering (a) the beam and (b) the crane as the system.

Analysis (*a*) The work is done on the beam and it is determined from

$$W = mg\Delta z = (2\times 3000\text{ lbm})(32.174\text{ ft/s}^2)\left(\frac{1\text{ lbf}}{32.174\text{ lbm}\cdot\text{ft/s}^2}\right)(24\text{ ft})$$

$$= \mathbf{144{,}000\ lbf\cdot ft}$$

$$= (144{,}000\text{ lbf}\cdot\text{ft})\left(\frac{1\text{ Btu}}{778.169\text{ lbf}\cdot\text{ft}}\right) = \mathbf{185\ Btu}$$



(*b*) Since the crane must produce the same amount of work as is required to lift the beam, the work done by the crane is

$$W = \mathbf{144{,}000\ lbf\cdot ft} = \mathbf{185\ Btu}$$

2-31E A man is pushing a cart with its contents up a ramp that is inclined at an angle of 10° from the horizontal. The work needed to move along this ramp is to be determined considering (a) the man and (b) the cart and its contents as the system.

Analysis (*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,

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

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

This is work that the man must do to raise the weight of the cart and contents, plus his own weight, a distance of $l\sin\theta$.

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

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

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

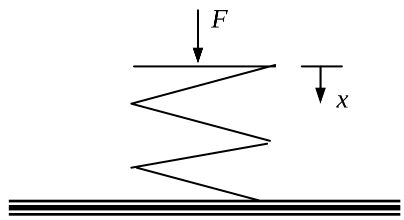
2-32E The work required to compress a spring is to be determined.

Analysis Since there is no preload, $F = kx$. Substituting this into the work expression gives

$$W = \int_1^2 F ds = \int_1^2 kxdx = k\int_1^2 xdx = \frac{k}{2}(x_2^2 - x_1^2)$$

$$= \frac{200\ \text{lbf/in}}{2}\left[(1\ \text{in})^2 - 0^2\right]\left(\frac{1\ \text{ft}}{12\ \text{in}}\right) = \mathbf{8.33\ lbf \cdot ft}$$

$$= (8.33\ \text{lbf}\cdot\text{ft})\left(\frac{1\ \text{Btu}}{778.169\ \text{lbf}\cdot\text{ft}}\right) = \mathbf{0.0107\ Btu}$$



2-33E The work required to expand a soap bubble is to be determined.

Analysis The surface tension work is determined from

$$W = \int_1^2 \sigma_s dA = \sigma(A_1 - A_2) = (0.005\ \text{lbf/ft})4\pi\left[(2/12\ \text{ft})^2 - (0.5/12\ \text{ft})^2\right]$$

$$= 0.00164\ \text{lbf}\cdot\text{ft} = (0.00164\ \text{lbf}\cdot\text{ft})\left(\frac{1\ \text{Btu}}{778.2\ \text{lbf}\cdot\text{ft}}\right) = \mathbf{2.11\times 10^{-6}\ Btu}$$

2-34E The work required to stretch a steel rod in a specieid length is to be determined.

Assumptions The Young's modulus does not change as the rod is stretched.

Analysis The original volume of the rod is

$$V_0 = \frac{\pi D^2}{4}L = \frac{\pi(0.5\ \text{in})^2}{4}(12\ \text{in}) = 2.356\ \text{in}^3$$

The work required to stretch the rod 0.125 in is

$$W = \frac{V_0 E}{2}(\varepsilon_2^2 - \varepsilon_1^2)$$

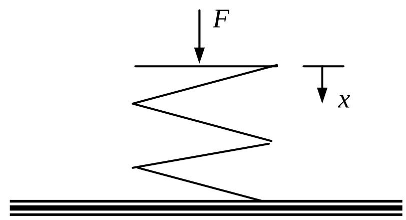
$$= \frac{(2.356\ \text{in}^3)(30{,}000\ \text{lbf/in}^2)}{2}\left[(0.125/12\ \text{in})^2 - 0^2\right]$$

$$= 2.835\ \text{lbf}\cdot\text{in} = (2.835\ \text{lbf}\cdot\text{in})\left(\frac{1\ \text{Btu}}{9338\ \text{lbf}\cdot\text{in}}\right) = \mathbf{4.11\times 10^{-4}\ Btu}$$

2-35E The work required to compress a spring is to be determined.

Analysis The force at any point during the deflection of the spring is given by $F = F_0 + kx$, where F_0 is the initial force and x is the deflection as measured from the point where the initial force occurred. From the perspective of the spring, this force acts in the direction opposite to that in which the spring is deflected. Then,

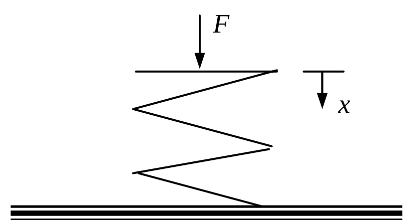
$$
\begin{aligned}
W &= \int_1^2 F ds = \int_1^2 (F_0 + kx)dx \\
&= F_0(x_2 - x_1) + \frac{k}{2}(x_2^2 - x_1^2) \\
&= (100 \text{ lbf})[(1-0)\text{in}] + \frac{200 \text{ lbf/in}}{2}(1^2 - 0^2)\text{in}^2 \\
&= 200 \text{ lbf} \cdot \text{in} \\
&= (200 \text{ lbf} \cdot \text{in})\left(\frac{1 \text{ Btu}}{778.169 \text{ lbf} \cdot \text{ft}}\right)\left(\frac{1 \text{ ft}}{12 \text{ in}}\right) = \mathbf{0.0214 \text{ Btu}}
\end{aligned}
$$



2-36 The work required to compress a spring is to be determined.

Analysis Since there is no preload, $F = kx$. Substituting this into the work expression gives

$$
\begin{aligned}
W &= \int_1^2 F ds = \int_1^2 kx dx = k\int_1^2 x dx = \frac{k}{2}(x_2^2 - x_1^2) \\
&= \frac{300 \text{ kN/m}}{2}\left[(0.03 \text{ m})^2 - 0^2\right] \\
&= 0.135 \text{ kN} \cdot \text{m} \\
&= (0.135 \text{ kN} \cdot \text{m})\left(\frac{1 \text{ kJ}}{1 \text{ kN} \cdot \text{m}}\right) = \mathbf{0.135 \text{ kJ}}
\end{aligned}
$$



2-37 A ski lift is operating steadily at 10 km/h. The power required to operate and also to accelerate this ski lift from rest to the operating speed are to be determined.

Assumptions **1** Air drag and friction are negligible. **2** The average mass of each loaded chair is 250 kg. **3** The mass of chairs is small relative to the mass of people, and thus the contribution of returning empty chairs to the motion is disregarded (this provides a safety factor).

Analysis The lift is 1000 m long and the chairs are spaced 20 m apart. Thus at any given time there are 1000/20 = 50 chairs being lifted. Considering that the mass of each chair is 250 kg, the load of the lift at any given time is

$$\text{Load} = (50 \text{ chairs})(250 \text{ kg/chair}) = 12{,}500 \text{ kg}$$

Neglecting the work done on the system by the returning empty chairs, the work needed to raise this mass by 200 m is

$$W_g = mg(z_2 - z_1) = (12{,}500 \text{ kg})(9.81 \text{ m/s}^2)(200 \text{ m})\left(\frac{1 \text{ kJ}}{1000 \text{ kg}\cdot\text{m}^2/\text{s}^2}\right) = 24{,}525 \text{ kJ}$$

At 10 km/h, it will take

$$\Delta t = \frac{\text{distance}}{\text{velocity}} = \frac{1 \text{ km}}{10 \text{ km/h}} = 0.1 \text{ h} = 360 \text{ s}$$

to do this work. Thus the power needed is

$$\dot{W}_g = \frac{W_g}{\Delta t} = \frac{24{,}525 \text{ kJ}}{360 \text{ s}} = \mathbf{68.1\,kW}$$

The velocity of the lift during steady operation, and the acceleration during start up are

$$V = (10 \text{ km/h})\left(\frac{1 \text{ m/s}}{3.6 \text{ km/h}}\right) = 2.778 \text{ m/s}$$

$$a = \frac{\Delta V}{\Delta t} = \frac{2.778 \text{ m/s} - 0}{5 \text{ s}} = 0.556 \text{ m/s}^2$$

During acceleration, the power needed is

$$\dot{W}_a = \frac{1}{2}m(V_2^2 - V_1^2)/\Delta t = \frac{1}{2}(12{,}500 \text{ kg})\left((2.778 \text{ m/s})^2 - 0\right)\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)/(5 \text{ s}) = 9.6 \text{ kW}$$

Assuming the power applied is constant, the acceleration will also be constant and the vertical distance traveled during acceleration will be

$$h = \frac{1}{2}at^2 \sin\alpha = \frac{1}{2}at^2\frac{200 \text{ m}}{1000 \text{ m}} = \frac{1}{2}(0.556 \text{ m/s}^2)(5 \text{ s})^2(0.2) = 1.39 \text{ m}$$

and

$$\dot{W}_g = mg(z_2 - z_1)/\Delta t = (12{,}500 \text{ kg})(9.81 \text{ m/s}^2)(1.39 \text{ m})\left(\frac{1 \text{ kJ/kg}}{1000 \text{ kg}\cdot\text{m}^2/\text{s}^2}\right)/(5 \text{ s}) = 34.1 \text{ kW}$$

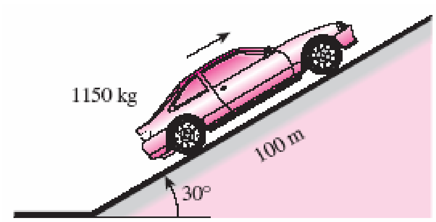
Thus,

$$\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = 9.6 + 34.1 = \mathbf{43.7\ kW}$$

2-38 A car is to climb a hill in 12 s. The power needed is to be determined for three different cases.

Assumptions Air drag, friction, and rolling resistance are negligible.

Analysis 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,

$$\dot{W}_g = mg(z_2 - z_1)/\Delta t = (1150\text{ kg})(9.81\text{ m/s}^2)(50\text{ m})\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right)/(12\text{ s}) = 47.0\text{ kW}$$

and $\quad \dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = 0 + 47.0 = \mathbf{47.0\ kW}$

(*b*) The power needed to accelerate is

$$\dot{W}_a = \frac{1}{2}m(V_2^2 - V_1^2)/\Delta t = \frac{1}{2}(1150\text{ kg})\left[(30\text{ m/s})^2 - 0\right]\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right)/(12\text{ s}) = 43.1\text{ kW}$$

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

(*c*) The power needed to decelerate is

$$\dot{W}_a = \frac{1}{2}m(V_2^2 - V_1^2)/\Delta t = \frac{1}{2}(1150\text{ kg})\left[(5\text{ m/s})^2 - (35\text{ m/s})^2\right]\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right)/(12\text{ s}) = -57.5\text{ kW}$$

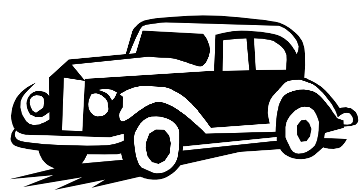
and $\quad \dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = -57.5 + 47.1 = \mathbf{-10.5\ kW}$ (breaking power)

2-39 A damaged car is being towed by a truck. The extra power needed is to be determined for three different cases.

Assumptions Air drag, friction, and rolling resistance are negligible.

Analysis 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*) Zero.

(*b*) $\dot{W}_a = 0$. Thus,

$$\dot{W}_{\text{total}} = \dot{W}_g = mg(z_2 - z_1)/\Delta t = mg\frac{\Delta z}{\Delta t} = mgV_z = mgV\sin 30^\circ$$

$$= (1200\text{ kg})(9.81\text{m/s}^2)\left(\frac{50{,}000\text{ m}}{3600\text{ s}}\right)\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)(0.5) = \mathbf{81.7\ kW}$$

(*c*) $\dot{W}_g = 0$. Thus,

$$\dot{W}_{\text{total}} = \dot{W}_a = \frac{1}{2}m(V_2^2 - V_1^2)/\Delta t = \frac{1}{2}(1200\text{ kg})\left(\left(\frac{90{,}000\text{ m}}{3600\text{ s}}\right)^2 - 0\right)\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)/(12\text{ s}) = \mathbf{31.3\ kW}$$

The First Law of Thermodynamics

2-40C No. This is the case for adiabatic systems only.

2-41C Energy can be transferred to or from a control volume as heat, various forms of work, and by mass transport.

2-42C Warmer. Because energy is added to the room air in the form of electrical work.

2-43E The high rolling resistance tires of a car are replaced by low rolling resistance ones. For a specified unit fuel cost, the money saved by switching to low resistance tires is to be determined.

Assumptions **1**The low rolling resistance tires deliver 2 mpg over all velocities. **2** The car is driven 15,000 miles per year.

Analysis The annual amount of fuel consumed by this car on high- and low-rolling resistance tires are

$$\text{Annual Fuel Consumption}_{\text{High}} = \frac{\text{Miles driven per year}}{\text{Miles per gallon}} = \frac{15{,}000 \text{ miles/year}}{35 \text{ miles/gal}} = 428.6 \text{ gal/year}$$

$$\text{Annual Fuel Consumption}_{\text{Low}} = \frac{\text{Miles driven per year}}{\text{Miles per gallon}} = \frac{15{,}000 \text{ miles/year}}{37 \text{ miles/gal}} = 405.4 \text{ gal/year}$$

Then the fuel and money saved per year become

$$\begin{aligned}\text{Fuel Savings} &= \text{Annual Fuel Consumption}_{\text{High}} - \text{Annual Fuel Consumption}_{\text{Low}} \\ &= 428.6 \text{ gal/year} - 405.4 \text{ gal/year} = 23.2 \text{ gal/year}\end{aligned}$$

$$\text{Cost savings} = (\text{Fuel savings})(\text{Unit cost of fuel}) = (23.2 \text{ gal/year})(\$2.20/\text{gal}) = \mathbf{\$51.0/year}$$

Discussion A typical tire lasts about 3 years, and thus the low rolling resistance tires have the potential to save about $150 to the car owner over the life of the tires, which is comparable to the installation cost of the tires.

2-44 The specific energy change of a system which is accelerated is to be determined.

Analysis Since the only property that changes for this system is the velocity, only the kinetic energy will change. The change in the specific energy is

$$\Delta \text{ke} = \frac{V_2^2 - V_1^2}{2} = \frac{(30 \text{ m/s})^2 - (0 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) = \mathbf{0.45 \text{ kJ/kg}}$$

2-45 The specific energy change of a system which is raised is to be determined.

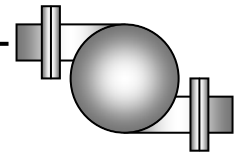
Analysis Since the only property that changes for this system is the elevation, only the potential energy will change. The change in the specific energy is then

$$\Delta\text{pe} = g(z_2 - z_1) = (9.8\ \text{m/s}^2)(100-0)\ \text{m}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = \mathbf{0.98\ kJ/kg}$$

2-46E A water pump increases water pressure. The power input is to be determined.

Analysis The power input is determined from

$$\dot{W} = \dot{\boldsymbol{V}}(P_2 - P_1)$$
$$= (1.2\ \text{ft}^3/\text{s})(50-10)\text{psia}\left(\frac{1\ \text{Btu}}{5.404\ \text{psia}\cdot\text{ft}^3}\right)\left(\frac{1\ \text{hp}}{0.7068\ \text{Btu/s}}\right)$$
$$= \mathbf{12.6\ hp}$$



The water temperature at the inlet does not have any significant effect on the required power.

2-47 A classroom is to be air-conditioned using window air-conditioning units. The cooling load is due to people, lights, and heat transfer through the walls and the windows. The number of 5-kW window air conditioning units required is to be determined.

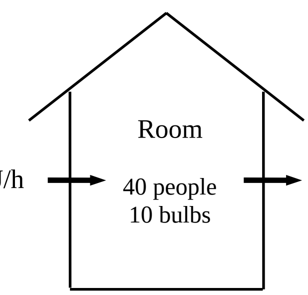
Assumptions There are no heat dissipating equipment (such as computers, TVs, or ranges) in the room.

Analysis The total cooling load of the room is determined from

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

where

$$\dot{Q}_{\text{lights}} = 10 \times 100\ \text{W} = 1\ \text{kW}$$
$$\dot{Q}_{\text{people}} = 40 \times 360\ \text{kJ / h} = 4\ \text{kW}$$
$$\dot{Q}_{\text{heat gain}} = 15{,}000\ \text{kJ / h} = 4.17\ \text{kW}$$



Substituting,

$$\dot{Q}_{\text{cooling}} = 1 + 4 + 4.17 = 9.17\ \text{kW}$$

Thus the number of air-conditioning units required is

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

2-48 The lighting energy consumption of a storage room is to be reduced by installing motion sensors. The amount of energy and money that will be saved as well as the simple payback period are to be determined.

Assumptions The electrical energy consumed by the ballasts is negligible.

Analysis The plant operates 12 hours a day, and thus currently the lights are on for the entire 12 hour period. The motion sensors installed will keep the lights on for 3 hours, and off for the remaining 9 hours every day. This corresponds to a total of 9×365 = 3285 off hours per year. Disregarding the ballast factor, the annual energy and cost savings become

Energy Savings = (Number of lamps)(Lamp wattage)(Reduction of annual operating hours)

= (24 lamps)(60 W/lamp)(3285 hours/year)

= **4730 kWh/year**

Cost Savings = (Energy Savings)(Unit cost of energy)

= (4730 kWh/year)($0.08/kWh)

= **$378/year**

The implementation cost of this measure is the sum of the purchase price of the sensor plus the labor,

Implementation Cost = Material + Labor = $32 + $40 = $72

This gives a simple payback period of

$$\text{Simple payback period} = \frac{\text{Implementation cost}}{\text{Annual cost savings}} = \frac{\$72}{\$378/\text{year}} = \mathbf{0.19\ year}\ \ (2.3\,\text{months})$$

Therefore, the motion sensor will pay for itself in about 2 months.

2-49 The classrooms and faculty offices of a university campus are not occupied an average of 4 hours a day, but the lights are kept on. The amounts of electricity and money the campus will save per year if the lights are turned off during unoccupied periods are to be determined.

Analysis The total electric power consumed by the lights in the classrooms and faculty offices is

$$\dot{E}_{\text{lighting, classroom}} = (\text{Power consumed per lamp}) \times (\text{No. of lamps}) = (200 \times 12 \times 110\text{ W}) = 264{,}000 = 264\text{ kW}$$

$$\dot{E}_{\text{lighting, offices}} = (\text{Power consumed per lamp}) \times (\text{No. of lamps}) = (400 \times 6 \times 110\text{ W}) = 264{,}000 = 264\text{ kW}$$

$$\dot{E}_{\text{lighting, total}} = \dot{E}_{\text{lighting, classroom}} + \dot{E}_{\text{lighting, offices}} = 264 + 264 = 528\text{ kW}$$

Noting that the campus is open 240 days a year, the total number of unoccupied work hours per year is

Unoccupied hours = (4 hours/day)(240 days/year) = 960 h/yr

Then the amount of electrical energy consumed per year during unoccupied work period and its cost are

$$\text{Energy savings} = (\dot{E}_{\text{lighting, total}})(\text{Unoccupied hours}) = (528\text{ kW})(960\text{ h/yr}) = 506{,}880\text{ kWh}$$

$$\text{Cost savings} = (\text{Energy savings})(\text{Unit cost of energy}) = (506{,}880\text{ kWh/yr})(\$0.082/\text{kWh}) = \mathbf{\$41{,}564/yr}$$

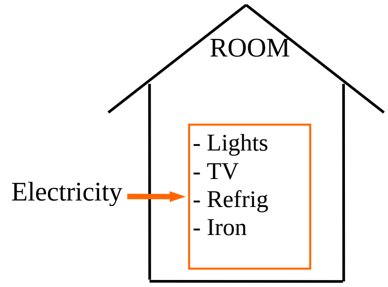
Discussion Note that simple conservation measures can result in significant energy and cost savings.

2-50 A room contains a light bulb, a TV set, a refrigerator, and an iron. The rate of increase of the energy content of the room when all of these electric devices are on is to be determined.

Assumptions **1** The room is well sealed, and heat loss from the room is negligible. **2** All the appliances are kept on.

Analysis Taking the room as the system, the rate form of the energy balance can be written as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}} / dt}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} \quad \rightarrow \quad dE_{\text{room}} / dt = \dot{E}_{in}$$



since no energy is leaving the room in any form, and thus $\dot{E}_{out} = 0$. Also,

$$\begin{aligned}\dot{E}_{\text{in}} &= \dot{E}_{\text{lights}} + \dot{E}_{\text{TV}} + \dot{E}_{\text{refrig}} + \dot{E}_{\text{iron}} \\ &= 100 + 110 + 200 + 1000 \text{ W} \\ &= 1410 \text{ W}\end{aligned}$$

Substituting, the rate of increase in the energy content of the room becomes

$$dE_{\text{room}} / dt = \dot{E}_{\text{in}} = \mathbf{1410\ W}$$

Discussion Note that some appliances such as refrigerators and irons operate intermittently, switching on and off as controlled by a thermostat. Therefore, the rate of energy transfer to the room, in general, will be less.

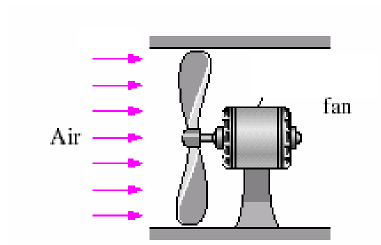
2-51 A fan is to accelerate quiescent air to a specified velocity at a specified flow rate. The minimum power that must be supplied to the fan is to be determined.

Assumptions The fan operates steadily.

Properties The density of air is given to be $\rho = 1.18$ kg/m^3.

Analysis A fan transmits the mechanical energy of the shaft (shaft power) to mechanical energy of air (kinetic energy). For a control volume that encloses the fan, the energy balance can be written as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}} / dt^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0 \quad \rightarrow \quad \dot{E}_{in} = \dot{E}_{out}$$



$$\dot{W}_{\text{sh, in}} = \dot{m}_{\text{air}} \text{ke}_{\text{out}} = \dot{m}_{\text{air}} \frac{V_{\text{out}}^2}{2}$$

where

$$\dot{m}_{\text{air}} = \rho \dot{\boldsymbol{V}} = (1.18 \text{ kg/m}^3)(9 \text{ m}^3/\text{s}) = 10.62 \text{ kg/s}$$

Substituting, the minimum power input required is determined to be

$$\dot{W}_{\text{sh, in}} = \dot{m}_{\text{air}} \frac{V_{\text{out}}^2}{2} = (10.62 \text{ kg/s}) \frac{(8 \text{ m/s})^2}{2} \left(\frac{1 \text{ J/kg}}{1 \text{ m}^2/\text{s}^2} \right) = 340 \text{ J/s} = \mathbf{340\ W}$$

Discussion The conservation of energy principle requires the energy to be conserved as it is converted from one form to another, and it does not allow any energy to be created or destroyed during a process. In reality, the power required will be considerably higher because of the losses associated with the conversion of mechanical shaft energy to kinetic energy of air.

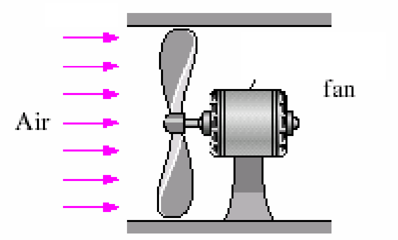
2-52E A fan accelerates air to a specified velocity in a square duct. The minimum electric power that must be supplied to the fan motor is to be determined.

Assumptions **1** The fan operates steadily. **2** There are no conversion losses.

Properties The density of air is given to be ρ = 0.075 lbm/ft^3.

Analysis A fan motor converts electrical energy to mechanical shaft energy, and the fan transmits the mechanical energy of the shaft (shaft power) to mechanical energy of air (kinetic energy). For a control volume that encloses the fan-motor unit, the energy balance can be written as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{\text{system}}/dt^{\nearrow 0 \text{ (steady)}}}_{\text{Rate of change in internal, kinetic, potential, etc. energies}} = 0 \quad \rightarrow \quad \dot{E}_{in} = \dot{E}_{out}$$



$$\dot{W}_{\text{elect, in}} = \dot{m}_{\text{air}} \text{ke}_{\text{out}} = \dot{m}_{\text{air}} \frac{V_{\text{out}}^2}{2}$$

where

$$\dot{m}_{\text{air}} = \rho VA = (0.075 \text{ lbm/ft}^3)(3 \times 3 \text{ ft}^2)(22 \text{ ft/s}) = 14.85 \text{ lbm/s}$$

Substituting, the minimum power input required is determined to be

$$\dot{W}_{\text{in}} = \dot{m}_{\text{air}} \frac{V_{\text{out}}^2}{2} = (14.85 \text{ lbm/s}) \frac{(22 \text{ ft/s})^2}{2} \left(\frac{1 \text{ Btu/lbm}}{25,037 \text{ ft}^2/\text{s}^2} \right) = 0.1435 \text{ Btu/s} = \mathbf{151 \text{ W}}$$

since 1 Btu = 1.055 kJ and 1 kJ/s = 1000 W.

Discussion The conservation of energy principle requires the energy to be conserved as it is converted from one form to another, and it does not allow any energy to be created or destroyed during a process. In reality, the power required will be considerably higher because of the losses associated with the conversion of electrical-to-mechanical shaft and mechanical shaft-to-kinetic energy of air.

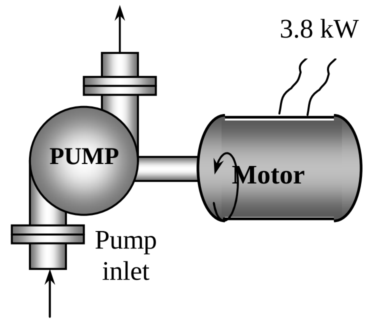
2-53 A gasoline pump raises the pressure to a specified value while consuming electric power at a specified rate. The maximum volume flow rate of gasoline is to be determined.

Assumptions **1** The gasoline pump operates steadily. **2** The changes in kinetic and potential energies across the pump are negligible.

Analysis For a control volume that encloses the pump-motor unit, the energy balance can be written as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc. energies}}} = 0 \quad \rightarrow \quad \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}(P\boldsymbol{v})_1 = \dot{m}(P\boldsymbol{v})_2 \quad \rightarrow \quad \dot{W}_{in} = \dot{m}(P_2 - P_1)\boldsymbol{v} = \dot{\boldsymbol{V}}\,\Delta P$$



since $\dot{m} = \dot{\boldsymbol{V}}/\boldsymbol{v}$ and the changes in kinetic and potential energies of gasoline are negligible, Solving for volume flow rate and substituting, the maximum flow rate is determined to be

$$\dot{\boldsymbol{V}}_{max} = \frac{\dot{W}_{in}}{\Delta P} = \frac{3.8 \text{ kJ/s}}{7 \text{ kPa}}\left(\frac{1 \text{ kPa}\cdot\text{m}^3}{1 \text{ kJ}}\right) = \mathbf{0.543\ m^3/s}$$

Discussion The conservation of energy principle requires the energy to be conserved as it is converted from one form to another, and it does not allow any energy to be created or destroyed during a process. In reality, the volume flow rate will be less because of the losses associated with the conversion of electrical-to-mechanical shaft and mechanical shaft-to-flow energy.

2-54 An inclined escalator is to move a certain number of people upstairs at a constant velocity. The minimum power required to drive this escalator is to be determined.

Assumptions **1** Air drag and friction are negligible. **2** The average mass of each person is 75 kg. **3** The escalator operates steadily, with no acceleration or breaking. **4** The mass of escalator itself is negligible.

Analysis At design conditions, the total mass moved by the escalator at any given time is

Mass = (30 persons)(75 kg/person) = 2250 kg

The vertical component of escalator velocity is

$$V_{\text{vert}} = V \sin 45° = (0.8 \text{ m/s})\sin 45°$$

Under stated assumptions, the power supplied is used to increase the potential energy of people. Taking the people on elevator as the closed system, the energy balance in the rate form can be written as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}/dt}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0 \quad \rightarrow \quad \dot{E}_{\text{in}} = dE_{\text{sys}}/dt \cong \frac{\Delta E_{\text{sys}}}{\Delta t}$$

$$\dot{W}_{\text{in}} = \frac{\Delta PE}{\Delta t} = \frac{mg\Delta z}{\Delta t} = mgV_{\text{vert}}$$

That is, under stated assumptions, the power input to the escalator must be equal to the rate of increase of the potential energy of people. Substituting, the required power input becomes

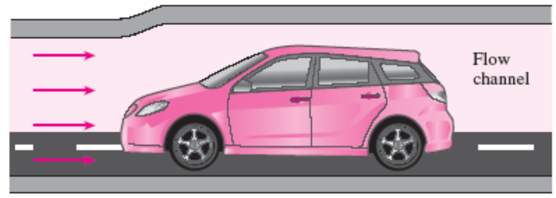
$$\dot{W}_{\text{in}} = mgV_{\text{vert}} = (2250 \text{ kg})(9.81 \text{ m/s}^2)(0.8 \text{ m/s})\sin 45° \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) = 12.5 \text{ kJ/s} = \mathbf{12.5 \text{ kW}}$$

When the escalator velocity is doubled to V = 1.6 m/s, the power needed to drive the escalator becomes

$$\dot{W}_{\text{in}} = mgV_{\text{vert}} = (2250 \text{ kg})(9.81 \text{ m/s}^2)(1.6 \text{ m/s})\sin 45° \left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) = 25.0 \text{ kJ/s} = \mathbf{25.0 \text{ kW}}$$

Discussion Note that the power needed to drive an escalator is proportional to the escalator velocity.

2-55 An automobile moving at a given velocity is considered. The power required to move the car and the area of the effective flow channel behind the car are to be determined.



Analysis The absolute pressure of the air is

$$P = (700\text{ mm Hg})\left(\frac{0.1333\text{ kPa}}{1\text{ mm Hg}}\right) = 93.31\text{ kPa}$$

and the specific volume of the air is

$$\boldsymbol{v} = \frac{RT}{P} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293\text{ K})}{93.31\text{ kPa}} = 0.9012\text{ m}^3/\text{kg}$$

The mass flow rate through the control volume is

$$\dot{m} = \frac{A_1V_1}{\boldsymbol{v}} = \frac{(3\text{ m}^2)(90/3.6\text{ m/s})}{0.9012\text{ m}^3/\text{kg}} = 83.22\text{ kg/s}$$

The power requirement is

$$\dot{W} = \dot{m}\frac{V_1^2 - V_2^2}{2} = (83.22\text{ kg/s})\frac{(90/3.6\text{ m/s})^2 - (82/3.6\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = \mathbf{4.42\text{ kW}}$$

The outlet area is

$$\dot{m} = \frac{A_2V_2}{\boldsymbol{v}} \longrightarrow A_2 = \frac{\dot{m}\boldsymbol{v}}{V_2} = \frac{(83.22\text{ kg/s})(0.9012\text{ m}^3/\text{kg})}{(82/3.6)\text{ m/s}} = \mathbf{3.29\text{ m}^2}$$

Energy Conversion Efficiencies

2-56C *Mechanical efficiency* is defined as the ratio of the mechanical energy output to the mechanical energy input. A mechanical efficiency of 100% for a hydraulic turbine means that the entire mechanical energy of the fluid is converted to mechanical (shaft) work.

2-57C The *combined pump-motor efficiency* of a pump/motor system is defined as the ratio of the increase in the mechanical energy of the fluid to the electrical power consumption of the motor,

$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\dot{E}_{\text{mech,out}} - \dot{E}_{\text{mech,in}}}{\dot{W}_{\text{elect,in}}} = \frac{\Delta\dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{elect,in}}} = \frac{\dot{W}_{\text{pump}}}{\dot{W}_{\text{elect,in}}}$$

The combined pump-motor efficiency cannot be greater than either of the pump or motor efficiency since both pump and motor efficiencies are less than 1, and the product of two numbers that are less than one is less than either of the numbers.

2-58C The turbine efficiency, generator efficiency, and *combined turbine-generator efficiency* are defined as follows:

$$\eta_{\text{turbine}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy extracted from the fluid}} = \frac{\dot{W}_{\text{shaft,out}}}{|\Delta\dot{E}_{\text{mech,fluid}}|}$$

$$\eta_{\text{generator}} = \frac{\text{Electrical power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{shaft,in}}}$$

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{E}_{\text{mech,in}} - \dot{E}_{\text{mech,out}}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta\dot{E}_{\text{mech,fluid}}|}$$

2-59C No, the combined pump-motor efficiency cannot be greater that either of the pump efficiency of the motor efficiency. This is because $\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}}$, and both η_{pump} and η_{motor} are less than one, and a number gets smaller when multiplied by a number smaller than one.

2-60 A hooded electric open burner and a gas burner are considered. The amount of the electrical energy used directly for cooking and the cost of energy per "utilized" kWh are to be determined.

Analysis The efficiency of the electric heater is given to be 73 percent. Therefore, a burner that consumes 3-kW of electrical energy will supply

$$\eta_{\text{gas}} = 38\%$$

$$\eta_{\text{electric}} = 73\%$$

$$\dot{Q}_{\text{utilized}} = (\text{Energy input}) \times (\text{Efficiency}) = (2.4\text{ kW})(0.73) = \mathbf{1.75\ kW}$$

of useful energy. The unit cost of utilized energy is inversely proportional to the efficiency, and is determined from

$$\text{Cost of utilized energy} = \frac{\text{Cost of energy input}}{\text{Efficiency}} = \frac{\$0.10/\text{kWh}}{0.73} = \mathbf{\$0.137/kWh}$$

Noting that the efficiency of a gas burner is 38 percent, the energy input to a gas burner that supplies utilized energy at the same rate (1.75 kW) is

$$\dot{Q}_{\text{input, gas}} = \frac{\dot{Q}_{\text{utilized}}}{\text{Efficiency}} = \frac{1.75\text{ kW}}{0.38} = \mathbf{4.61\ kW} \quad (= 15{,}700\text{ Btu/h})$$

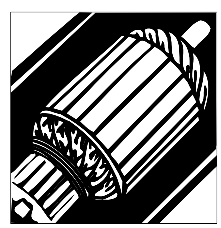
since 1 kW = 3412 Btu/h. Therefore, a gas burner should have a rating of at least 15,700 Btu/h to perform as well as the electric unit. Noting that 1 therm = 29.3 kWh, the unit cost of utilized energy in the case of gas burner is determined the same way to be

$$\text{Cost of utilized energy} = \frac{\text{Cost of energy input}}{\text{Efficiency}} = \frac{\$1.20/(29.3\text{ kWh})}{0.38} = \mathbf{\$0.108/kWh}$$

2-61 A worn out standard motor is replaced by a high efficiency one. The reduction in the internal heat gain due to the higher efficiency under full load conditions is to be determined.

Assumptions **1** The motor and the equipment driven by the motor are in the same room. **2** The motor operates at full load so that $f_{\text{load}} = 1$.

Analysis The heat generated by a motor is due to its inefficiency, and the difference between the heat generated by two motors that deliver the same shaft power is simply the difference between the electric power drawn by the motors,



$$\dot{W}_{\text{in, electric, standard}} = \dot{W}_{\text{shaft}} / \eta_{\text{motor}} = (75 \times 746\text{ W})/0.91 = 61{,}484\text{ W}$$

$$\dot{W}_{\text{in, electric, efficient}} = \dot{W}_{\text{shaft}} / \eta_{\text{motor}} = (75 \times 746\text{ W})/0.954 = 58{,}648\text{ W}$$

Then the reduction in heat generation becomes

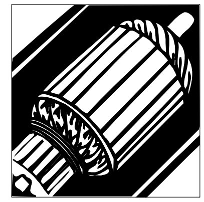
$$\dot{Q}_{\text{reduction}} = \dot{W}_{\text{in, electric, standard}} - \dot{W}_{\text{in, electric, efficient}} = 61{,}484 - 58{,}648 = \mathbf{2836\ W}$$

2-62 An electric car is powered by an electric motor mounted in the engine compartment. The rate of heat supply by the motor to the engine compartment at full load conditions is to be determined.

Assumptions The motor operates at full load so that the load factor is 1.

Analysis The heat generated by a motor is due to its inefficiency, and is equal to the difference between the electrical energy it consumes and the shaft power it delivers,

$$\dot{W}_{\text{in, electric}} = \dot{W}_{\text{shaft}} / \eta_{\text{motor}} = (90 \text{ hp})/0.91 = 98.90 \text{ hp}$$
$$\dot{Q}_{\text{generation}} = \dot{W}_{\text{in, electric}} - \dot{W}_{\text{shaft out}} = 98.90 - 90 = 8.90 \text{ hp} = \mathbf{6.64\ kW}$$



since 1 hp = 0.746 kW.

Discussion Note that the electrical energy not converted to mechanical power is converted to heat.

2-63 A worn out standard motor is to be replaced by a high efficiency one. The amount of electrical energy and money savings as a result of installing the high efficiency motor instead of the standard one as well as the simple payback period are to be determined.

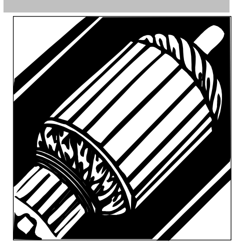
Assumptions The load factor of the motor remains constant at 0.75.

Analysis The electric power drawn by each motor and their difference can be expressed as

$$\dot{W}_{\text{electric in, standard}} = \dot{W}_{\text{shaft}} / \eta_{\text{standard}} = (\text{Power rating})(\text{Load factor}) / \eta_{\text{standard}}$$
$$\dot{W}_{\text{electric in, efficient}} = \dot{W}_{\text{shaft}} / \eta_{\text{efficient}} = (\text{Power rating})(\text{Load factor}) / \eta_{\text{efficient}}$$
$$\text{Power savings} = \dot{W}_{\text{electric in, standard}} - \dot{W}_{\text{electric in, efficient}}$$
$$= (\text{Power rating})(\text{Load factor})[1/\eta_{\text{standard}} - 1/\eta_{\text{efficient}}]$$

where η_{standard} is the efficiency of the standard motor, and $\eta_{\text{efficient}}$ is the efficiency of the comparable high efficiency motor. Then the annual energy and cost savings associated with the installation of the high efficiency motor are determined to be

$\eta_{\text{old}} = 91.0\%$
$\eta_{\text{new}} = 95.4\%$



Energy Savings = (Power savings)(Operating Hours)

= (Power Rating)(Operating Hours)(Load Factor)($1/\eta_{\text{standard}} - 1/\eta_{\text{efficient}}$)

= (75 hp)(0.746 kW/hp)(4,368 hours/year)(0.75)(1/0.91 - 1/0.954)

= **9,290 kWh/year**

Cost Savings = (Energy savings)(Unit cost of energy)

= (9,290 kWh/year)($0.08/kWh)

= **$743/year**

The implementation cost of this measure consists of the excess cost the high efficiency motor over the standard one. That is,

Implementation Cost = Cost differential = $5,520 - $5,449 = $71

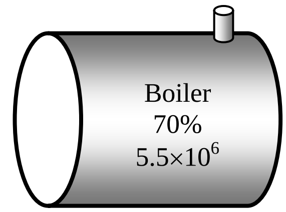
This gives a simple payback period of

$$\text{Simple payback period} = \frac{\text{Implementation cost}}{\text{Annual cost savings}} = \frac{\$71}{\$743/\text{ year}} = \mathbf{0.096\ year}\ (\text{or } 1.1 \text{ months})$$

Therefore, the high-efficiency motor will pay for its cost differential in about one month.

2-64E The combustion efficiency of a furnace is raised from 0.7 to 0.8 by tuning it up. The annual energy and cost savings as a result of tuning up the boiler are to be determined.

Assumptions The boiler operates at full load while operating.



Analysis The heat output of boiler is related to the fuel energy input to the boiler by

Boiler output = (Boiler input)(Combustion efficiency)

or $$\dot{Q}_{\text{out}} = \dot{Q}_{\text{in}}\eta_{\text{furnace}}$$

The current rate of heat input to the boiler is given to be $\dot{Q}_{\text{in, current}} = 5.5\times10^6$ Btu/h .

Then the rate of useful heat output of the boiler becomes

$$\dot{Q}_{\text{out}} = (\dot{Q}_{\text{in}}\eta_{\text{furnace}})_{\text{current}} = (5.5\times10^6 \text{ Btu/h})(0.7) = 3.85\times10^6 \text{ Btu/h}$$

The boiler must supply useful heat at the same rate after the tune up. Therefore, the rate of heat input to the boiler after the tune up and the rate of energy savings become

$$\dot{Q}_{\text{in, new}} = \dot{Q}_{\text{out}} / \eta_{\text{furnace, new}} = (3.85\times10^6 \text{ Btu/h})/0.8 = 4.81\times10^6 \text{ Btu/h}$$
$$\dot{Q}_{\text{in, saved}} = \dot{Q}_{\text{in, current}} - \dot{Q}_{\text{in, new}} = 5.5\times10^6 - 4.81\times10^6 = 0.69\times10^6 \text{ Btu/h}$$

Then the annual energy and cost savings associated with tuning up the boiler become

Energy Savings $= \dot{Q}_{\text{in, saved}}$ (Operation hours)

$= (0.69\times10^6$ Btu/h)(4200 h/year) = $\mathbf{2.89\times10^9}$ **Btu/yr**

Cost Savings = (Energy Savings)(Unit cost of energy)

$= (2.89\times10^9$ Btu/yr)($4.35/$10^6$ Btu) = **$12,600/year**

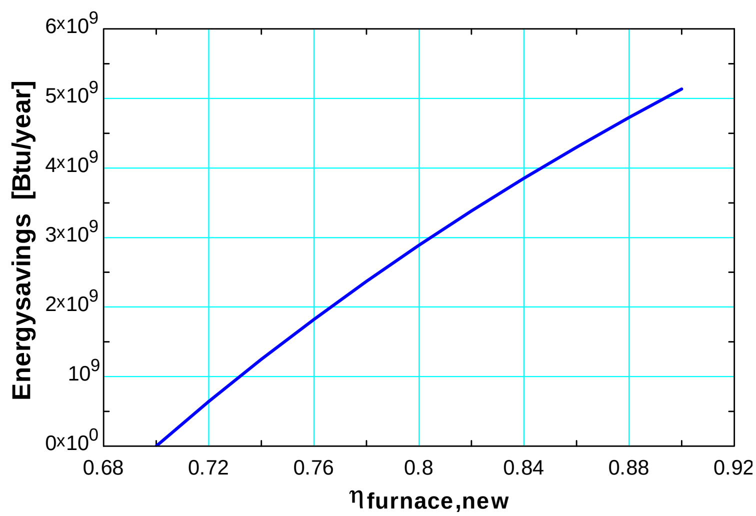
Discussion Notice that tuning up the boiler will save $12,600 a year, which is a significant amount. The implementation cost of this measure is negligible if the adjustment can be made by in-house personnel. Otherwise it is worthwhile to have an authorized representative of the boiler manufacturer to service the boiler twice a year.

2-65E Problem 2-64E is reconsidered. The effects of the unit cost of energy and combustion efficiency on the annual energy used and the cost savings as the efficiency varies from 0.7 to 0.9 and the unit cost varies from $4 to $6 per million Btu are the investigated. The annual energy saved and the cost savings are to be plotted against the efficiency for unit costs of $4, $5, and $6 per million Btu.

Analysis The problem is solved using EES, and the solution is given below.

```
"Given"
Q_dot_in_current=5.5E6 [Btu/h]
eta_furnace_current=0.7
eta_furnace_new=0.8
Hours=4200 [h/year]
UnitCost=4.35E-6 [$/Btu]

"Analysis"
Q_dot_out=Q_dot_in_current*eta_furnace_current
Q_dot_in_new=Q_dot_out/eta_furnace_new
Q_dot_in_saved=Q_dot_in_current-Q_dot_in_new
Energysavings=Q_dot_in_saved*Hours
CostSavings=EnergySavings*UnitCost
```

$\eta_{furnace,new}$	EnergySavings [Btu/year]	CostSavings [$/year]
0.7	0.00E+00	0
0.72	6.42E+08	3208
0.74	1.25E+09	6243
0.76	1.82E+09	9118
0.78	2.37E+09	11846
0.8	2.89E+09	14437
0.82	3.38E+09	16902
0.84	3.85E+09	19250
0.86	4.30E+09	21488
0.88	4.73E+09	23625
0.9	5.13E+09	25667



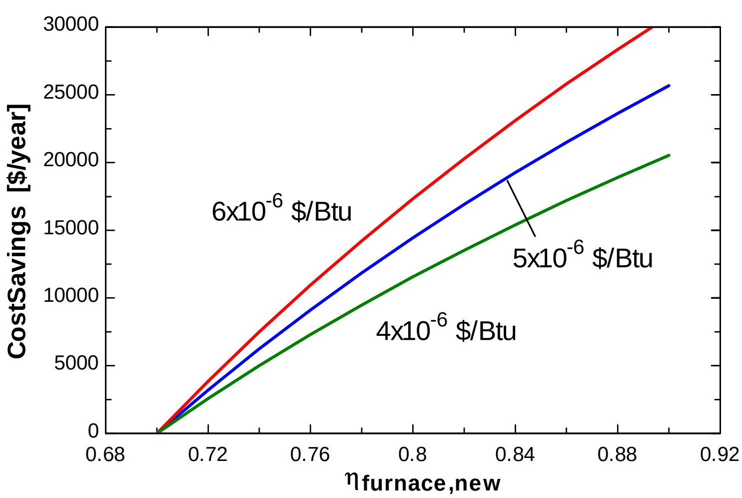


Table values are for UnitCost = 5E-5 [$/Btu]

2-66 Several people are working out in an exercise room. The rate of heat gain from people and the equipment is to be determined.

Assumptions The average rate of heat dissipated by people in an exercise room is 525 W.

Analysis The 8 weight lifting machines do not have any motors, and thus they do not contribute to the internal heat gain directly. The usage factors of the motors of the treadmills are taken to be unity since they are used constantly during peak periods. Noting that 1 hp = 746 W, the total heat generated by the motors is

$$\begin{aligned}\dot{Q}_{\text{motors}} &= (\text{No. of motors}) \times \dot{W}_{\text{motor}} \times f_{\text{load}} \times f_{\text{usage}} / \eta_{\text{motor}} \\ &= 4 \times (2.5 \times 746\text{ W}) \times 0.70 \times 1.0/0.77 = 6782\text{ W}\end{aligned}$$

The heat gain from 14 people is

$$\dot{Q}_{\text{people}} = (\text{No. of people}) \times \dot{Q}_{\text{person}} = 14 \times (525\text{ W}) = 7350\text{ W}$$

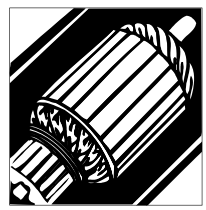
Then the total rate of heat gain of the exercise room during peak period becomes

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{motors}} + \dot{Q}_{\text{people}} = 6782 + 7350 = \mathbf{14{,}132\ W}$$

2-67 A room is cooled by circulating chilled water through a heat exchanger, and the air is circulated through the heat exchanger by a fan. The contribution of the fan-motor assembly to the cooling load of the room is to be determined.

Assumptions The fan motor operates at full load so that $f_{\text{load}} = 1$.

Analysis The entire electrical energy consumed by the motor, including the shaft power delivered to the fan, is eventually dissipated as heat. Therefore, the contribution of the fan-motor assembly to the cooling load of the room is equal to the electrical energy it consumes,



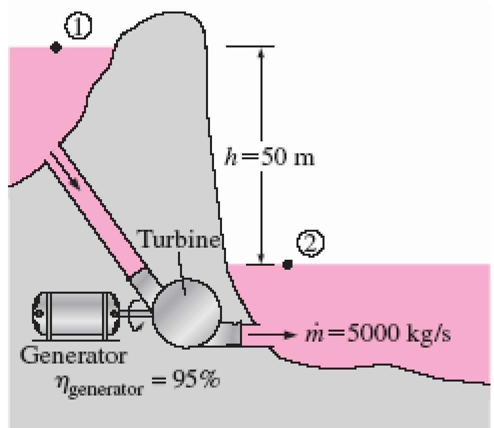
$$\begin{aligned}\dot{Q}_{\text{internal generation}} &= \dot{W}_{\text{in, electric}} = \dot{W}_{\text{shaft}} / \eta_{\text{motor}} \\ &= (0.25\text{ hp})/0.54 = 0.463\text{ hp} = \mathbf{345\ W}\end{aligned}$$

since 1 hp = 746 W.

2-68 A hydraulic turbine-generator is to generate electricity from the water of a lake. The overall efficiency, the turbine efficiency, and the shaft power are to be determined.

Assumptions **1** The elevation of the lake and that of the discharge site remains constant. **2** Irreversible losses in the pipes are negligible.

Properties The density of water can be taken to be ρ = 1000 kg/m^3. The gravitational acceleration is g = 9.81 m/s^2.



Analysis (*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

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

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

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

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

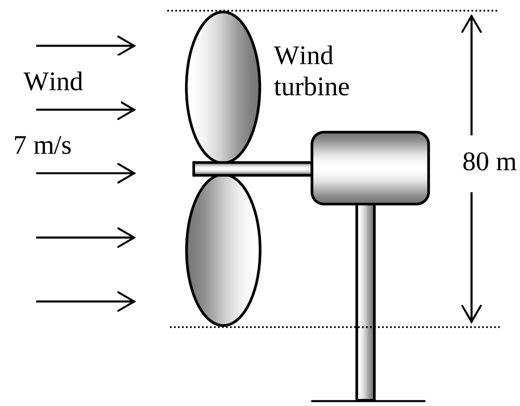
(*c*) The shaft power output is determined from the definition of mechanical efficiency,

$$\dot{W}_{\text{shaft,out}} = \eta_{\text{turbine}}\,|\Delta\dot{E}_{\text{mech,fluid}}| = (0.800)(2455\text{ kW}) = 1964\text{ kW} \approx \mathbf{1960\text{ kW}}$$

Therefore, the lake supplies 2455 kW of mechanical energy to the turbine, which converts 1964 kW of it to shaft work that drives the generator, which generates 1862 kW of electric power.

2-69 Wind is blowing steadily at a certain velocity. The mechanical energy of air per unit mass, the power generation potential, and the actual electric power generation are to be determined.

Assumptions **1** The wind is blowing steadily at a constant uniform velocity. **2** The efficiency of the wind turbine is independent of the wind speed.



Properties The density of air is given to be $\rho = 1.25$ kg/m^3.

Analysis Kinetic energy is the only form of mechanical energy the wind possesses, and it can be converted to work entirely. Therefore, the power potential of the wind is its kinetic energy, which is $V^2/2$ per unit mass, and $\dot{m}V^2/2$ for a given mass flow rate:

$$e_{\text{mech}} = ke = \frac{V^2}{2} = \frac{(7\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 0.0245\text{ kJ/kg}$$

$$\dot{m} = \rho VA = \rho V\frac{\pi D^2}{4} = (1.25\text{ kg/m}^3)(7\text{ m/s})\frac{\pi(80\text{ m})^2}{4} = 43{,}982\text{ kg/s}$$

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (43{,}982\text{ kg/s})(0.0245\text{ kJ/kg}) = \mathbf{1078\ kW}$$

The actual electric power generation is determined by multiplying the power generation potential by the efficiency,

$$\dot{W}_{\text{elect}} = \eta_{\text{wind turbine}}\dot{W}_{\max} = (0.30)(1078\text{ kW}) = \mathbf{323\ kW}$$

Therefore, 323 kW of actual power can be generated by this wind turbine at the stated conditions.

Discussion The power generation of a wind turbine is proportional to the cube of the wind velocity, and thus the power generation will change strongly with the wind conditions.

2-70 Problem 2-69 is reconsidered. The effect of wind velocity and the blade span diameter on wind power generation as the velocity varies from 5 m/s to 20 m/s in increments of 5 m/s, and the diameter varies from 20 m to 120 m in increments of 20 m is to be investigated.

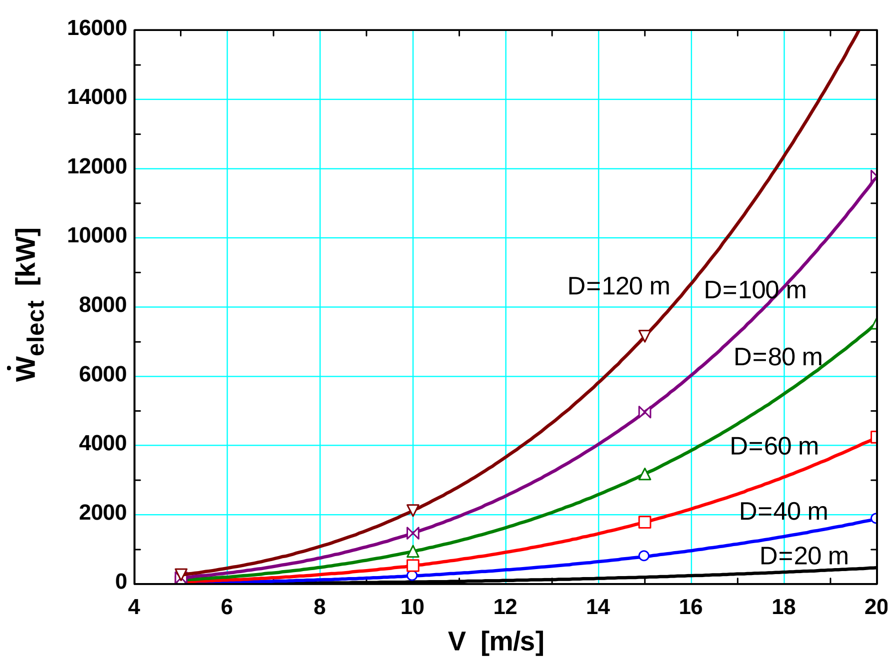
Analysis The problem is solved using EES, and the solution is given below.

```
"Given"
V=7 [m/s]
D=80 [m]
eta_overall=0.30
rho=1.25 [kg/m^3]

"Analysis"
g=9.81 [m/s^2]
A=pi*D^2/4
m_dot=rho*A*V
W_dot_max=m_dot*V^2/2*Convert(m^2/s^2, kJ/kg)
W_dot_elect=eta_overall*W_dot_max
```

Parametric Table

Table 1

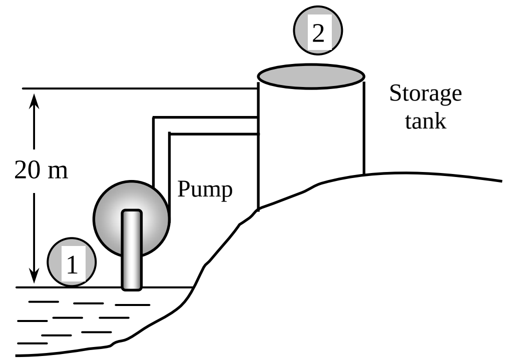
1..24	D [m]	V [m/s]	$\dot{m}$ [kg/s]	$\dot{W}_{elect}$ [kW]
Run 1	20	5	1963	7.363
Run 2	20	10	3927	58.9
Run 3	20	15	5890	198.8
Run 4	20	20	7854	471.2
Run 5	40	5	7854	29.45
Run 6	40	10	15708	235.6
Run 7	40	15	23562	795.2
Run 8	40	20	31416	1885
Run 9	60	5	17671	66.27
Run 10	60	10	35343	530.1
Run 11	60	15	53014	1789
Run 12	60	20	70686	4241
Run 13	80	5	31416	117.8
Run 14	80	10	62832	942.5
Run 15	80	15	94248	3181
Run 16	80	20	125664	7540
Run 17	100	5	49087	184.1
Run 18	100	10	98175	1473
Run 19	100	15	147262	4970
Run 20	100	20	196350	11781
Run 21	120	5	70686	265.1
Run 22	120	10	141372	2121
Run 23	120	15	212058	7157
Run 24	120	20	282743	16965



2-71 Water is pumped from a lake to a storage tank at a specified rate. The overall efficiency of the pump-motor unit and the pressure difference between the inlet and the exit of the pump are to be determined.

Assumptions **1** The elevations of the tank and the lake remain constant. **2** Frictional losses in the pipes are negligible. **3** The changes in kinetic energy are negligible. **4** The elevation difference across the pump is negligible.

Properties We take the density of water to be $\rho = 1000$ kg/m^3.



Analysis (*a*) We take the free surface of the lake to be point 1 and the free surfaces of the storage tank to be point 2. We also take the lake surface as the reference level ($z_1 = 0$), and thus the potential energy at points 1 and 2 are $pe_1 = 0$ and $pe_2 = gz_2$. The flow energy at both points is zero since both 1 and 2 are open to the atmosphere ($P_1 = P_2 = P_{atm}$). Further, the kinetic energy at both points is zero ($ke_1 = ke_2 = 0$) since the water at both locations is essentially stationary. The mass flow rate of water and its potential energy at point 2 are

$$\dot{m} = \rho\dot{V} = (1000 \text{ kg/m}^3)(0.070 \text{ m}^3\text{/s}) = 70 \text{ kg/s}$$

$$pe_2 = gz_2 = (9.81 \text{ m/s}^2)(20 \text{ m})\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2\text{/s}^2}\right) = 0.196 \text{ kJ/kg}$$

Then the rate of increase of the mechanical energy of water becomes

$$\Delta\dot{E}_{\text{mech,fluid}} = \dot{m}(e_{\text{mech,out}} - e_{\text{mech,in}}) = \dot{m}(pe_2 - 0) = \dot{m}pe_2 = (70 \text{ kg/s})(0.196 \text{ kJ/kg}) = 13.7 \text{ kW}$$

The overall efficiency of the combined pump-motor unit is determined from its definition,

$$\eta_{\text{pump-motor}} = \frac{\Delta\dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{elect,in}}} = \frac{13.7 \text{ kW}}{20.4 \text{ kW}} = 0.672 \quad \text{or} \quad \mathbf{67.2\%}$$

(*b*) Now we consider the pump. The change in the mechanical energy of water as it flows through the pump consists of the change in the flow energy only since the elevation difference across the pump and the change in the kinetic energy are negligible. Also, this change must be equal to the useful mechanical energy supplied by the pump, which is 13.7 kW:

$$\Delta\dot{E}_{\text{mech,fluid}} = \dot{m}(e_{\text{mech,out}} - e_{\text{mech,in}}) = \dot{m}\frac{P_2 - P_1}{\rho} = \dot{V}\Delta P$$

Solving for ΔP and substituting,

$$\Delta P = \frac{\Delta\dot{E}_{\text{mech,fluid}}}{\dot{V}} = \frac{13.7 \text{ kJ/s}}{0.070 \text{ m}^3\text{/s}}\left(\frac{1 \text{ kPa}\cdot\text{m}^3}{1 \text{ kJ}}\right) = \mathbf{196 \text{ kPa}}$$

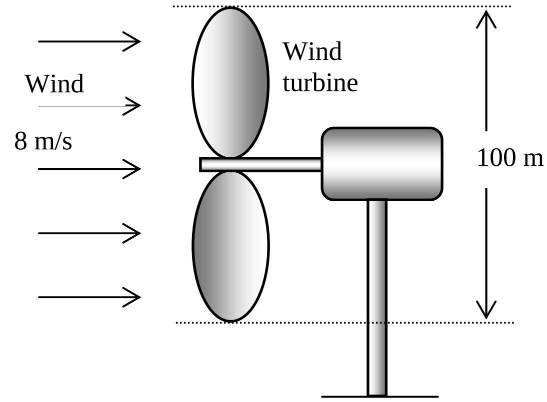
Therefore, the pump must boost the pressure of water by 196 kPa in order to raise its elevation by 20 m.

Discussion Note that only two-thirds of the electric energy consumed by the pump-motor is converted to the mechanical energy of water; the remaining one-third is wasted because of the inefficiencies of the pump and the motor.

2-72 A large wind turbine is installed at a location where the wind is blowing steadily at a certain velocity. The electric power generation, the daily electricity production, and the monetary value of this electricity are to be determined.

Assumptions **1** The wind is blowing steadily at a constant uniform velocity. **2** The efficiency of the wind turbine is independent of the wind speed.

Properties The density of air is given to be $\rho = 1.25\ \text{kg/m}^3$.



Analysis Kinetic energy is the only form of mechanical energy the wind possesses, and it can be converted to work entirely. Therefore, the power potential of the wind is its kinetic energy, which is $V^2/2$ per unit mass, and $\dot{m}V^2/2$ for a given mass flow rate:

$$e_{\text{mech}} = ke = \frac{V^2}{2} = \frac{(8\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 0.032\ \text{kJ/kg}$$

$$\dot{m} = \rho VA = \rho V\frac{\pi D^2}{4} = (1.25\ \text{kg/m}^3)(8\ \text{m/s})\frac{\pi(100\ \text{m})^2}{4} = 78{,}540\ \text{kg/s}$$

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (78{,}540\ \text{kg/s})(0.032\ \text{kJ/kg}) = 2513\ \text{kW}$$

The actual electric power generation is determined from

$$\dot{W}_{\text{elect}} = \eta_{\text{wind turbine}}\dot{W}_{\max} = (0.32)(2513\ \text{kW}) = \mathbf{804.2\ kW}$$

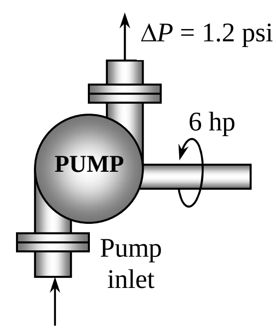
Then the amount of electricity generated per day and its monetary value become

Amount of electricity = (Wind power)(Operating hours)=(804.2 kW)(24 h) =**19,300 kWh**

Revenues = (Amount of electricity)(Unit price) = (19,300 kWh)($0.06/kWh) = **$1158** (per day)

Discussion Note that a single wind turbine can generate several thousand dollars worth of electricity every day at a reasonable cost, which explains the overwhelming popularity of wind turbines in recent years.

2-73E A water pump raises the pressure of water by a specified amount at a specified flow rate while consuming a known amount of electric power. The mechanical efficiency of the pump is to be determined.



Assumptions **1** The pump operates steadily. **2** The changes in velocity and elevation across the pump are negligible. **3** Water is incompressible.

Analysis To determine the mechanical efficiency of the pump, we need to know the increase in the mechanical energy of the fluid as it flows through the pump, which is

$$\Delta\dot{E}_{\text{mech,fluid}} = \dot{m}(e_{\text{mech,out}} - e_{\text{mech,in}}) = \dot{m}[(P\boldsymbol{v})_2 - (P\boldsymbol{v})_1] = \dot{m}(P_2 - P_1)\boldsymbol{v}$$

$$= \dot{\boldsymbol{V}}(P_2 - P_1) = (15\ \text{ft}^3/\text{s})(1.2\ \text{psi})\left(\frac{1\ \text{Btu}}{5.404\ \text{psi}\cdot\text{ft}^3}\right) = 3.33\ \text{Btu/s} = 4.71\ \text{hp}$$

since 1 hp = 0.7068 Btu/s, $\dot{m} = \rho\dot{\boldsymbol{V}} = \dot{\boldsymbol{V}}/\boldsymbol{v}$, and there is no change in kinetic and potential energies of the fluid. Then the mechanical efficiency of the pump becomes

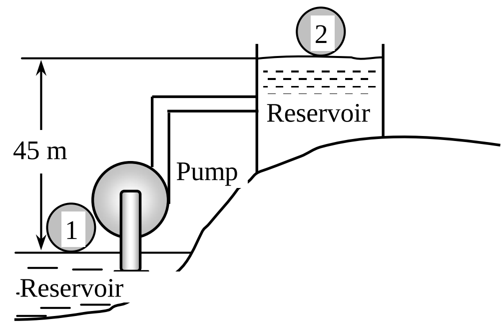
$$\eta_{\text{pump}} = \frac{\Delta\dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{pump, shaft}}} = \frac{4.71\ \text{hp}}{6\ \text{hp}} = 0.786 \quad \text{or} \quad \mathbf{78.6\%}$$

Discussion The overall efficiency of this pump will be lower than 83.8% because of the inefficiency of the electric motor that drives the pump.

2-74 Water is pumped from a lower reservoir to a higher reservoir at a specified rate. For a specified shaft power input, the power that is converted to thermal energy is to be determined.

Assumptions **1** The pump operates steadily. **2** The elevations of the reservoirs remain constant. **3** The changes in kinetic energy are negligible.

Properties We take the density of water to be ρ = 1000 kg/m^3.



Analysis The elevation of water and thus its potential energy changes during pumping, but it experiences no changes in its velocity and pressure. Therefore, the change in the total mechanical energy of water is equal to the change in its potential energy, which is gz per unit mass, and $\dot{m}gz$ for a given mass flow rate. That is,

$$\Delta\dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\Delta pe = \dot{m}g\Delta z = \rho\dot{V}g\Delta z$$

$$= (1000\ \text{kg/m}^3)(0.03\ \text{m}^3/\text{s})(9.81\ \text{m/s}^2)(45\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kW}}{1000\ \text{N}\cdot\text{m/s}}\right) = 13.2\ \text{kW}$$

Then the mechanical power lost because of frictional effects becomes

$$\dot{W}_{\text{frict}} = \dot{W}_{\text{pump, in}} - \Delta\dot{E}_{\text{mech}} = 20 - 13.2\ \text{kW} = \mathbf{6.8\ kW}$$

Discussion The 6.8 kW of power is used to overcome the friction in the piping system. The effect of frictional losses in a pump is always to convert mechanical energy to an equivalent amount of thermal energy, which results in a slight rise in fluid temperature. Note that this pumping process could be accomplished by a 13.2 kW pump (rather than 20 kW) if there were no frictional losses in the system. In this ideal case, the pump would function as a turbine when the water is allowed to flow from the upper reservoir to the lower reservoir and extract 13.2 kW of power from the water.

2-75 The mass flow rate of water through the hydraulic turbines of a dam is to be determined.

Analysis The mass flow rate is determined from

$$\dot{W} = \dot{m}g(z_2 - z_1) \longrightarrow \dot{m} = \frac{\dot{W}}{g(z_2 - z_1)} = \frac{100{,}000\ \text{kJ/s}}{(9.8\ \text{m/s}^2)(206 - 0)\ \text{m}\left(\dfrac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)} = \mathbf{49{,}500\ kg/s}$$

2-76 A pump is pumping oil at a specified rate. The pressure rise of oil in the pump is measured, and the motor efficiency is specified. The mechanical efficiency of the pump is to be determined.

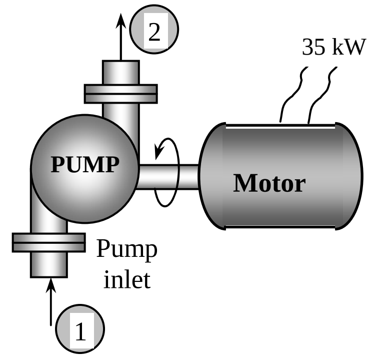
Assumptions **1** The flow is steady and incompressible. **2** The elevation difference across the pump is negligible.

Properties The density of oil is given to be ρ = 860 kg/m³.

Analysis Then the total mechanical energy of a fluid is the sum of the potential, flow, and kinetic energies, and is expressed per unit mass as $e_{\text{mech}} = gh + Pv + V^2/2$. To determine the mechanical efficiency of the pump, we need to know the increase in the mechanical energy of the fluid as it flows through the pump, which is

$$\Delta\dot{E}_{\text{mech,fluid}} = \dot{m}(e_{\text{mech,out}} - e_{\text{mech,in}}) = \dot{m}\left((Pv)_2 + \frac{V_2^2}{2} - (Pv)_1 - \frac{V_1^2}{2}\right) = \dot{\boldsymbol{V}}\left((P_2 - P_1) + \rho\frac{V_2^2 - V_1^2}{2}\right)$$

since $\dot{m} = \rho\dot{\boldsymbol{V}} = \dot{\boldsymbol{V}}/\boldsymbol{v}$, and there is no change in the potential energy of the fluid. Also,



$$V_1 = \frac{\dot{\boldsymbol{V}}}{A_1} = \frac{\dot{\boldsymbol{V}}}{\pi D_1^2/4} = \frac{0.1\,\text{m}^3/\text{s}}{\pi(0.08\,\text{m})^2/4} = 19.9\,\text{m/s}$$

$$V_2 = \frac{\dot{\boldsymbol{V}}}{A_2} = \frac{\dot{\boldsymbol{V}}}{\pi D_2^2/4} = \frac{0.1\,\text{m}^3/\text{s}}{\pi(0.12\,\text{m})^2/4} = 8.84\,\text{m/s}$$

Substituting, the useful pumping power is determined to be

$$\begin{aligned}\dot{W}_{\text{pump,u}} &= \Delta\dot{E}_{\text{mech,fluid}}\\ &= (0.1\,\text{m}^3/\text{s})\left(400\,\text{kN/m}^2 + (860\,\text{kg/m}^3)\frac{(8.84\,\text{m/s})^2 - (19.9\,\text{m/s})^2}{2}\left(\frac{1\,\text{kN}}{1000\,\text{kg}\cdot\text{m/s}^2}\right)\right)\left(\frac{1\,\text{kW}}{1\,\text{kN}\cdot\text{m/s}}\right)\\ &= 26.3\,\text{kW}\end{aligned}$$

Then the shaft power and the mechanical efficiency of the pump become

$$\dot{W}_{\text{pump,shaft}} = \eta_{\text{motor}}\dot{W}_{\text{electric}} = (0.90)(35\,\text{kW}) = 31.5\,\text{kW}$$

$$\eta_{\text{pump}} = \frac{\dot{W}_{\text{pump, u}}}{\dot{W}_{\text{pump, shaft}}} = \frac{26.3\,\text{kW}}{31.5\,\text{kW}} = 0.836 = \mathbf{83.6\%}$$

Discussion The overall efficiency of this pump/motor unit is the product of the mechanical and motor efficiencies, which is 0.9×0.836 = 0.75.

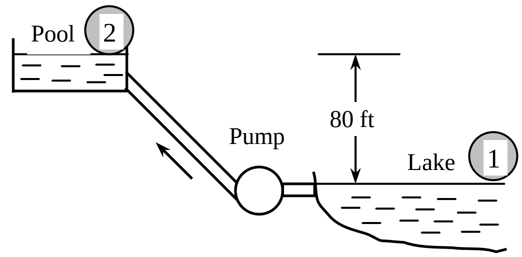
2-77E Water is pumped from a lake to a nearby pool by a pump with specified power and efficiency. The mechanical power used to overcome frictional effects is to be determined.

Assumptions **1** The flow is steady and incompressible. **2** The elevation difference between the lake and the free surface of the pool is constant. **3** The average flow velocity is constant since pipe diameter is constant.

Properties We take the density of water to be ρ = 62.4 lbm/ft^3.

Analysis The useful mechanical pumping power delivered to water is

$$\dot{W}_{\text{pump,u}} = \eta_{\text{pump}}\dot{W}_{\text{pump}} = (0.80)(20 \text{ hp}) = 16 \text{ hp}$$



The elevation of water and thus its potential energy changes during pumping, but it experiences no changes in its velocity and pressure. Therefore, the change in the total mechanical energy of water is equal to the change in its potential energy, which is gz per unit mass, and $\dot{m}gz$ for a given mass flow rate. That is,

$$\Delta\dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\Delta pe = \dot{m}g\Delta z = \rho\dot{V}g\Delta z$$

Substituting, the rate of change of mechanical energy of water becomes

$$\Delta\dot{E}_{\text{mech}} = (62.4 \text{ lbm/ft}^3)(1.5 \text{ ft}^3\text{/s})(32.2 \text{ ft/s}^2)(80 \text{ ft})\left(\frac{1 \text{ lbf}}{32.2 \text{ lbm}\cdot\text{ft/s}^2}\right)\left(\frac{1 \text{ hp}}{550 \text{ lbf}\cdot\text{ft/s}}\right) = 13.63 \text{ hp}$$

Then the mechanical power lost in piping because of frictional effects becomes

$$\dot{W}_{\text{frict}} = \dot{W}_{\text{pump, u}} - \Delta\dot{E}_{\text{mech}} = 16 - 13.63 \text{ hp} = \mathbf{2.37 \text{ hp}}$$

Discussion Note that the pump must supply to the water an additional useful mechanical power of 2.37 hp to overcome the frictional losses in pipes.

2-78 A wind turbine produces 180 kW of power. The average velocity of the air and the conversion efficiency of the turbine are to be determined.

Assumptions The wind turbine operates steadily.

Properties The density of air is given to be 1.31 kg/m^3.

Analysis (*a*) The blade diameter and the blade span area are

$$D = \frac{V_{\text{tip}}}{\pi \dot{n}} = \frac{(250\text{ km/h})\left(\dfrac{1\text{ m/s}}{3.6\text{ km/h}}\right)}{\pi (15\text{ L/min})\left(\dfrac{1\text{ min}}{60\text{ s}}\right)} = 88.42\text{ m}$$

$$A = \frac{\pi D^2}{4} = \frac{\pi (88.42\text{ m})^2}{4} = 6140\text{ m}^2$$

Then the average velocity of air through the wind turbine becomes

$$V = \frac{\dot{m}}{\rho A} = \frac{42{,}000\text{ kg/s}}{(1.31\text{ kg/m}^3)(6140\text{ m}^2)} = \mathbf{5.23\text{ m/s}}$$

(*b*) The kinetic energy of the air flowing through the turbine is

$$\dot{\text{KE}} = \frac{1}{2}\dot{m}\text{V}^2 = \frac{1}{2}(42{,}000\text{ kg/s})(5.23\text{ m/s})^2 = 574.3\text{ kW}$$

Then the conversion efficiency of the turbine becomes

$$\eta = \frac{\dot{W}}{\dot{\text{KE}}} = \frac{180\text{ kW}}{574.3\text{ kW}} = \mathbf{0.313} = \mathbf{31.3\%}$$

Discussion Note that about one-third of the kinetic energy of the wind is converted to power by the wind turbine, which is typical of actual turbines.

Energy and Environment

2-79C Energy conversion pollutes the soil, the water, and the air, and the environmental pollution is a serious threat to vegetation, wild life, and human health. The emissions emitted during the combustion of fossil fuels are responsible for smog, acid rain, and global warming and climate change. The primary chemicals that pollute the air are hydrocarbons (HC, also referred to as volatile organic compounds, VOC), nitrogen oxides (NOx), and carbon monoxide (CO). The primary source of these pollutants is the motor vehicles.

2-80C Smog is the brown haze that builds up in a large stagnant air mass, and hangs over populated areas on calm hot summer days. Smog is made up mostly of ground-level ozone (O_3), but it also contains numerous other chemicals, including carbon monoxide (CO), particulate matter such as soot and dust, volatile organic compounds (VOC) such as benzene, butane, and other hydrocarbons. Ground-level ozone is formed when hydrocarbons and nitrogen oxides react in the presence of sunlight in hot calm days. Ozone irritates eyes and damage the air sacs in the lungs where oxygen and carbon dioxide are exchanged, causing eventual hardening of this soft and spongy tissue. It also causes shortness of breath, wheezing, fatigue, headaches, nausea, and aggravate respiratory problems such as asthma.

2-81C Fossil fuels include small amounts of sulfur. The sulfur in the fuel reacts with oxygen to form sulfur dioxide (SO_2), which is an air pollutant. The sulfur oxides and nitric oxides react with water vapor and other chemicals high in the atmosphere in the presence of sunlight to form sulfuric and nitric acids. The acids formed usually dissolve in the suspended water droplets in clouds or fog. These acid-laden droplets are washed from the air on to the soil by rain or snow. This is known as *acid rain*. It is called “rain” since it comes down with rain droplets.

As a result of acid rain, many lakes and rivers in industrial areas have become too acidic for fish to grow. Forests in those areas also experience a slow death due to absorbing the acids through their leaves, needles, and roots. Even marble structures deteriorate due to acid rain.

2-82C Carbon monoxide, which is a colorless, odorless, poisonous gas that deprives the body's organs from getting enough oxygen by binding with the red blood cells that would otherwise carry oxygen. At low levels, carbon monoxide decreases the amount of oxygen supplied to the brain and other organs and muscles, slows body reactions and reflexes, and impairs judgment. It poses a serious threat to people with heart disease because of the fragile condition of the circulatory system and to fetuses because of the oxygen needs of the developing brain. At high levels, it can be fatal, as evidenced by numerous deaths caused by cars that are warmed up in closed garages or by exhaust gases leaking into the cars.

2-83C Carbon dioxide (CO_2), water vapor, and trace amounts of some other gases such as methane and nitrogen oxides act like a blanket and keep the earth warm at night by blocking the heat radiated from the earth. This is known as the *greenhouse effect*. The greenhouse effect makes life on earth possible by keeping the earth warm. But excessive amounts of these gases disturb the delicate balance by trapping too much energy, which causes the average temperature of the earth to rise and the climate at some localities to change. These undesirable consequences of the greenhouse effect are referred to as *global warming* or *global climate change*. The greenhouse effect can be reduced by reducing the net production of CO_2 by consuming less energy (for example, by buying energy efficient cars and appliances) and planting trees.

2-84E A person trades in his Ford Taurus for a Ford Explorer. The extra amount of CO_2 emitted by the Explorer within 5 years is to be determined.

Assumptions The Explorer is assumed to use 940 gallons of gasoline a year compared to 715 gallons for Taurus.

Analysis The extra amount of gasoline the Explorer will use within 5 years is

$$\begin{aligned}\text{Extra Gasoline} &= \text{(Extra per year)(No. of years)}\\ &= (940 - 715\text{ gal/yr})(5\text{ yr})\\ &= 1125\text{ gal}\\ \text{Extra } CO_2 \text{ produced} &= \text{(Extra gallons of gasoline used)}(CO_2 \text{ emission per gallon})\\ &= (1125\text{ gal})(19.7\text{ lbm/gal})\\ &= \mathbf{22{,}163\ lbm\ CO_2}\end{aligned}$$

Discussion Note that the car we choose to drive has a significant effect on the amount of greenhouse gases produced.

2-85 A power plant that burns natural gas produces 0.59 kg of carbon dioxide (CO_2) per kWh. The amount of CO_2 production that is due to the refrigerators in a city is to be determined.

Assumptions The city uses electricity produced by a natural gas power plant.

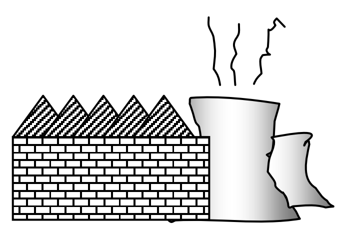
Properties 0.59 kg of CO_2 is produced per kWh of electricity generated (given).

Analysis Noting that there are 300,000 households in the city and each household consumes 700 kWh of electricity for refrigeration, the total amount of CO_2 produced is

$$\begin{aligned}\text{Amount of } CO_2 \text{ produced} &= \text{(Amount of electricity consumed)(Amount of } CO_2 \text{ per kWh)}\\ &= \text{(300,000 household)(700 kWh/year household)(0.59 kg/kWh)}\\ &= 1.23\times10^{8}\ CO_2\text{ kg/year}\\ &= \mathbf{123{,}000\ \ CO_2\ ton/year}\end{aligned}$$

Therefore, the refrigerators in this city are responsible for the production of 123,000 tons of CO_2.

2-86 A power plant that burns coal, produces 1.1 kg of carbon dioxide (CO_2) per kWh. The amount of CO_2 production that is due to the refrigerators in a city is to be determined.



Assumptions The city uses electricity produced by a coal power plant.

Properties 1.1 kg of CO_2 is produced per kWh of electricity generated (given).

Analysis Noting that there are 300,000 households in the city and each household consumes 700 kWh of electricity for refrigeration, the total amount of CO_2 produced is

$$\begin{aligned}\text{Amount of } CO_2 \text{ produced} &= \text{(Amount of electricity consumed)(Amount of } CO_2 \text{ per kWh)}\\ &= \text{(300,000 household)(700 kWh/household)(1.1 kg/kWh)}\\ &= 2.31\times10^{8}\ CO_2\text{ kg/year}\\ &= \mathbf{231{,}000\ \ CO_2\ ton/year}\end{aligned}$$

Therefore, the refrigerators in this city are responsible for the production of 231,000 tons of CO_2.

2-87E A household uses fuel oil for heating, and electricity for other energy needs. Now the household reduces its energy use by 20%. The reduction in the CO_2 production this household is responsible for is to be determined.

Properties The amount of CO_2 produced is 1.54 lbm per kWh and 26.4 lbm per gallon of fuel oil (given).

Analysis Noting that this household consumes 11,000 kWh of electricity and 1500 gallons of fuel oil per year, the amount of CO_2 production this household is responsible for is

$$\begin{aligned}\text{Amount of } CO_2 \text{ produced} &= (\text{Amount of electricity consumed})(\text{Amount of } CO_2 \text{ per kWh})\\ &\quad + (\text{Amount of fuel oil consumed})(\text{Amount of } CO_2 \text{ per gallon})\\ &= (11{,}000 \text{ kWh/yr})(1.54 \text{ lbm/kWh}) + (1500 \text{ gal/yr})(26.4 \text{ lbm/gal})\\ &= 56{,}540 \;\; CO_2 \text{ lbm/year}\end{aligned}$$

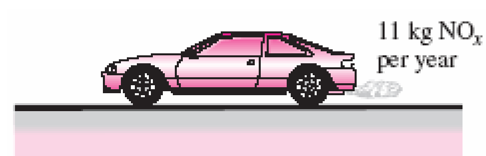
Then reducing the electricity and fuel oil usage by 15% will reduce the annual amount of CO_2 production by this household by

$$\begin{aligned}\text{Reduction in } CO_2 \text{ produced} &= (0.15)(\text{Current amount of } CO_2 \text{ production})\\ &= (0.15)(56{,}540 \;\; CO_2 \text{ kg/year})\\ &= \mathbf{8481 \;\; CO_2 \;\; lbm/year}\end{aligned}$$

Therefore, any measure that saves energy also reduces the amount of pollution emitted to the environment.

2-88 A household has 2 cars, a natural gas furnace for heating, and uses electricity for other energy needs. The annual amount of NO_x emission to the atmosphere this household is responsible for is to be determined.

Properties The amount of NO_x produced is 7.1 g per kWh, 4.3 g per therm of natural gas, and 11 kg per car (given).



Analysis Noting that this household has 2 cars, consumes 1200 therms of natural gas, and 9,000 kWh of electricity per year, the amount of NO_x production this household is responsible for is

$$\begin{aligned}\text{Amount of } NO_x \text{ produced} &= (\text{No. of cars})(\text{Amount of } NO_x \text{ produced per car})\\ &\quad + (\text{Amount of electricity consumed})(\text{Amount of } NO_x \text{ per kWh})\\ &\quad + (\text{Amount of gas consumed})(\text{Amount of } NO_x \text{ per gallon})\\ &= (2 \text{ cars})(11 \text{ kg/car}) + (9000 \text{ kWh/yr})(0.0071 \text{ kg/kWh})\\ &\qquad + (1200 \text{ therms/yr})(0.0043 \text{ kg/therm})\\ &= \mathbf{91.06 \;\; NO_x \;\; kg/year}\end{aligned}$$

Discussion Any measure that saves energy will also reduce the amount of pollution emitted to the atmosphere.

Special Topic: Mechanisms of Heat Transfer

2-89C The three mechanisms of heat transfer are conduction, convection, and radiation.

2-90C Diamond has a higher thermal conductivity than silver, and thus diamond is a better conductor of heat.

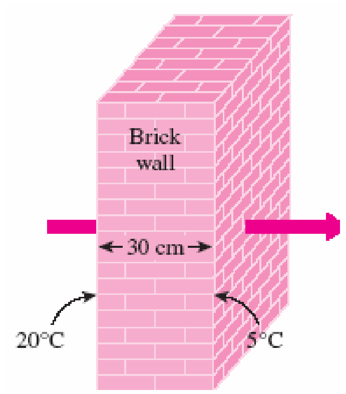
2-91C No. It is purely by radiation.

2-92C In forced convection, the fluid is forced to move by external means such as a fan, pump, or the wind. The fluid motion in natural convection is due to buoyancy effects only.

2-93C A blackbody is an idealized body that emits the maximum amount of radiation at a given temperature, and that absorbs all the radiation incident on it. Real bodies emit and absorb less radiation than a blackbody at the same temperature.

2-94C Emissivity is the ratio of the radiation emitted by a surface to the radiation emitted by a blackbody at the same temperature. Absorptivity is the fraction of radiation incident on a surface that is absorbed by the surface. The Kirchhoff's law of radiation states that the emissivity and the absorptivity of a surface are equal at the same temperature and wavelength.

2-95 The inner and outer surfaces of a brick wall are maintained at specified temperatures. The rate of heat transfer through the wall is to be determined.



Assumptions **1** Steady operating conditions exist since the surface temperatures of the wall remain constant at the specified values. **2** Thermal properties of the wall are constant.

Properties The thermal conductivity of the wall is given to be $k = 0.69$ W/m·°C.

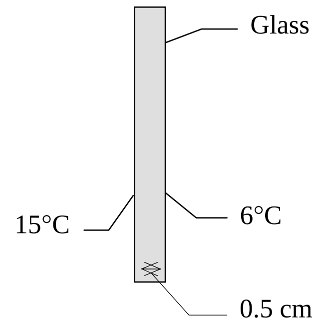
Analysis Under steady conditions, the rate of heat transfer through the wall is

$$\dot{Q}_{\text{cond}} = kA\frac{\Delta T}{L} = (0.69 \text{ W/m}\cdot°\text{C})(5\times 6 \text{ m}^2)\frac{(20-5)°\text{C}}{0.3 \text{ m}} = \mathbf{1035\ W}$$

2-96 The inner and outer surfaces of a window glass are maintained at specified temperatures. The amount of heat transferred through the glass in 5 h is to be determined.

Assumptions **1** Steady operating conditions exist since the surface temperatures of the glass remain constant at the specified values. **2** Thermal properties of the glass are constant.

Properties The thermal conductivity of the glass is given to be k = 0.78 W/m·°C.



Analysis Under steady conditions, the rate of heat transfer through the glass by conduction is

$$\dot{Q}_{\text{cond}} = kA\frac{\Delta T}{L} = (0.78\text{ W/m}\cdot°\text{C})(2\times 2\text{ m}^2)\frac{(15-6)°\text{C}}{0.005\text{ m}} = 5616\text{ W}$$

Then the amount of heat transferred over a period of 10 h becomes

$$Q = \dot{Q}_{\text{cond}}\Delta t = (5.616\text{ kJ/s})(10\times 3600\text{s}) = \mathbf{202{,}200\ kJ}$$

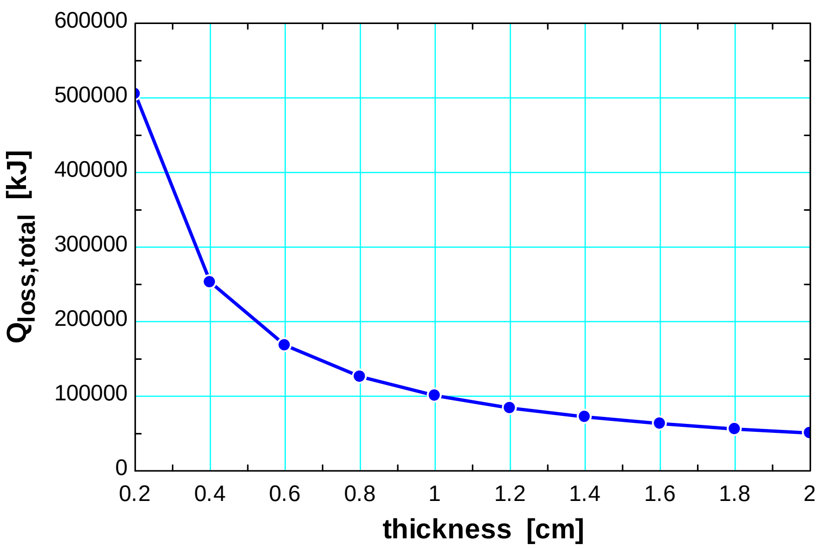
If the thickness of the glass is doubled to 1 cm, then the amount of heat transferred will go down by half to **101,100 kJ**.

2-97 Reconsider Prob. 2-96. Using EES (or other) software, investigate the effect of glass thickness on heat loss for the specified glass surface temperatures. Let the glass thickness vary from 0.2 cm to 2 cm. Plot the heat loss versus the glass thickness, and discuss the results.

Analysis The problem is solved using EES, and the solution is given below.

```
FUNCTION  klookup(material$)
If material$='Glass'  then klookup:=0.78
If material$='Brick'  then klookup:=0.72
If material$='Fiber Glass'  then klookup:=0.043
If material$='Air'  then klookup:=0.026
If material$='Wood(oak)'  then klookup:=0.17

END

L=2 [m]
W=2 [m]
material$='Glass'
T_in=15 [C]
T_out=6 [C]
k=0.78 [W/m-C]
t=10 [hr]
thickness=0.5 [cm]
A=L*W
Q_dot_loss=A*k*(T_in-T_out)/(thickness*convert(cm,m))
Q_loss_total=Q_dot_loss*t*convert(hr,s)*convert(J,kJ)
```

Thickness [cm]	$Q_{loss,total}$ [kJ
0.2	505440
0.4	252720
0.6	168480
0.8	126360
1	101088
1.2	84240
1.4	72206
1.6	63180
1.8	56160
2	50544

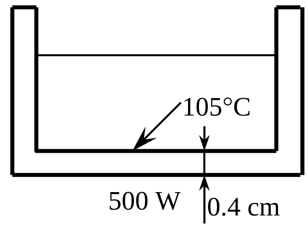


2-98 Heat is transferred steadily to boiling water in the pan through its bottom. The inner surface temperature of the bottom of the pan is given. The temperature of the outer surface is to be determined.

Assumptions **1** Steady operating conditions exist since the surface temperatures of the pan remain constant at the specified values. **2** Thermal properties of the aluminum pan are constant.

Properties The thermal conductivity of the aluminum is given to be k = 237 W/m·°C.

Analysis The heat transfer surface area is



$$A = \pi r^2 = \pi(0.1\text{ m})^2 = 0.0314\text{ m}^2$$

Under steady conditions, the rate of heat transfer through the bottom of the pan by conduction is

$$\dot{Q} = kA\frac{\Delta T}{L} = kA\frac{T_2 - T_1}{L}$$

Substituting,

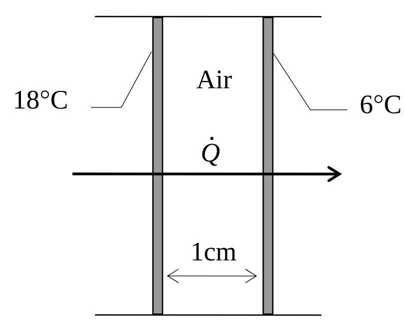
$$500\text{ W} = (237\text{ W/m}\cdot^\circ\text{C})(0.0314\text{ m}^2)\frac{T_2 - 105^\circ\text{C}}{0.004\text{ m}}$$

which gives

$$T_2 = \mathbf{105.3^\circ C}$$

2-99 The inner and outer glasses of a double pane window with a 1-cm air space are at specified temperatures. The rate of heat transfer through the window is to be determined.

Assumptions **1** Steady operating conditions exist since the surface temperatures of the glass remain constant at the specified values. **2** Heat transfer through the window is one-dimensional. **3** Thermal properties of the air are constant. **4** The air trapped between the two glasses is still, and thus heat transfer is by conduction only.

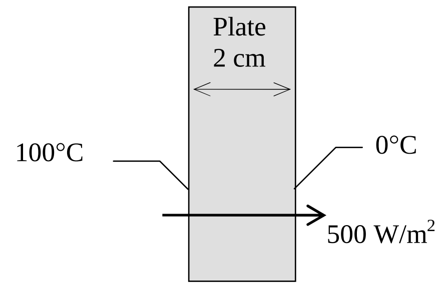


Properties The thermal conductivity of air at room temperature is k = 0.026 W/m.°C (Table 2-3).

Analysis Under steady conditions, the rate of heat transfer through the window by conduction is

$$\dot{Q}_{\text{cond}} = kA\frac{\Delta T}{L} = (0.026\text{ W/m}\cdot^\circ\text{C})(2\times 2\text{ m}^2)\frac{(18-6)^\circ\text{C}}{0.01\text{ m}} = \mathbf{125\ W} = \mathbf{0.125\ kW}$$

2-100 Two surfaces of a flat plate are maintained at specified temperatures, and the rate of heat transfer through the plate is measured. The thermal conductivity of the plate material is to be determined.



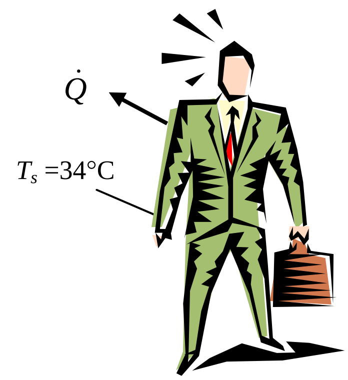
Assumptions **1** Steady operating conditions exist since the surface temperatures of the plate remain constant at the specified values. **2** Heat transfer through the plate is one-dimensional. **3** Thermal properties of the plate are constant.

Analysis The thermal conductivity is determined directly from the steady one-dimensional heat conduction relation to be

$$\dot{Q} = kA\frac{T_1 - T_2}{L}$$

$$k = \frac{(\dot{Q}/A)L}{T_1 - T_2} = \frac{(500\ \text{W/m}^2)(0.02\ \text{m})}{(100 - 0)°\text{C}} = \mathbf{0.1\ W/m.°C}$$

2-101 A person is standing in a room at a specified temperature. The rate of heat transfer between a person and the surrounding air by convection is to be determined.



Assumptions **1** Steady operating conditions exist. **2** Heat transfer by radiation is not considered. **3** The environment is at a uniform temperature.

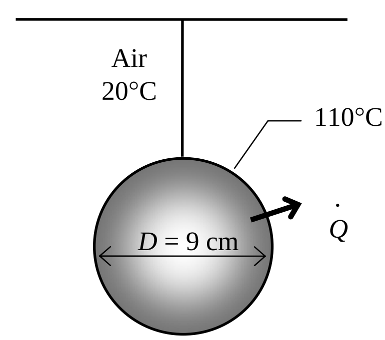
Analysis The heat transfer surface area of the person is

$$A = \pi DL = \pi(0.3\ \text{m})(1.70\ \text{m}) = 1.60\ \text{m}^2$$

Under steady conditions, the rate of heat transfer by convection is

$$\dot{Q}_{\text{conv}} = hA\Delta T = (15\ \text{W/m}^2\cdot°\text{C})(1.60\ \text{m}^2)(34 - 20)°\text{C} = \mathbf{336\ W}$$

2-102 A spherical ball whose surface is maintained at a temperature of 110°C is suspended in the middle of a room at 20°C. The total rate of heat transfer from the ball is to be determined.



Assumptions **1** Steady operating conditions exist since the ball surface and the surrounding air and surfaces remain at constant temperatures. **2** The thermal properties of the ball and the convection heat transfer coefficient are constant and uniform.

Properties The emissivity of the ball surface is given to be ε = 0.8.

Analysis The heat transfer surface area is

$$A = \pi D^2 = \pi(0.09\ \text{m})^2 = 0.02545\ \text{m}^2$$

Under steady conditions, the rates of convection and radiation heat transfer are

$$\dot{Q}_{\text{conv}} = hA\Delta T = (15\ \text{W/m}^2\cdot°\text{C})(0.02545\ \text{m}^2)(110 - 20)°\text{C} = 34.35\ \text{W}$$

$$\dot{Q}_{\text{rad}} = \varepsilon\sigma A(T_s^4 - T_o^4) = 0.8(0.02545\ \text{m}^2)(5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)[(383\ \text{K})^4 - (293\ \text{K})^4] = 16.33\ \text{W}$$

Therefore,

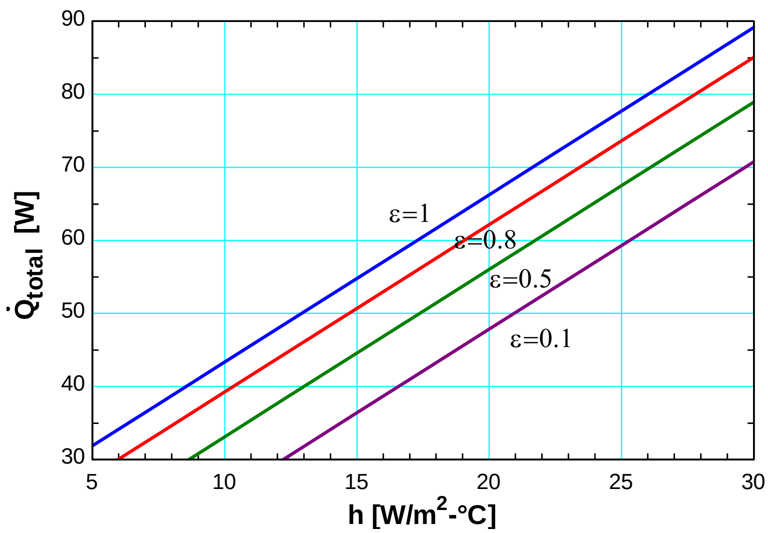
$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = 34.35 + 16.33 = \mathbf{50.7\ W}$$

2-103 Reconsider Prob. 2-102. Using EES (or other) software, investigate the effect of the convection heat transfer coefficient and surface emissivity on the heat transfer rate from the ball. Let the heat transfer coefficient vary from 5 W/m^2.°C to 30 W/m^2.°C. Plot the rate of heat transfer against the convection heat transfer coefficient for the surface emissivities of 0.1, 0.5, 0.8, and 1, and discuss the results.

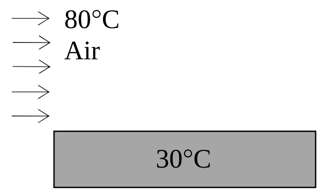
Analysis The problem is solved using EES, and the solution is given below.

```
"Given"
D=0.09 [m]
T_s=ConvertTemp(C,K,110)
T_f=ConvertTemp(C,K,20)
h=15 [W/m^2-C]
epsilon=0.8

"Properties"
sigma=5.67E-8 [W/m^2-K^4]

"Analysis"
A=pi*D^2
Q_dot_conv=h*A*(T_s-T_f)
Q_dot_rad=epsilon*sigma*A*(T_s^4-T_f^4)
Q_dot_total=Q_dot_conv+Q_dot_rad
```

h [W/m^2-C]	Q_{total} [W]
5	27.8
7.5	33.53
10	39.25
12.5	44.98
15	50.7
17.5	56.43
20	62.16
22.5	67.88
25	73.61
27.5	79.33
30	85.06



2-104 Hot air is blown over a flat surface at a specified temperature. The rate of heat transfer from the air to the plate is to be determined.

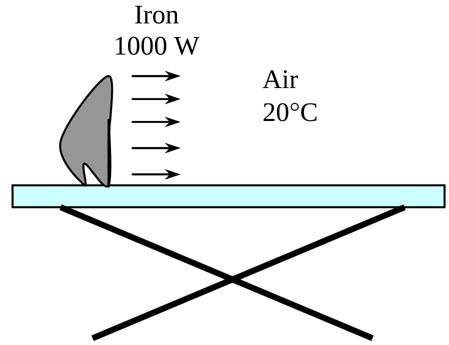


Assumptions **1** Steady operating conditions exist. **2** Heat transfer by radiation is not considered. **3** The convection heat transfer coefficient is constant and uniform over the surface.

Analysis Under steady conditions, the rate of heat transfer by convection is

$$\begin{aligned}\dot{Q}_{\text{conv}} &= hA\Delta T\\ &= (55\ \text{W/m}^2\cdot{}^\circ\text{C})(2\times 4\ \text{m}^2)(80-30)^\circ\text{C}\\ &= \mathbf{22{,}000\ W} = \mathbf{22\ kW}\end{aligned}$$

2-105 A 1000-W iron is left on the iron board with its base exposed to the air at 20°C. The temperature of the base of the iron is to be determined in steady operation.



Assumptions **1** Steady operating conditions exist. **2** The thermal properties of the iron base and the convection heat transfer coefficient are constant and uniform. **3** The temperature of the surrounding surfaces is the same as the temperature of the surrounding air.

Properties The emissivity of the base surface is given to be $\varepsilon = 0.6$.

Analysis At steady conditions, the 1000 W of energy supplied to the iron will be dissipated to the surroundings by convection and radiation heat transfer. Therefore,

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = 1000\ \text{W}$$

where

$$\dot{Q}_{\text{conv}} = hA\Delta T = (35\ \text{W/m}^2\cdot\text{K})(0.02\ \text{m}^2)(T_s - 293\ \text{K}) = 0.7(T_s - 293\ \text{K})\ \text{W}$$

and

$$\begin{aligned}\dot{Q}_{\text{rad}} &= \varepsilon\sigma A(T_s^4 - T_o^4) = 0.6(0.02\ \text{m}^2)(5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)[\text{T}_s^4 - (293\ \text{K})^4]\\ &= 0.06804\times10^{-8}[T_s^4 - (293\ \text{K})^4]\ \text{W}\end{aligned}$$

Substituting,

$$1000\ \text{W} = 0.7(T_s - 293\ \text{K}) + 0.06804\times10^{-8}[T_s^4 - (293\ \text{K})^4]$$

Solving by trial and error gives

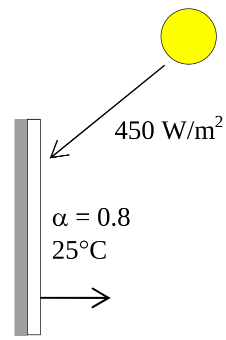
$$T_s = \mathbf{947\ K} = \mathbf{674^\circ C}$$

Discussion We note that the iron will dissipate all the energy it receives by convection and radiation when its surface temperature reaches 947 K.

2-106 The backside of the thin metal plate is insulated and the front side is exposed to solar radiation. The surface temperature of the plate is to be determined when it stabilizes.

Assumptions **1** Steady operating conditions exist. **2** Heat transfer through the insulated side of the plate is negligible. **3** The heat transfer coefficient is constant and uniform over the plate. **4** Heat loss by radiation is negligible.

Properties The solar absorptivity of the plate is given to be α = 0.8.



Analysis When the heat loss from the plate by convection equals the solar radiation absorbed, the surface temperature of the plate can be determined from

$$\dot{Q}_{\text{solarabsorbed}} = \dot{Q}_{\text{conv}}$$
$$\alpha \dot{Q}_{\text{solar}} = hA(T_s - T_o)$$
$$0.8 \times A \times 450 \text{ W/m}^2 = (50 \text{ W/m}^2 \cdot {}^\circ\text{C})A(T_s - 25)$$

Canceling the surface area A and solving for T_s gives

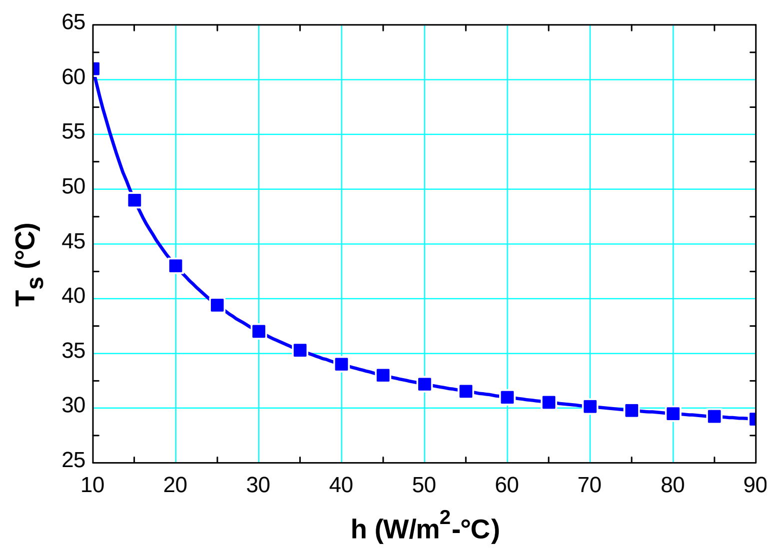
$$T_s = \mathbf{32.2^\circ C}$$

2-107 Reconsider Prob. 2-106. Using EES (or other) software, investigate the effect of the convection heat transfer coefficient on the surface temperature of the plate. Let the heat transfer coefficient vary from 10 W/m^2.°C to 90 W/m^2.°C. Plot the surface temperature against the convection heat transfer coefficient, and discuss the results.

Analysis The problem is solved using EES, and the solution is given below.

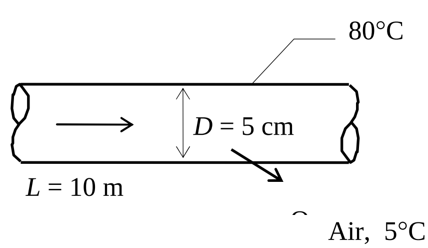
```
"Given"
alpha=0.8
q_dot_solar=450 [W/m^2]
T_f=25 [C]
h=50 [W/m^2-C]

"Analysis"
q_dot_solarabsorbed=alpha*q_dot_solar
q_dot_conv=h*(T_s-T_f)
q_dot_solarabsorbed=q_dot_conv
```

h [W/m^2-C]	T_s [C]
10	61
15	49
20	43
25	39.4
30	37
35	35.29
40	34
45	33
50	32.2
55	31.55
60	31
65	30.54
70	30.14
75	29.8
80	29.5
85	29.24
90	29



2-108 A hot water pipe at 80°C is losing heat to the surrounding air at 5°C by natural convection with a heat transfer coefficient of 25 W/ m^2.°C. The rate of heat loss from the pipe by convection is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Heat transfer by radiation is not considered. **3** The convection heat transfer coefficient is constant and uniform over the surface.



Analysis The heat transfer surface area is

$$A = (\pi D)L = 3.14\text{x}(0.05 \text{ m})(10 \text{ m}) = 1.571 \text{ m}^2$$

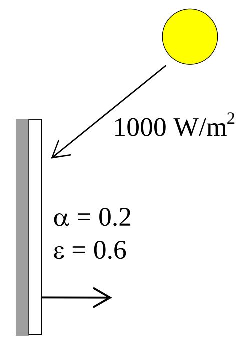
Under steady conditions, the rate of heat transfer by convection is

$$\dot{Q}_{\text{conv}} = hA\Delta T = (25 \text{ W/m}^2\cdot°\text{C})(1.571 \text{ m}^2)(80-5)°\text{C} = \mathbf{2945\ W} = \mathbf{2.95\ kW}$$

2-109 A spacecraft in space absorbs solar radiation while losing heat to deep space by thermal radiation. The surface temperature of the spacecraft is to be determined when steady conditions are reached..

Assumptions **1** Steady operating conditions exist since the surface temperatures of the wall remain constant at the specified values. **2** Thermal properties of the spacecraft are constant.

Properties The outer surface of a spacecraft has an emissivity of 0.6 and an absorptivity of 0.2.



Analysis When the heat loss from the outer surface of the spacecraft by radiation equals the solar radiation absorbed, the surface temperature can be determined from

$$\dot{Q}_{\text{solarabsorbed}} = \dot{Q}_{\text{rad}}$$

$$\alpha \dot{Q}_{\text{solar}} = \varepsilon \sigma A (T_s^4 - T_{\text{space}}^4)$$

$$0.2 \times A \times (1000 \text{ W/m}^2) = 0.6 \times A \times (5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)[T_s^4 - (0 \text{ K})^4]$$

Canceling the surface area A and solving for T_s gives

$$T_s = \mathbf{276.9 \ K}$$

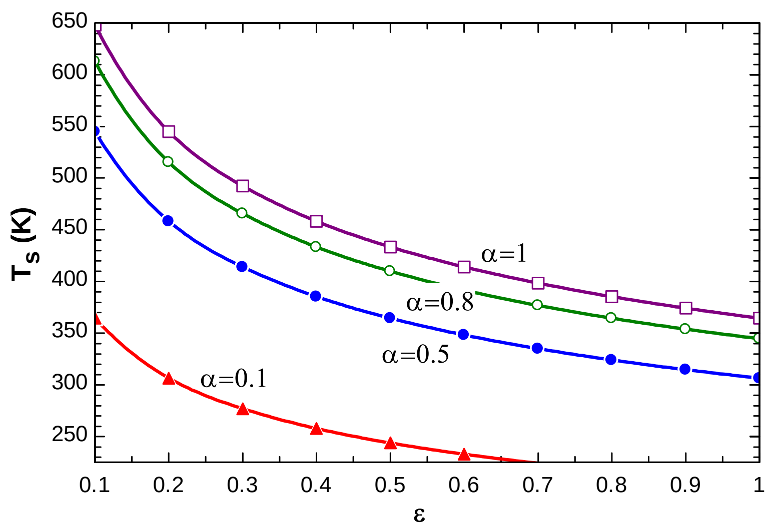
2-110 Reconsider Prob. 2-109. Using EES (or other) software, investigate the effect of the surface emissivity and absorptivity of the spacecraft on the equilibrium surface temperature. Plot the surface temperature against emissivity for solar absorptivities of 0.1, 0.5, 0.8, and 1, and discuss the results.

Analysis The problem is solved using EES, and the solution is given below.

```
"Given"
epsilon=0.2
alpha=0.6
q_dot_solar=1000 [W/m^2]
T_f=0 [K] "space temperature"

"Properties"
sigma=5.67E-8 [W/m^2-K^4]

"Analysis"
q_dot_solarabsorbed=alpha*q_dot_solar
q_dot_rad=epsilon*sigma*(T_s^4-T_f^4)
q_dot_solarabsorbed=q_dot_rad
```

ε	T_s [K]
0.1	648
0.2	544.9
0.3	492.4
0.4	458.2
0.5	433.4
0.6	414.1
0.7	398.4
0.8	385.3
0.9	374.1
1	364.4

Table for ε = 1

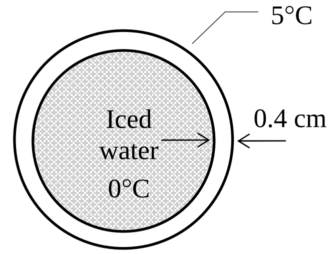


2-111 A hollow spherical iron container is filled with iced water at 0°C. The rate of heat loss from the sphere and the rate at which ice melts in the container are to be determined.

Assumptions **1** Steady operating conditions exist since the surface temperatures of the wall remain constant at the specified values. **2** Heat transfer through the shell is one-dimensional. **3** Thermal properties of the iron shell are constant. **4** The inner surface of the shell is at the same temperature as the iced water, 0°C.

Properties The thermal conductivity of iron is k = 80.2 W/m·°C (Table 2-3). The heat of fusion of water is at 1 atm is 333.7 kJ/kg.

Analysis This spherical shell can be approximated as a plate of thickness 0.4 cm and surface area



$$A = \pi D^2 = 3.14\times(0.2\text{ m})^2 = 0.126\text{ m}^2$$

Then the rate of heat transfer through the shell by conduction is

$$\dot{Q}_{\text{cond}} = kA\frac{\Delta T}{L} = (80.2\text{ W/m}\cdot^\circ\text{C})(0.126\text{ m}^2)\frac{(5-0)^\circ\text{C}}{0.004\text{ m}} = \mathbf{12{,}632\ W}$$

Considering that it takes 333.7 kJ of energy to melt 1 kg of ice at 0°C, the rate at which ice melts in the container can be determined from

$$\dot{m}_{\text{ice}} = \frac{\dot{Q}}{h_{if}} = \frac{12.632\text{ kJ/s}}{333.7\text{ kJ/kg}} = \mathbf{0.038\ kg/s}$$

Discussion We should point out that this result is slightly in error for approximating a curved wall as a plain wall. The error in this case is very small because of the large diameter to thickness ratio. For better accuracy, we could use the inner surface area (D = 19.2 cm) or the mean surface area (D = 19.6 cm) in the calculations.

Review Problems

2-112 A classroom has a specified number of students, instructors, and fluorescent light bulbs. The rate of internal heat generation in this classroom is to be determined.

Assumptions **1** There is a mix of men, women, and children in the classroom. **2** The amount of light (and thus energy) leaving the room through the windows is negligible.

Properties The average rate of heat generation from people seated in a room/office is given to be 100 W.

Analysis The amount of heat dissipated by the lamps is equal to the amount of electrical energy consumed by the lamps, including the 10% additional electricity consumed by the ballasts. Therefore,

$$\dot{Q}_{\text{lighting}} = (\text{Energy consumed per lamp}) \times (\text{No. of lamps})$$
$$= (40 \text{ W})(1.1)(18) = 792 \text{ W}$$
$$\dot{Q}_{\text{people}} = (\text{No. of people}) \times \dot{Q}_{\text{person}} = 56 \times (100 \text{ W}) = 5600 \text{ W}$$

Then the total rate of heat gain (or the internal heat load) of the classroom from the lights and people become

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{lighting}} + \dot{Q}_{\text{people}} = 792 + 5600 = \mathbf{6392 \text{ W}}$$

2-113 A decision is to be made between a cheaper but inefficient natural gas heater and an expensive but efficient natural gas heater for a house.

Assumptions The two heaters are comparable in all aspects other than the initial cost and efficiency.

Analysis Other things being equal, the logical choice is the heater that will cost less during its lifetime. The total cost of a system during its lifetime (the initial, operation, maintenance, etc.) can be determined by performing a life cycle cost analysis. A simpler alternative is to determine the simple payback period.

Gas Heater
$\eta_1 = 82\%$
$\eta_2 = 95\%$

The annual heating cost is given to be $1200. Noting that the existing heater is 55% efficient, only 55% of that energy (and thus money) is delivered to the house, and the rest is wasted due to the inefficiency of the heater. Therefore, the monetary value of the heating load of the house is

$$\text{Cost of useful heat} = (55\%)(\text{Current annual heating cost})$$
$$= 0.55 \times (\$1200/\text{yr}) = \$660/\text{yr}$$

This is how much it would cost to heat this house with a heater that is 100% efficient. For heaters that are less efficient, the annual heating cost is determined by dividing $660 by the efficiency:

82% heater: Annual cost of heating = (Cost of useful heat)/Efficiency = ($660/yr)/0.82 = $805/yr

95% heater: Annual cost of heating = (Cost of useful heat)/Efficiency = ($660/yr)/0.95 = $695/yr

Annual cost savings with the efficient heater = 805 - 695 = $110

Excess initial cost of the efficient heater = 2700 - 1600 = $1100

The simple payback period becomes

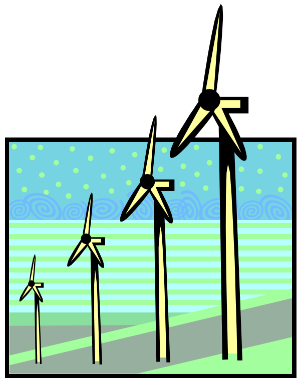
$$\text{Simple payback period} = \frac{\text{Excess initial cost}}{\text{Annaul cost savings}} = \frac{\$1100}{\$110/\text{yr}} = \mathbf{10 \text{ years}}$$

Therefore, the more efficient heater will pay for the $1100 cost differential in this case in 10 years, which is more than the 8-year limit. Therefore, the purchase of the cheaper and less efficient heater is a better buy in this case.

2-114 A wind turbine is rotating at 20 rpm under steady winds of 30 km/h. The power produced, the tip speed of the blade, and the revenue generated by the wind turbine per year are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The wind turbine operates continuously during the entire year at the specified conditions.

Properties The density of air is given to be $\rho = 1.20$ kg/m^3.



Analysis (*a*) The blade span area and the mass flow rate of air through the turbine are

$$A = \pi D^2/4 = \pi(80\text{ m})^2/4 = 5027\text{ m}^2$$

$$V = (30\text{ km/h})\left(\frac{1000\text{ m}}{1\text{ km}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right) = 8.333\text{ m/s}$$

$$\dot{m} = \rho A V = (1.2\text{ kg/m}^3)(5027\text{ m}^2)(8.333\text{ m/s}) = 50{,}270\text{ kg/s}$$

Noting that the kinetic energy of a unit mass is $V^2/2$ and the wind turbine captures 35% of this energy, the power generated by this wind turbine becomes

$$\dot{W} = \eta\left(\frac{1}{2}\dot{m}V^2\right) = (0.35)\frac{1}{2}(50{,}270\text{ kg/s})(8.333\text{ m/s})^2\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = \mathbf{610.9\ kW}$$

(*b*) Noting that the tip of blade travels a distance of πD per revolution, the tip velocity of the turbine blade for an rpm of $\dot{n}$ becomes

$$V_{\text{tip}} = \pi D\dot{n} = \pi(80\text{ m})(20/\text{min}) = 5027\text{ m/min} = 83.8\text{ m/s} = \mathbf{302\ km/h}$$

(*c*) The amount of electricity produced and the revenue generated per year are

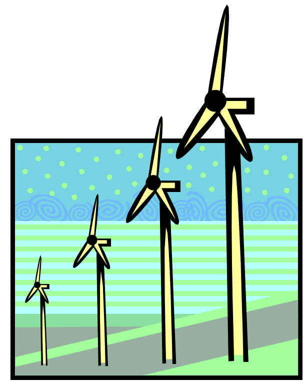
$$\text{Electricity produced} = \dot{W}\Delta t = (610.9\text{ kW})(365\times 24\text{ h/year})$$
$$= 5.351\times 10^6\text{ kWh/year}$$

$$\text{Revenue generated} = (\text{Electricity produced})(\text{Unit price}) = (5.351\times 10^6\text{ kWh/year})(\$0.06/\text{kWh})$$
$$= \mathbf{\$321{,}100/year}$$

2-115 A wind turbine is rotating at 20 rpm under steady winds of 20 km/h. The power produced, the tip speed of the blade, and the revenue generated by the wind turbine per year are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The wind turbine operates continuously during the entire year at the specified conditions.

Properties The density of air is given to be $\rho = 1.20\ \text{kg/m}^3$.



Analysis (*a*) The blade span area and the mass flow rate of air through the turbine are

$$A = \pi D^2/4 = \pi(80\ \text{m})^2/4 = 5027\ \text{m}^2$$

$$V = (20\ \text{km/h})\left(\frac{1000\ \text{m}}{1\ \text{km}}\right)\left(\frac{1\ \text{h}}{3600\ \text{s}}\right) = 5.556\ \text{m/s}$$

$$\dot{m} = \rho AV = (1.2\ \text{kg/m}^3)(5027\ \text{m}^2)(5.556\ \text{m/s}) = 33{,}510\ \text{kg/s}$$

Noting that the kinetic energy of a unit mass is $V^2/2$ and the wind turbine captures 35% of this energy, the power generated by this wind turbine becomes

$$\dot{W} = \eta\left(\frac{1}{2}\dot{m}V^2\right) = (0.35)\frac{1}{2}(33{,}510\ \text{kg/s})(6.944\ \text{m/s})^2\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = \mathbf{181.0\ kW}$$

(*b*) Noting that the tip of blade travels a distance of πD per revolution, the tip velocity of the turbine blade for an rpm of $\dot{n}$ becomes

$$V_{\text{tip}} = \pi D\dot{n} = \pi(80\ \text{m})(20/\text{min}) = 5027\ \text{m/min} = 83.8\ \text{m/s} = \mathbf{302\ km/h}$$

(*c*) The amount of electricity produced and the revenue generated per year are

$$\begin{aligned}\text{Electricity produced} &= \dot{W}\Delta t = (181.0\ \text{kW})(365 \times 24\ \text{h/year})\\ &= 1{,}585{,}535\ \text{kWh/year}\\ \text{Revenue generated} &= (\text{Electricity produced})(\text{Unit price}) = (1{,}585{,}535\ \text{kWh/year})(\$0.06/\text{kWh})\\ &= \mathbf{\$95{,}130/year}\end{aligned}$$

2-116E The energy contents, unit costs, and typical conversion efficiencies of various energy sources for use in water heaters are given. The lowest cost energy source is to be determined.

Assumptions The differences in installation costs of different water heaters are not considered.

Properties The energy contents, unit costs, and typical conversion efficiencies of different systems are given in the problem statement.

Analysis The unit cost of each Btu of useful energy supplied to the water heater by each system can be determined from

$$\text{Unit cost of useful energy} = \frac{\text{Unit cost of energy supplied}}{\text{Conversion efficiency}}$$

Substituting,

Natural gas heater: $\text{Unit cost of useful energy} = \frac{\$0.012/\text{ft}^3}{0.55}\left(\frac{1\,\text{ft}^3}{1025\,\text{Btu}}\right) = \$21.3\times10^{-6}\ /\ \text{Btu}$

Heating by oil heater: $\text{Unit cost of useful energy} = \frac{\$1.15/\text{gal}}{0.55}\left(\frac{1\,\text{gal}}{138{,}700\ \text{Btu}}\right) = \$15.1\times10^{-6}\ /\ \text{Btu}$

Electric heater: $\text{Unit cost of useful energy} = \frac{\$0.084/\text{kWh})}{0.90}\left(\frac{1\,\text{kWh}}{3412\ \text{Btu}}\right) = \$27.4\times10^{-6}\ /\ \text{Btu}$

Therefore, the lowest cost energy source for hot water heaters in this case is **oil**.

2-117 A home owner is considering three different heating systems for heating his house. The system with the lowest energy cost is to be determined.

Assumptions The differences in installation costs of different heating systems are not considered.

Properties The energy contents, unit costs, and typical conversion efficiencies of different systems are given in the problem statement.

Analysis The unit cost of each Btu of useful energy supplied to the house by each system can be determined from

$$\text{Unit cost of useful energy} = \frac{\text{Unit cost of energy supplied}}{\text{Conversion efficiency}}$$

Substituting,

Natural gas heater: $\text{Unit cost of useful energy} = \frac{\$1.24/\text{therm}}{0.87}\left(\frac{1\,\text{therm}}{105{,}500\ \text{kJ}}\right) = \$13.5\times10^{-6}\ /\ \text{kJ}$

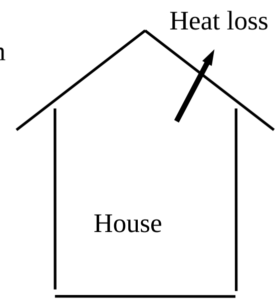
Heating oil heater: $\text{Unit cost of useful energy} = \frac{\$1.25/\text{gal}}{0.87}\left(\frac{1\,\text{gal}}{138{,}500\ \text{kJ}}\right) = \$10.4\times10^{-6}\ /\ \text{kJ}$

Electric heater: $\text{Unit cost of useful energy} = \frac{\$0.09/\text{kWh})}{1.0}\left(\frac{1\,\text{kWh}}{3600\ \text{kJ}}\right) = \$25.0\times10^{-6}\ /\ \text{kJ}$

Therefore, the system with the lowest energy cost for heating the house is the **heating oil heater**.

2-118 The heating and cooling costs of a poorly insulated house can be reduced by up to 30 percent by adding adequate insulation. The time it will take for the added insulation to pay for itself from the energy it saves is to be determined.

Assumptions It is given that the annual energy usage of a house is \$1200 a year, and 46% of it is used for heating and cooling. The cost of added insulation is given to be \$200.



Analysis The amount of money that would be saved per year is determined directly from

$$\text{Money saved} = (\$1200/\text{year})(0.46)(0.30) = \$166/\text{yr}$$

Then the simple payback period becomes

$$\text{Payback period} = \frac{\text{Cost}}{\text{Money saved}} = \frac{\$200}{\$166/\text{yr}} = \mathbf{1.2\ yr}$$

Therefore, the proposed measure will pay for itself in less than one and a half year.

2-119 Caulking and weather-stripping doors and windows to reduce air leaks can reduce the energy use of a house by up to 10 percent. The time it will take for the caulking and weather-stripping to pay for itself from the energy it saves is to be determined.

Assumptions It is given that the annual energy usage of a house is \$1100 a year, and the cost of caulking and weather-stripping a house is \$60.

Analysis The amount of money that would be saved per year is determined directly from

$$\text{Money saved} = (\$1100/\text{year})(0.10) = \$110/\text{yr}$$

Then the simple payback period becomes

$$\text{Payback period} = \frac{\text{Cost}}{\text{Money saved}} = \frac{\$60}{\$110/\text{yr}} = \mathbf{0.546\ yr}$$

Therefore, the proposed measure will pay for itself in less than half a year.

2-120E The energy stored in the spring of a railroad car is to be expressed in different units.

Analysis Using appropriate conversion factors, we obtain

(*a*) $$W = (5000\ \text{lbf}\cdot\text{ft})\left(\frac{32.174\ \text{lbm}\cdot\text{ft/s}^2}{1\ \text{lbf}}\right) = \mathbf{160{,}870\ lbm\cdot ft^2/s^2}$$

(*b*) $$W = (5000\ \text{lbf}\cdot\text{ft})\left(\frac{0.33303\ \text{yd}}{1\ \text{ft}}\right) = \mathbf{1665\ lbf\cdot yd}$$

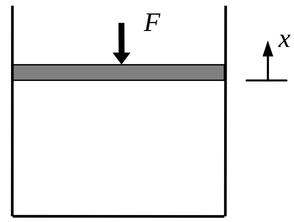
(*c*) $$W = (5000\ \text{lbf}\cdot\text{ft})\left(\frac{32.174\ \text{lbm}\cdot\text{ft/s}^2}{1\ \text{lbf}}\right)\left(\frac{1\ \text{mile}}{5280\ \text{ft}}\right)^2\left(\frac{3600\ \text{s}}{1\ \text{h}}\right)^2 = \mathbf{74{,}785\ lbm\cdot mile^2/h^2}$$

2-121E The work required to compress a gas in a gas spring is to be determined.

Assumptions All forces except that generated by the gas spring will be neglected.

Analysis When the expression given in the problem statement is substituted into the work integral relation, and advantage is taken of the fact that the force and displacement vectors are collinear, the result is

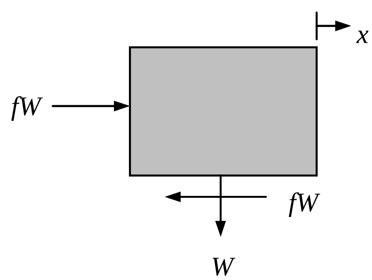
$$
\begin{aligned}
W &= \int_1^2 F ds = \int_1^2 \frac{\text{Constant}}{x^k} dx \\
&= \frac{\text{Constant}}{1-k}(x_2^{1-k} - x_1^{1-k}) \\
&= \frac{200\ \text{lbf}\cdot\text{in}^{1.4}}{1-1.4}\left[(4\ \text{in})^{-0.4} - (1\ \text{in})^{-0.4}\right]\left(\frac{1\ \text{ft}}{12\ \text{in}}\right) \\
&= 17.74\ \text{lbf}\cdot\text{ft} \\
&= (17.74\ \text{lbf}\cdot\text{ft})\left(\frac{1\ \text{Btu}}{778.169\ \text{lbf}\cdot\text{ft}}\right) = \mathbf{0.0228\ Btu}
\end{aligned}
$$



2-122E A man pushes a block along a horizontal plane. The work required to move the block is to be determined considering (a) the man and (b) the block as the system.

Analysis The work applied to the block to overcome the friction is found by using the work integral,

$$
\begin{aligned}
W &= \int_1^2 F ds = \int_1^2 fW(x_2 - x_1) \\
&= (0.2)(100\ \text{lbf})(100\ \text{ft}) \\
&= 2000\ \text{lbf}\cdot\text{ft} \\
&= (2000\ \text{lbf}\cdot\text{ft})\left(\frac{1\ \text{Btu}}{778.169\ \text{lbf}\cdot\text{ft}}\right) = \mathbf{2.57\ Btu}
\end{aligned}
$$



The man must then produce the amount of work

$$W = \mathbf{2.57\ Btu}$$

2-123 A diesel engine burning light diesel fuel that contains sulfur is considered. The rate of sulfur that ends up in the exhaust and the rate of sulfurous acid given off to the environment are to be determined.

Assumptions **1** All of the sulfur in the fuel ends up in the exhaust. **2** For one kmol of sulfur in the exhaust, one kmol of sulfurous acid is added to the environment.

Properties The molar mass of sulfur is 32 kg/kmol.

Analysis The mass flow rates of fuel and the sulfur in the exhaust are

$$\dot{m}_{\text{fuel}} = \frac{\dot{m}_{\text{air}}}{\text{AF}} = \frac{(336\text{ kg air/h})}{(18\text{ kg air/kg fuel})} = 18.67\ \text{ kg fuel/h}$$

$$\dot{m}_{\text{Sulfur}} = (750\times10^{-6})\dot{m}_{\text{fuel}} = (750\times10^{-6})(18.67\text{ kg/h}) = \mathbf{0.014\ \ kg/h}$$

The rate of sulfurous acid given off to the environment is

$$\dot{m}_{\text{H2SO3}} = \frac{M_{\text{H2SO3}}}{M_{\text{Sulfur}}}\dot{m}_{\text{Sulfur}} = \frac{2\times1+32+3\times16}{32}(0.014\text{ kg/h}) = \mathbf{0.036\ kg/h}$$

Discussion This problem shows why the sulfur percentage in diesel fuel must be below certain value to satisfy regulations.

2-124 Lead is a very toxic engine emission. Leaded gasoline contains lead that ends up in the exhaust. The amount of lead put out to the atmosphere per year for a given city is to be determined.

Assumptions 35% of lead is exhausted to the environment.

Analysis The gasoline consumption and the lead emission are

$$\begin{aligned}\text{Gasoline Consumption} &= (5000\text{ cars})(15{,}000\ \text{ km/car - year})(8.5\text{ L/100 km}) = 6.375\times10^{6}\ \text{ L/year}\\ \text{Lead Emission} &= (\text{GaolineConsumption})m_{\text{lead}}\,f_{\text{lead}}\\ &= (6.375\times10^{6}\ \text{ L/year})(0.15\times10^{-3}\ \text{ kg/L})(0.35)\\ &= \mathbf{335\ kg/year}\end{aligned}$$

Discussion Note that a huge amount of lead emission is avoided by the use of unleaded gasoline.

2-125E The power required to pump a specified rate of water to a specified elevation is to be determined.

Properties The density of water is taken to be 62.4 lbm/ft^3 (Table A-3E).

Analysis The required power is determined from

$$\begin{aligned}\dot{W} &= \dot{m}g(z_2 - z_1) = \rho\dot{V}g(z_2 - z_1)\\ &= (62.4\text{ lbm/ft}^3)(200\text{ gal/min})\left(\frac{35.315\text{ ft}^3/\text{s}}{15{,}850\text{ gal/min}}\right)(32.174\text{ ft/s}^2)(300\text{ ft})\left(\frac{1\text{ lbf}}{32.174\text{ lbm}\cdot\text{ft/s}^2}\right)\\ &= 8342\text{ lbf}\cdot\text{ft/s} = (8342\text{ lbf}\cdot\text{ft/s})\left(\frac{1\text{ kW}}{737.56\text{ lbf}\cdot\text{ft/s}}\right) = \mathbf{11.3\ kW}\end{aligned}$$

2-126 The power that could be produced by a water wheel is to be determined.

Properties The density of water is taken to be 1000 m^3/kg (Table A-3).

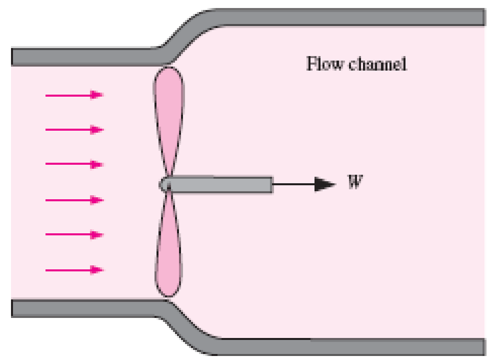
Analysis The power production is determined from

$$\dot{W} = \dot{m}g(z_2 - z_1) = \rho\dot{V}g(z_2 - z_1)$$

$$= (1000\ \text{kg/m}^3)(0.320/60\ \text{m}^3\text{/s})(9.81\ \text{m/s}^2)(14\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = \mathbf{0.732\ kW}$$

2-127 The flow of air through a flow channel is considered. The diameter of the wind channel downstream from the rotor and the power produced by the windmill are to be determined.

Analysis The specific volume of the air is



$$v = \frac{RT}{P} = \frac{(0.287\ \text{kPa}\cdot\text{m}^3\text{/kg}\cdot\text{K})(293\ \text{K})}{100\ \text{kPa}} = 0.8409\ \text{m}^3\text{/kg}$$

The diameter of the wind channel downstream from the rotor is

$$A_1V_1 = A_2V_2 \longrightarrow (\pi D_1^2/4)V_1 = (\pi D_2^2/4)V_2$$

$$\longrightarrow D_2 = D_1\sqrt{\frac{V_1}{V_2}} = (7\ \text{m})\sqrt{\frac{10\ \text{m/s}}{9\ \text{m/s}}} = \mathbf{7.38\ m}$$

The mass flow rate through the wind mill is

$$\dot{m} = \frac{A_1V_1}{v} = \frac{\pi(7\ \text{m})^2(10\ \text{m/s})}{4(0.8409\ \text{m}^3\text{/kg})} = 457.7\ \text{kg/s}$$

The power produced is then

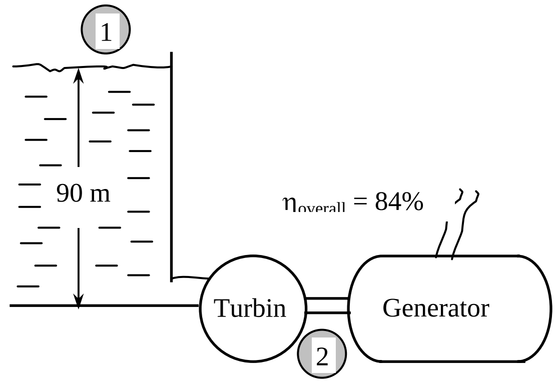
$$\dot{W} = \dot{m}\frac{V_1^2 - V_2^2}{2} = (457.7\ \text{kg/s})\frac{(10\ \text{m/s})^2 - (9\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = \mathbf{4.35\ kW}$$

2-128 The available head, flow rate, and efficiency of a hydroelectric turbine are given. The electric power output is to be determined.

Assumptions **1** The flow is steady. **2** Water levels at the reservoir and the discharge site remain constant. **3** Frictional losses in piping are negligible.

Properties We take the density of water to be ρ = 1000 kg/m^3 = 1 kg/L.

Analysis The total mechanical energy the water in a dam possesses is equivalent to the potential energy of water at the free surface of the dam (relative to free surface of discharge water), and it can be converted to work entirely. Therefore, the power potential of water is its potential energy, which is *gz* per unit mass, and $\dot{m}gz$ for a given mass flow rate.



$$e_{\text{mech}} = pe = gz = (9.81\ \text{m/s}^2)(90\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 0.8829\ \text{kJ/kg}$$

The mass flow rate is

$$\dot{m} = \rho\dot{\boldsymbol{V}} = (1000\ \text{kg/m}^3)(65\ \text{m}^3/\text{s}) = 65{,}000\ \text{kg/s}$$

Then the maximum and actual electric power generation become

$$\dot{W}_{\text{max}} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (65{,}000\ \text{kg/s})(0.8829\ \text{kJ/kg})\left(\frac{1\ \text{MW}}{1000\ \text{kJ/s}}\right) = 57.39\ \text{MW}$$

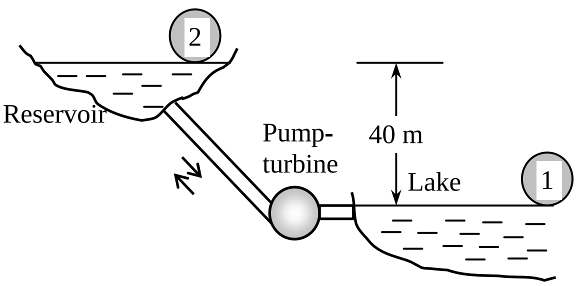
$$\dot{W}_{\text{electric}} = \eta_{\text{overall}}\dot{W}_{\text{max}} = 0.84(57.39\ \text{MW}) = \mathbf{48.2\ MW}$$

Discussion Note that the power generation would increase by more than 1 MW for each percentage point improvement in the efficiency of the turbine–generator unit.

2-129 An entrepreneur is to build a large reservoir above the lake level, and pump water from the lake to the reservoir at night using cheap power, and let the water flow from the reservoir back to the lake during the day, producing power. The potential revenue this system can generate per year is to be determined.

Assumptions **1** The flow in each direction is steady and incompressible. **2** The elevation difference between the lake and the reservoir can be taken to be constant, and the elevation change of reservoir during charging and discharging is disregarded. **3** Frictional losses in piping are negligible. **4** The system operates every day of the year for 10 hours in each mode.

Properties We take the density of water to be ρ = 1000 kg/m^3.



Analysis The total mechanical energy of water in an upper reservoir relative to water in a lower reservoir is equivalent to the potential energy of water at the free surface of this reservoir relative to free surface of the lower reservoir. Therefore, the power potential of water is its potential energy, which is gz per unit mass, and $\dot{m}gz$ for a given mass flow rate. This also represents the minimum power required to pump water from the lower reservoir to the higher reservoir.

$$\dot{W}_{\text{max, turbine}} = \dot{W}_{\text{min, pump}} = \dot{W}_{\text{ideal}} = \Delta\dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\Delta pe = \dot{m}g\Delta z = \rho\dot{V}g\Delta z$$
$$= (1000\ \text{kg/m}^3)(2\ \text{m}^3/\text{s})(9.81\ \text{m/s}^2)(40\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kW}}{1000\ \text{N}\cdot\text{m/s}}\right)$$
$$= 784.8\ \text{kW}$$

The actual pump and turbine electric powers are

$$\dot{W}_{\text{pump, elect}} = \frac{\dot{W}_{\text{ideal}}}{\eta_{\text{pump-motor}}} = \frac{784.8\ \text{kW}}{0.75} = 1046\ \text{kW}$$

$$\dot{W}_{\text{turbine}} = \eta_{\text{turbine-gen}}\dot{W}_{\text{ideal}} = 0.75(784.8\ \text{kW}) = 588.6\ \text{kW}$$

Then the power consumption cost of the pump, the revenue generated by the turbine, and the net income (revenue minus cost) per year become

$$\text{Cost} = \dot{W}_{\text{pump, elect}}\Delta t \times \text{Unit price} = (1046\ \text{kW})(365\times 10\ \text{h/year})(\$0.03/\text{kWh}) = \$114{,}500/\text{year}$$

$$\text{Reveue} = \dot{W}_{\text{turbine}}\Delta t \times \text{Unit price} = (588.6\ \text{kW})(365\times 10\ \text{h/year})(\$0.08/\text{kWh}) = \$171{,}900/\text{year}$$

Net income = Revenue – Cost = 171,900 –114,500 = **$57,400/year**

Discussion It appears that this pump-turbine system has a potential to generate net revenues of about $57,000 per year. A decision on such a system will depend on the initial cost of the system, its life, the operating and maintenance costs, the interest rate, and the length of the contract period, among other things.

Fundamentals of Engineering (FE) Exam Problems

2-130 A 2-kW electric resistance heater in a room is turned on and kept on for 50 min. The amount of energy transferred to the room by the heater is

(a) 2 kJ (b) 100 kJ (c) 3000 kJ (d) 6000 kJ (e) 12,000 kJ

Answer (d) 6000 kJ

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
We= 2 "kJ/s"
time=50*60 "s"
We_total=We*time "kJ"

"Some Wrong Solutions with Common Mistakes:"
W1_Etotal=We*time/60 "using minutes instead of s"
W2_Etotal=We "ignoring time"
```

2-131 In a hot summer day, the air in a well-sealed room is circulated by a 0.50-hp (shaft) fan driven by a 65% efficient motor. (Note that the motor delivers 0.50 hp of net shaft power to the fan). The rate of energy supply from the fan-motor assembly to the room is

(a) 0.769 kJ/s (b) 0.325 kJ/s (c) 0.574 kJ/s (d) 0.373 kJ/s (e) 0.242 kJ/s

Answer (c) 0.574 kJ/s

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
Eff=0.65
W_fan=0.50*0.7457 "kW"
E=W_fan/Eff  "kJ/s"

"Some Wrong Solutions with Common Mistakes:"
W1_E=W_fan*Eff "Multiplying by efficiency"
W2_E=W_fan "Ignoring efficiency"
W3_E=W_fan/Eff/0.7457 "Using hp instead of kW"
```

2-132 A fan is to accelerate quiescent air to a velocity to 12 m/s at a rate of 3 m^3/min. If the density of air is 1.15 kg/m^3, the minimum power that must be supplied to the fan is

(a) 248 W (b) 72 W (c) 497 W (d) 216 W (e) 162 W

Answer (a) 248 W

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
rho=1.15
V=12
Vdot=3 "m3/s"
mdot=rho*Vdot "kg/s"
We=mdot*V^2/2

"Some Wrong Solutions with Common Mistakes:"
W1_We=Vdot*V^2/2 "Using volume flow rate"
W2_We=mdot*V^2 "forgetting the 2"
W3_We=V^2/2 "not using mass flow rate"
```

2-133 A 900-kg car cruising at a constant speed of 60 km/h is to accelerate to 100 km/h in 4 s. The additional power needed to achieve this acceleration is

(a) 56 kW (b) 222 kW (c) 2.5 kW (d) 62 kW (e) 90 kW

Answer (a) 56 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
m=900 "kg"
V1=60 "km/h"
V2=100 "km/h"
Dt=4 "s"
Wa=m*((V2/3.6)^2-(V1/3.6)^2)/2000/Dt "kW"

"Some Wrong Solutions with Common Mistakes:"
W1_Wa=((V2/3.6)^2-(V1/3.6)^2)/2/Dt "Not using mass"
W2_Wa=m*((V2)^2-(V1)^2)/2000/Dt "Not using conversion factor"
W3_Wa=m*((V2/3.6)^2-(V1/3.6)^2)/2000 "Not using time interval"
W4_Wa=m*((V2/3.6)-(V1/3.6))/1000/Dt "Using velocities"
```

2-134 The elevator of a large building is to raise a net mass of 400 kg at a constant speed of 12 m/s using an electric motor. Minimum power rating of the motor should be

(a) 0 kW (b) 4.8 kW (c) 47 kW (d) 12 kW (e) 36 kW

Answer (c) 47 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
m=400 "kg"
V=12 "m/s"
g=9.81 "m/s2"
Wg=m*g*V/1000 "kW"

"Some Wrong Solutions with Common Mistakes:"
W1_Wg=m*V "Not using g"
W2_Wg=m*g*V^2/2000 "Using kinetic energy"
W3_Wg=m*g/V "Using wrong relation"
```

2-135 Electric power is to be generated in a hydroelectric power plant that receives water at a rate of 70 m^3/s from an elevation of 65 m using a turbine–generator with an efficiency of 85 percent. When frictional losses in piping are disregarded, the electric power output of this plant is

(a) 3.9 MW (b) 38 MW (c) 45 MW (d) 53 MW (e) 65 MW

Answer (b) 38 MW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
Vdot=70 "m3/s"
z=65 "m"
g=9.81 "m/s2"
Eff=0.85
rho=1000 "kg/m3"
We=rho*Vdot*g*z*Eff/10^6 "MW"

"Some Wrong Solutions with Common Mistakes:"
W1_We=rho*Vdot*z*Eff/10^6 "Not using g"
W2_We=rho*Vdot*g*z/Eff/10^6 "Dividing by efficiency"
W3_We=rho*Vdot*g*z/10^6 "Not using efficiency"
```

2-136 A 75 hp (shaft) compressor in a facility that operates at full load for 2500 hours a year is powered by an electric motor that has an efficiency of 93 percent. If the unit cost of electricity is $0.06/kWh, the annual electricity cost of this compressor is

(a) $7802 (b) $9021 (c) $12,100 (d) $8389 (e) $10,460

Answer (b) $9021

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
Wcomp=75 "hp"
Hours=2500 “h/year”
Eff=0.93
price=0.06 “$/kWh”
We=Wcomp*0.7457*Hours/Eff
Cost=We*price

"Some Wrong Solutions with Common Mistakes:"
W1_cost= Wcomp*0.7457*Hours*price*Eff “multiplying by efficiency”
W2_cost= Wcomp*Hours*price/Eff “not using conversion”
W3_cost= Wcomp*Hours*price*Eff “multiplying by efficiency and not using conversion”
W4_cost= Wcomp*0.7457*Hours*price “Not using efficiency”
```

2-137 Consider a refrigerator that consumes 320 W of electric power when it is running. If the refrigerator runs only one quarter of the time and the unit cost of electricity is $0.09/kWh, the electricity cost of this refrigerator per month (30 days) is

(a) $3.56 (b) $5.18 (c) $8.54 (d) $9.28 (e) $20.74

Answer (b) $5.18

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
We=0.320 "kW"
Hours=0.25*(24*30) "h/year"
price=0.09 "$/kWh"
Cost=We*hours*price

"Some Wrong Solutions with Common Mistakes:"
W1_cost= We*24*30*price "running continuously"
```

2-138 A 2-kW pump is used to pump kerosene (ρ = 0.820 kg/L) from a tank on the ground to a tank at a higher elevation. Both tanks are open to the atmosphere, and the elevation difference between the free surfaces of the tanks is 30 m. The maximum volume flow rate of kerosene is

(a) 8.3 L/s (b) 7.2 L/s (c) 6.8 L/s (d) 12.1 L/s (e) 17.8 L/s

Answer (a) 8.3 L/s

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
W=2 "kW"
rho=0.820 "kg/L"
z=30 "m"
g=9.81 "m/s2"
W=rho*Vdot*g*z/1000

"Some Wrong Solutions with Common Mistakes:"
W=W1_Vdot*g*z/1000 "Not using density"
```

2-139 A glycerin pump is powered by a 5-kW electric motor. The pressure differential between the outlet and the inlet of the pump at full load is measured to be 211 kPa. If the flow rate through the pump is 18 L/s and the changes in elevation and the flow velocity across the pump are negligible, the overall efficiency of the pump is

(a) 69% (b) 72% (c) 76% (d) 79% (e) 82%

Answer (c) 76%

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
We=5 "kW"
Vdot= 0.018 "m3/s"
DP=211 "kPa"
Emech=Vdot*DP
Emech=Eff*We
```

The following problems are based on the optional special topic of heat transfer

2-140 A 10-cm high and 20-cm wide circuit board houses on its surface 100 closely spaced chips, each generating heat at a rate of 0.08 W and transferring it by convection to the surrounding air at 25°C. Heat transfer from the back surface of the board is negligible. If the convection heat transfer coefficient on the surface of the board is 10 W/m^2.°C and radiation heat transfer is negligible, the average surface temperature of the chips is

(a) 26°C (b) 45°C (c) 15°C (d) 80°C (e) 65°C

Answer (e) 65°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
A=0.10*0.20 "m^2"
Q= 100*0.08 "W"
Tair=25 "C"
h=10 "W/m^2.C"
Q= h*A*(Ts-Tair) "W"

"Some Wrong Solutions with Common Mistakes:"
Q= h*(W1_Ts-Tair) "Not using area"
Q= h*2*A*(W2_Ts-Tair) "Using both sides of surfaces"
Q= h*A*(W3_Ts+Tair) "Adding temperatures instead of subtracting"
Q/100= h*A*(W4_Ts-Tair) "Considering 1 chip only"
```

2-141 A 50-cm-long, 0.2-cm-diameter electric resistance wire submerged in water is used to determine the boiling heat transfer coefficient in water at 1 atm experimentally. The surface temperature of the wire is measured to be 130°C when a wattmeter indicates the electric power consumption to be 4.1 kW. Then the heat transfer coefficient is

(a) 43,500 W/m^2.°C (b) 137 W/m^2.°C (c) 68,330 W/m^2.°C (d) 10,038 W/m^2.°C

(e) 37,540 W/m^2.°C

Answer (a) 43,500 W/m^2.°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
L=0.5 "m"
D=0.002 "m"
A=pi*D*L "m^2"
We=4.1 "kW"
Ts=130 "C"
Tf=100 "C    (Boiling temperature of water at 1 atm)"
We= h*A*(Ts-Tf) "W"

"Some Wrong Solutions with Common Mistakes:"
We= W1_h*(Ts-Tf) "Not using area"
We= W2_h*(L*pi*D^2/4)*(Ts-Tf) "Using volume instead of area"
We= W3_h*A*Ts "Using Ts instead of temp difference"
```

2-142 A 3-m^2 hot black surface at 80°C is losing heat to the surrounding air at 25°C by convection with a convection heat transfer coefficient of 12 W/m^2.°C, and by radiation to the surrounding surfaces at 15°C. The total rate of heat loss from the surface is

(a) 1987 W (b) 2239 W (c) 2348 W (d) 3451 W (e) 3811 W

Answer (d) 3451 W

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
sigma=5.67E-8 "W/m^2.K^4"
eps=1
A=3 "m^2"
h_conv=12 "W/m^2.C"
Ts=80 "C"
Tf=25 "C"
Tsurr=15 "C"
Q_conv=h_conv*A*(Ts-Tf)  "W"
Q_rad=eps*sigma*A*((Ts+273)^4-(Tsurr+273)^4) "W"
Q_total=Q_conv+Q_rad "W"

"Some Wrong Solutions with Common Mistakes:"
W1_Ql=Q_conv "Ignoring radiation"
W2_Q=Q_rad "ignoring convection"
W3_Q=Q_conv+eps*sigma*A*(Ts^4-Tsurr^4) "Using C in radiation calculations"
W4_Q=Q_total/A "not using area"
```

2-143 Heat is transferred steadily through a 0.2-m thick 8 m by 4 m wall at a rate of 2.4 kW. The inner and outer surface temperatures of the wall are measured to be 15°C to 5°C. The average thermal conductivity of the wall is

(a) 0.002 W/m.°C (b) 0.75 W/m.°C (c) 1.0 W/m.°C (d) 1.5 W/m.°C (e) 3.0 W/m.°C

Answer (d) 1.5 W/m.°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
A=8*4 "m^2"
L=0.2 "m"
T1=15 "C"
T2=5 "C"
Q=2400  "W"
Q=k*A*(T1-T2)/L "W"

"Some Wrong Solutions with Common Mistakes:"
Q=W1_k*(T1-T2)/L "Not using area"
Q=W2_k*2*A*(T1-T2)/L  "Using areas of both surfaces"
Q=W3_k*A*(T1+T2)/L  "Adding temperatures instead of subtracting"
Q=W4_k*A*L*(T1-T2) "Multiplying by thickness instead of dividing by it"
```

2-144 The roof of an electrically heated house is 7 m long, 10 m wide, and 0.25 m thick. It is made of a flat layer of concrete whose thermal conductivity is 0.92 W/m.°C. During a certain winter night, the temperatures of the inner and outer surfaces of the roof are measured to be 15°C and 4°C, respectively. The average rate of heat loss through the roof that night was

(a) 41 W (b) 177 W (c) 4894 W (d) 5567 W (e) 2834 W

Answer (e) 2834 W

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
A=7*10 "m^2"
L=0.25 "m"
k=0.92 "W/m.C"
T1=15 "C"
T2=4 "C"
Q_cond=k*A*(T1-T2)/L "W"

"Some Wrong Solutions with Common Mistakes:"
W1_Q=k*(T1-T2)/L "Not using area"
W2_Q=k*2*A*(T1-T2)/L  "Using areas of both surfaces"
W3_Q=k*A*(T1+T2)/L  "Adding temperatures instead of subtracting"
W4_Q=k*A*L*(T1-T2) "Multiplying by thickness instead of dividing by it"
```

2-145 … 2-151 Design and Essay Problems