Chapter 2

ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS

Forms of Energy

2-1C In electric heaters, electrical energy is converted to sensible internal energy.

2-2C The forms of energy involved are electrical energy and sensible internal energy. Electrical energy is converted to sensible internal energy, which is transferred to the water as heat.

2-3C 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.

2-4C 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.

2-5C The internal energy of a system is made up of sensible, latent, chemical and nuclear energies. The sensible internal energy is due to translational, rotational, and vibrational effects.

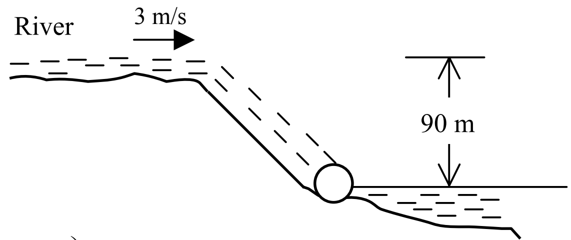
2-6C Thermal energy is the sensible and latent forms of internal energy, and it is referred to as heat in daily life.

2-7C 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.

2-8 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

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

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

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

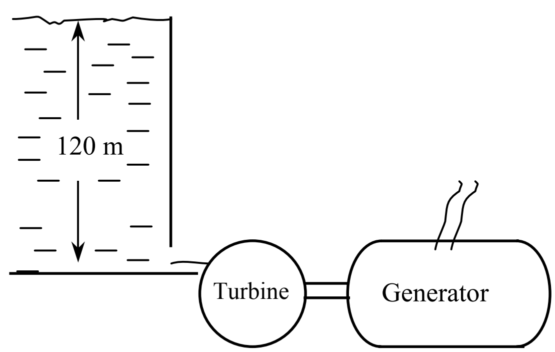
$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (500{,}000\,\text{kg/s})(0.887\ \text{kJ/kg}) = 444{,}000\,\text{kW} = \mathbf{444\ MW}$$

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.

2-9 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.

$$e_{\text{mech}} = pe = gz = (9.81\,\text{m/s}^2)(120\,\text{m})\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = 1.177\,\text{kJ/kg}$$

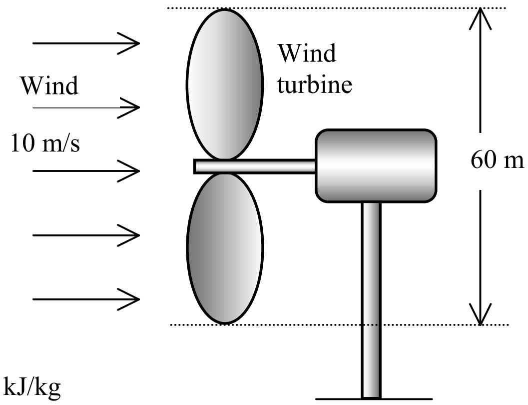
Then the power generation potential becomes

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (1500\,\text{kg/s})(1.177\,\text{kJ/kg})\left(\frac{1\,\text{kW}}{1\,\text{kJ/s}}\right) = \mathbf{1766\,kW}$$

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.

2-10 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 $\rho = 1.25$ 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:

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

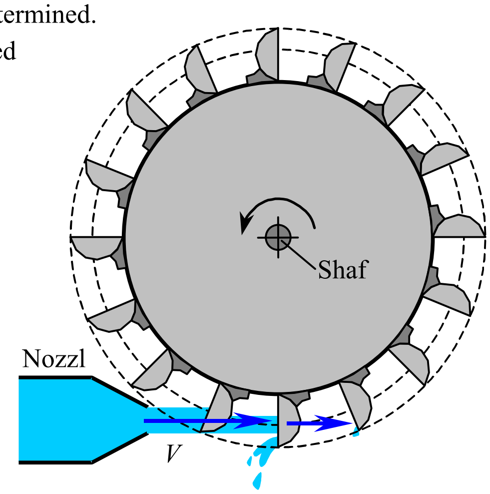
$$\dot{m} = \rho VA = \rho V\frac{\pi D^2}{4} = (1.25\text{ kg/m}^3)(10\text{ m/s})\frac{\pi(60\text{ m})^2}{4} = 35{,}340\text{ kg/s}$$

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

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.

2-11 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:

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

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

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

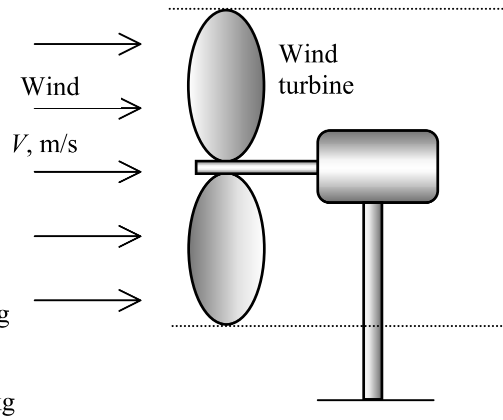
Therefore, 216 kW of power can be generated by this water jet at the stated conditions.

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

2-12 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

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

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

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

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

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

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

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

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

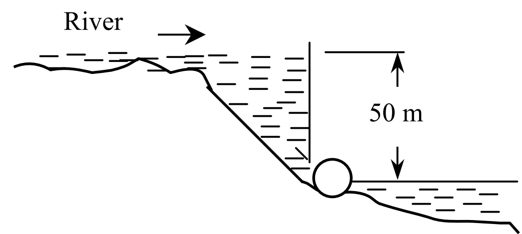
Discussion Note the power generation of a wind turbine is proportional to the cube of the wind velocity, and thus the average wind velocity is the primary consideration in wind power generation decisions.

2-13 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 $\rho = 1000\ \text{kg/m}^3$.

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.



$$e_{\text{mech}} = pe = gz = (9.81\ \text{m/s}^2)(50\ \text{m})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 0.4905\ \text{kJ/kg}$$

The mass flow rate is

$$\dot{m} = \rho\dot{\boldsymbol{V}} = (1000\ \text{kg/m}^3)(240\ \text{m}^3/\text{s}) = 240{,}000\ \text{kg/s}$$

Then the power generation potential becomes

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (240{,}000\ \text{kg/s})(0.4905\ \text{kJ/kg})\left(\frac{1\ \text{MW}}{1000\ \text{kJ/s}}\right) = \mathbf{118\ MW}$$

Therefore, 118 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 118 MW because of losses and inefficiencies.

2-14 A person with his suitcase goes up to the 10th 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 10th 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.

Energy Transfer by Heat and Work

2-15C Energy can cross the boundaries of a closed system in two forms: heat and work.

2-16C The form of energy that crosses the boundary of a closed system because of a temperature difference is heat; all other forms are work.

2-17C 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.

2-18C It is a work interaction.

2-19C It is a work interaction since the electrons are crossing the system boundary, thus doing electrical work.

2-20C It is a heat interaction since it is due to the temperature difference between the sun and the room.

2-21C This is neither a heat nor a work interaction since no energy is crossing the system boundary. This is simply the conversion of one form of internal energy (chemical energy) to another form (sensible energy).

2-22C 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.

2-23C The caloric theory is based on the assumption that heat is a fluid-like substance called the "caloric" which is a massless, colorless, odorless substance. It was abandoned in the middle of the nineteenth century after it was shown that there is no such thing as the caloric.

Mechanical Forms of Work

2-24C The work done is the same, but the power is different.

2-25C The work done is the same, but the power is different.

2-26 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,

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

2-27 A car is accelerated from 10 to 60 km/h on an uphill road. The work needed to achieve this is to be determined.

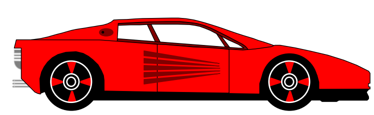
Analysis The total work required is the sum of the changes in potential and kinetic energies,

$$W_a = \frac{1}{2}m\left(V_2^2 - V_1^2\right) = \frac{1}{2}(1300\text{ kg})\left(\left(\frac{60{,}000\text{ m}}{3600\text{ s}}\right)^2 - \left(\frac{10{,}000\text{ m}}{3600\text{ s}}\right)^2\right)\left(\frac{1\text{ kJ}}{1000\ \text{kg}\cdot\text{m}^2/\text{s}^2}\right) = 175.5\text{ kJ}$$

and $$W_g = mg\left(z_2 - z_1\right) = (1300\text{ kg})(9.81\text{ m/s}^2)(40\text{ m})\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right) = 510.0\text{ kJ}$$

Thus,

$$W_{\text{total}} = W_a + W_g = 175.5 + 510.0 = \mathbf{686\ kJ}$$



2-28E The engine of a car develops 450 hp at 3000 rpm. The torque transmitted through the shaft is to be determined.

Analysis The torque is determined from

$$\text{T} = \frac{\dot{W}_{\text{sh}}}{2\pi\dot{n}} = \frac{450\text{ hp}}{2\pi\left(3000/60\right)/\text{s}}\left(\frac{550\text{ lbf}\cdot\text{ft/s}}{1\text{ hp}}\right) = \mathbf{788\ lbf\cdot ft}$$

2-29 A linear spring is elongated by 20 cm from its rest position. The work done is to be determined.

Analysis The spring work can be determined from

$$W_{spring} = \frac{1}{2}k(x_2^2 - x_1^2) = \frac{1}{2}(70\text{ kN/m})(0.2^2 - 0)\text{ m}^2 = 1.4\text{ kN}\cdot\text{m} = \mathbf{1.4\ kJ}$$

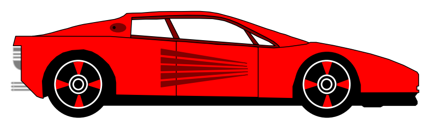
2-30 The engine of a car develops 75 kW of power. The acceleration time of this car from rest to 100 km/h on a level road is to be determined.

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

$$W_a = \frac{1}{2}m\left(\mathrm{V}_2^2 - \mathrm{V}_1^2\right) = \frac{1}{2}(1500\text{ kg})\left(\left(\frac{100{,}000\text{ m}}{3600\text{ s}}\right)^2 - 0\right)\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right) = 578.7\text{ kJ}$$

Thus the time required is

$$\Delta t = \frac{W_a}{\dot{W}_a} = \frac{578.7\text{ kJ}}{75\text{ kJ/s}} = \mathbf{7.72\ s}$$



This answer is not realistic because part of the power will be used against the air drag, friction, and rolling resistance.

2-31 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,

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

2-32 A car is to climb a hill in 10 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,

$$\dot{W}_g = mg(z_2 - z_1)/\Delta t = (2000\text{ kg})(9.81\text{ m/s}^2)(50\text{ m})\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right)/(10\text{ s}) = 98.1\text{ kW}$$

and $\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = 0 + 98.1 = \mathbf{98.1\ kW}$

(b) The power needed to accelerate is

$$\dot{W}_a = \frac{1}{2}m(V_2^2 - V_1^2)/\Delta t = \frac{1}{2}(2000\text{ kg})\left[(30\text{ m/s})^2 - 0\right]\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right)/(10\text{ s}) = 90\text{ kW}$$

and $\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = 90 + 98.1 = \mathbf{188.1\ kW}$

(c) The power needed to decelerate is

$$\dot{W}_a = \frac{1}{2}m(V_2^2 - V_1^2)/\Delta t = \frac{1}{2}(2000\text{ kg})\left[(5\text{ m/s})^2 - (35\text{ m/s})^2\right]\left(\frac{1\text{ kJ}}{1000\text{ kg}\cdot\text{m}^2/\text{s}^2}\right)/(10\text{ s}) = -120\text{ kW}$$

and $\dot{W}_{\text{total}} = \dot{W}_a + \dot{W}_g = -120 + 98.1 = \mathbf{-21.9\ kW}$ (breaking power)

2-33 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

2-34C No. This is the case for adiabatic systems only.

2-35C Warmer. Because energy is added to the room air in the form of electrical work.

2-36C Energy can be transferred to or from a control volume as heat, various forms of work, and by mass transport.

2-37 Water is heated in a pan on top of a range while being stirred. The energy of the water at the end of the process is to be determined.

Assumptions The pan is stationary and thus the changes in kinetic and potential energies are negligible.

Analysis We take the water in the pan as our system. This is a closed system since no mass enters or leaves. Applying the energy balance on this system gives

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

$$Q_{\text{in}} + W_{\text{sh,in}} - Q_{\text{out}} = \Delta U = U_2 - U_1$$

$$30 \text{ kJ} + 0.5 \text{ kJ} - 5 \text{ kJ} = U_2 - 10 \text{ kJ}$$

$$U_2 = \mathbf{35.5 \ kJ}$$

Therefore, the final internal energy of the system is 35.5 kJ.

2-38E Water is heated in a cylinder on top of a range. The change in the energy of the water during this process is to be determined.

Assumptions The pan is stationary and thus the changes in kinetic and potential energies are negligible.

Analysis We take the water in the cylinder as the system. This is a closed system since no mass enters or leaves. Applying the energy balance on this system gives

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

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

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

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

Therefore, the energy content of the system increases by 52 Btu during this process.

2-39 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

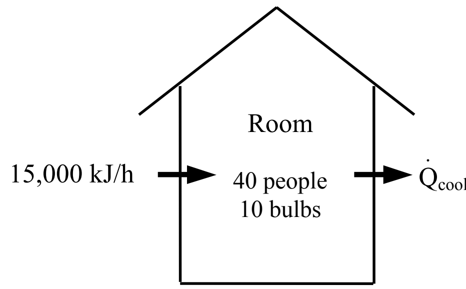
$$\dot{Q}_{\text{cooling}} = \dot{Q}_{\text{lights}} + \dot{Q}_{\text{people}} + \dot{Q}_{\text{heat gain}}$$

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

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

2-40 An industrial facility is to replace its 40-W standard fluorescent lamps by their 35-W high efficiency counterparts. The amount of energy and money that will be saved a year as well as the simple payback period are to be determined.

Analysis The reduction in the total electric power consumed by the lighting as a result of switching to the high efficiency fluorescent is

Wattage reduction = (Wattage reduction per lamp)(Number of lamps)
= (40 - 34 W/lamp)(700 lamps)
= 4200 W

Then using the relations given earlier, the energy and cost savings associated with the replacement of the high efficiency fluorescent lamps are determined to be

Energy Savings = (Total wattage reduction)(Ballast factor)(Operating hours)
= (4.2 kW)(1.1)(2800 h/year)
= **12,936 kWh/year**

Cost Savings = (Energy savings)(Unit electricity cost)
= (12,936 kWh/year)($0.08/kWh)
= **$1035/year**

The implementation cost of this measure is simply the extra cost of the energy efficient fluorescent bulbs relative to standard ones, and is determined to be

Implementation Cost = (Cost difference of lamps)(Number of lamps)
= [($2.26-$1.77)/lamp](700 lamps)
= $343

This gives a simple payback period of

$$\text{Simple payback period} = \frac{\text{Implementation cost}}{\text{Annual cost savings}} = \frac{\$343}{\$1035/\text{year}} = \textbf{0.33 year} \text{ (4.0 months)}$$

Discussion Note that if all the lamps were burned out today and are replaced by high-efficiency lamps instead of the conventional ones, the savings from electricity cost would pay for the cost differential in about 4 months. The electricity saved will also help the environment by reducing the amount of CO_2, CO, NO_x, etc. associated with the generation of electricity in a power plant.

2-41 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.

2-42 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.

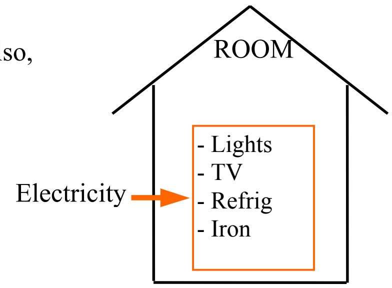
2-43 A room contains a light bulb, a TV set, a refrigerator, and an iron. The rate of increase of the energy content of the room when all of these electric devices are on is to be determined.

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

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

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.

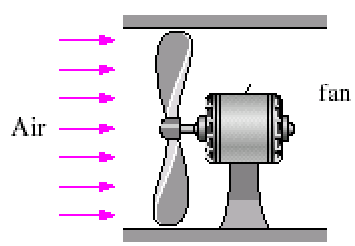
2-44 A fan is to accelerate quiescent air to a specified velocity at a specified flow rate. The minimum power that must be supplied to the fan is to be determined.

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

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



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

where

$$\dot{m}_{\text{air}} = \rho \dot{\boldsymbol{V}} = (1.18 \text{ kg/m}^3)(4 \text{ m}^3\text{/s}) = 4.72 \text{ kg/s}$$

Substituting, the minimum power input required is determined to be

$$\dot{W}_{\text{sh, in}} = \dot{m}_{\text{air}} \frac{V_{\text{out}}^2}{2} = (4.72 \text{ kg/s}) \frac{(10 \text{ m/s})^2}{2} \left(\frac{1 \text{ J/kg}}{1 \text{ m}^2/\text{s}^2} \right) = 236 \text{ J/s} = \mathbf{236\ W}$$

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.

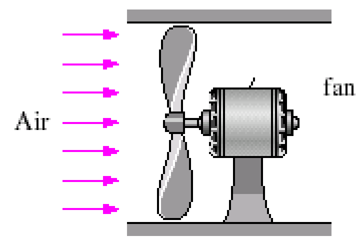
2-45E A fan accelerates air to a specified velocity in a square duct. The minimum electric power that must be supplied to the fan motor is to be determined.

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

Properties The density of air is given to be $\rho = 0.075$ 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

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



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

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

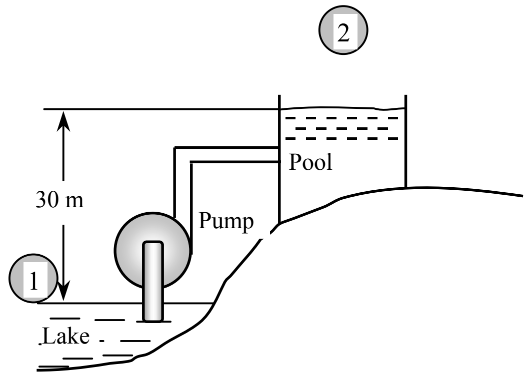
$$\dot{W}_{\text{in}} = \dot{m}_{\text{air}} \frac{V_{\text{out}}^2}{2} = (14.85 \text{ lbm/s}) \frac{(22 \text{ ft/s})^2}{2} \left(\frac{1 \text{ Btu/lbm}}{25{,}037 \text{ ft}^2/\text{s}^2} \right) = 0.1435 \text{ Btu/s} = \mathbf{151 \text{ W}}$$

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.

2-46 A water pump is claimed to raise water to a specified elevation at a specified rate while consuming electric power at a specified rate. The validity of this claim is to be investigated.

Assumptions **1** The water pump operates steadily. **2** Both the lake and the pool are open to the atmosphere, and the flow velocities in them are negligible.



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

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

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

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{\text{in}} + \dot{m}\text{pe}_1 = \dot{m}\text{pe}_2 \quad \rightarrow \quad \dot{W}_{\text{in}} = \dot{m}\Delta\text{pe} = \dot{m}g(z_2 - z_1)$$

since the changes in kinetic and flow energies of water are negligible. Also,

$$\dot{m} = \rho\dot{V} = (1\text{ kg/L})(50\text{ L/s}) = 50\text{ kg/s}$$

Substituting, the minimum power input required is determined to be

$$\dot{W}_{\text{in}} = \dot{m}g(z_2 - z_1) = (50\text{ kg/s})(9.81\text{ m/s}^2)(30\text{ m})\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 14.7\text{ kJ/s} = \mathbf{14.7\ kW}$$

which is much greater than 2 kW. Therefore, the claim is **false.**

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 than 14.7 kW because of the losses associated with the conversion of electrical-to-mechanical shaft and mechanical shaft-to-potential energy of water.

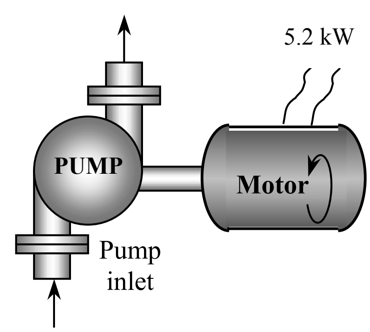
2-47 A gasoline pump raises the pressure to a specified value while consuming electric power at a specified rate. The maximum volume flow rate of gasoline is to be determined.

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

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

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



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

$$\dot{\boldsymbol{V}}_{\text{max}} = \frac{\dot{W}_{\text{in}}}{\Delta\text{P}} = \frac{5.2\text{ kJ/s}}{5\text{ kPa}}\left(\frac{1\text{ kPa}\cdot\text{m}^3}{1\text{ kJ}}\right) = \mathbf{1.04\ m^3/s}$$

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.

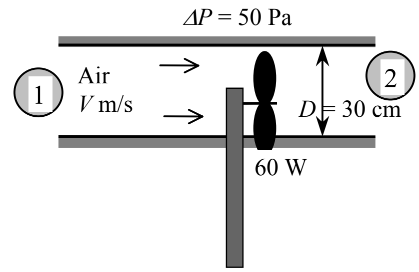
2-48 The fan of a central heating system circulates air through the ducts. For a specified pressure rise, the highest possible average flow velocity is to be determined.

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

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

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

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



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

$$\dot{V}_{max} = \frac{\dot{W}_{in}}{\Delta P} = \frac{60\text{ J/s}}{50\text{ Pa}}\left(\frac{1\text{ Pa}\cdot\text{m}^3}{1\text{ J}}\right) = 1.2\text{ m}^3/\text{s}$$

$$V_{max} = \frac{\dot{V}_{max}}{A_c} = \frac{\dot{V}_{max}}{\pi D^2/4} = \frac{1.2\text{ m}^3/\text{s}}{\pi(0.30\text{ m})^2/4} = \mathbf{17.0\ m/s}$$

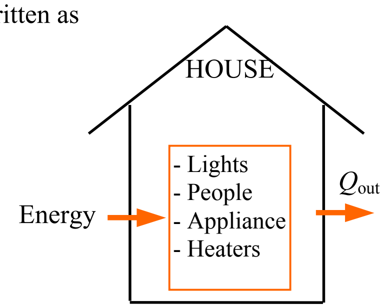
Discussion The conservation of energy principle requires the energy to be conserved as it is converted from one form to another, and it does not allow any energy to be created or destroyed during a process. In reality, the velocity will be less because of the losses associated with the conversion of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

2-49E The heat loss from a house is to be made up by heat gain from people, lights, appliances, and resistance heaters. For a specified rate of heat loss, the required rated power of resistance heaters is to be determined.

Assumptions **1** The house is well-sealed, so no air enters or heaves the house. **2** All the lights and appliances are kept on. **3** The house temperature remains constant.

Analysis Taking the house as the system, the energy balance can be written as

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



where $\dot{E}_{out} = \dot{Q}_{out} = 60{,}000\text{ Btu/h}$ and

$$\dot{E}_{in} = \dot{E}_{people} + \dot{E}_{lights} + \dot{E}_{appliance} + \dot{E}_{heater} = 6000\text{ Btu/h} + \dot{E}_{heater}$$

Substituting, the required power rating of the heaters becomes

$$\dot{E}_{heater} = 60{,}000 - 6000 = 54{,}000\text{ Btu/h}\left(\frac{1\text{ kW}}{3412\text{ Btu/h}}\right) = \mathbf{15.8\ kW}$$

Discussion When the energy gain of the house equals the energy loss, the temperature of the house remains constant. But when the energy supplied drops below the heat loss, the house temperature starts dropping.

2-50 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

$$\text{Mass} = (30\text{ persons})(75\text{ kg/person}) = 2250\text{ kg}$$

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.

2-51 A car cruising at a constant speed to accelerate to a specified speed within a specified time. The additional power needed to achieve this acceleration is to be determined.

Assumptions **1** The additional air drag, friction, and rolling resistance are not considered. **2** The road is a level road.

Analysis We consider the entire car as the system, except that let's assume the power is supplied to the engine externally for simplicity (rather that internally by the combustion of a fuel and the associated energy conversion processes). The energy balance for the entire mass of the car can be written in the rate form as

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

$$\dot{W}_{\text{in}} = \frac{\Delta KE}{\Delta t} = \frac{m(V_2^2 - V_1^2)/2}{\Delta t}$$

since we are considering the change in the energy content of the car due to a change in its kinetic energy (acceleration). Substituting, the required additional power input to achieve the indicated acceleration becomes

$$\dot{W}_{\text{in}} = m\frac{V_2^2 - V_1^2}{2\Delta t} = (1400\text{ kg})\frac{(110/3.6\text{ m/s})^2 - (70/3.6\text{ m/s})^2}{2(5\text{ s})}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 77.8\text{ kJ/s} = \mathbf{77.8\ kW}$$

since 1 m/s = 3.6 km/h. If the total mass of the car were 700 kg only, the power needed would be

$$\dot{W}_{\text{in}} = m\frac{V_2^2 - V_1^2}{2\Delta t} = (700\text{ kg})\frac{(110/3.6\text{ m/s})^2 - (70/3.6\text{ m/s})^2}{2(5\text{ s})}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = \mathbf{38.9\ kW}$$

Discussion Note that the power needed to accelerate a car is inversely proportional to the acceleration time. Therefore, the short acceleration times are indicative of powerful engines.

Energy Conversion Efficiencies

2-52C *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.

2-53C 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.

2-54C The turbine efficiency, generator efficiency, and *combined turbine-generator efficiency* are defined as follows:

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

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

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

2-55C 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.

2-56 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

$$\eta_{\text{gas}} = 38\%$$
$$\eta_{\text{electric}} = 73\%$$

$$\dot{Q}_{\text{utilized}} = (\text{Energy input}) \times (\text{Efficiency}) = (3\,\text{kW})(0.73) = \mathbf{2.19\ kW}$$

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

$$\text{Cost of utilized energy} = \frac{\text{Cost of energy input}}{\text{Efficiency}} = \frac{\$0.07/\text{kWh}}{0.73} = \mathbf{\$0.096/kWh}$$

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 (2.19 kW) is

$$\dot{Q}_{\text{input, gas}} = \frac{\dot{Q}_{\text{utilized}}}{\text{Efficiency}} = \frac{2.19\,\text{kW}}{0.38} = \mathbf{5.76\ kW} \ \ (= 19{,}660\ \text{Btu/h})$$

since 1 kW = 3412 Btu/h. Therefore, a gas burner should have a rating of at least 19,660 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

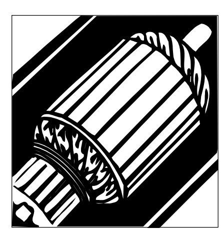
$$\text{Cost of utilized energy} = \frac{\text{Cost of energy input}}{\text{Efficiency}} = \frac{\$1.20/(29.3\,\text{kWh})}{0.38} = \mathbf{\$0.108/kWh}$$

2-57 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

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

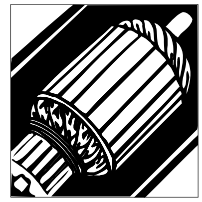
2-58 An electric car is powered by an electric motor mounted in the engine compartment. The rate of heat supply by the motor to the engine compartment at full load conditions is to be determined.

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.

2-59 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

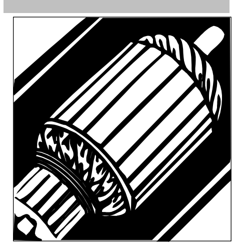
Energy Savings = (Power savings)(Operating Hours)

= (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**

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



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

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

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

2-60E 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.

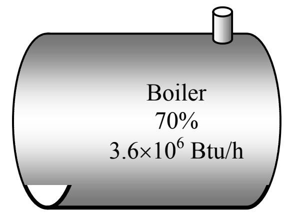
Analysis The heat output of boiler is related to the fuel energy input to the boiler by

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 $\dot{Q}_{\text{in, current}} = 3.6\times10^6 \text{ Btu/h}$.

Then the rate of useful heat output of the boiler becomes

$$\dot{Q}_{\text{out}} = (\dot{Q}_{\text{in}}\eta_{\text{furnace}})_{\text{current}} = (3.6\times10^6 \text{ Btu/h})(0.7) = 2.52\times10^6 \text{ Btu/h}$$



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

$$\dot{Q}_{\text{in, new}} = \dot{Q}_{\text{out}} / \eta_{\text{furnace, new}} = (2.52\times10^6 \text{ Btu/h})/0.8 = 3.15\times10^6 \text{ Btu/h}$$

$$\dot{Q}_{\text{in, saved}} = \dot{Q}_{\text{in, current}} - \dot{Q}_{\text{in, new}} = 3.6\times10^6 - 3.15\times10^6 = 0.45\times10^6 \text{ Btu/h}$$

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

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

$= (0.45\times10^6 \text{ Btu/h})(1500 \text{ h/year}) =$ $\mathbf{675\times10^6}$ **Btu/yr**

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

$= (675\times10^6 \text{ Btu/yr})(\$4.35 \text{ per } 10^6 \text{ Btu}) =$ **$2936/year**

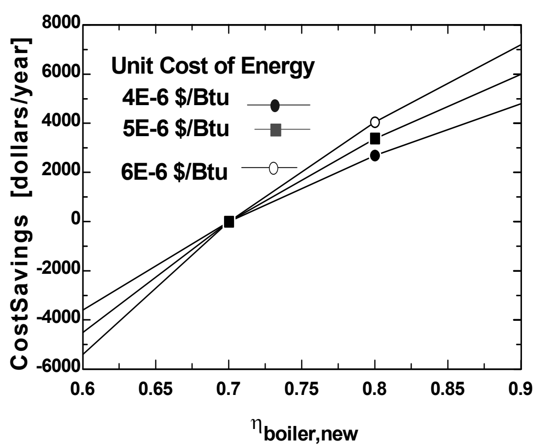
Discussion Notice that tuning up the boiler will save $2936 a year, which is a significant amount. The implementation cost of this measure is negligible if the adjustment can be made by in-house personnel. Otherwise it is worthwhile to have an authorized representative of the boiler manufacturer to service the boiler twice a year.

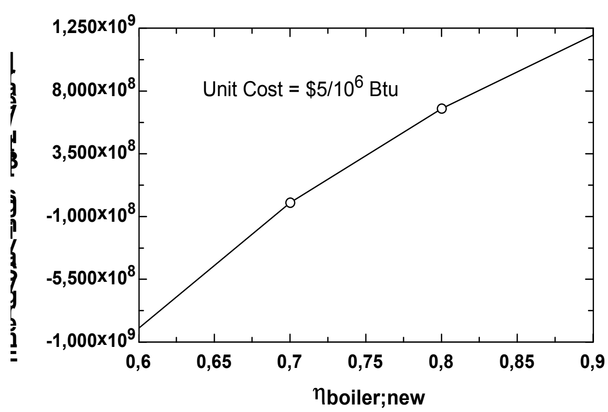
2-61E EES Problem 2-60E is reconsidered. The effects of the unit cost of energy and combustion efficiency on the annual energy used and the cost savings as the efficiency varies from 0.6 to 0.9 and the unit cost varies from \$4 to \$6 per million Btu are the investigated. The annual energy saved and 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.

```
"Knowns:"
eta_boiler_current = 0.7
eta_boiler_new = 0.8
Q_dot_in_current = 3.6E+6 "[Btu/h]"
DELTAt = 1500 "[h/year]"
UnitCost_energy = 5E-6 "[dollars/Btu]"
"Analysis: The heat output of boiler is related to the fuel energy input to the boiler by
    Boiler output = (Boiler input)(Combustion efficiency)
Then the rate of useful heat output of the boiler becomes"

Q_dot_out=Q_dot_in_current*eta_boiler_current "[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 "

Q_dot_in_new=Q_dot_out/eta_boiler_new "[Btu/h]"
Q_dot_in_saved=Q_dot_in_current - Q_dot_in_new "[Btu/h]"

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

    EnergySavings   =Q_dot_in_saved*DELTAt "[Btu/year]"
    CostSavings = EnergySavings*UnitCost_energy "[dollars/year]"

"Discussion Notice that tuning up the boiler will save $2936 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. "
```

CostSavings [dollars/year]	EnergySavings [Btu/year]	$\eta_{boiler,new}$
-4500	-9.000E+08	0.6
0	0	0.7
3375	6.750E+08	0.8
6000	1.200E+09	0.9





2-62 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

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

2-63 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,

$$\begin{aligned}\dot{Q}_{\text{lighting}} &= (\text{Energy consumed per lamp}) \times (\text{No. of lamps}) \\ &= (40\ \text{W})(1.1)(18) = 792\ \text{W}\end{aligned}$$

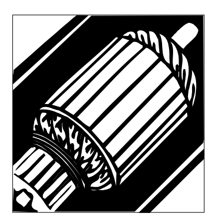
$$\dot{Q}_{\text{people}} = (\text{No. of people}) \times \dot{Q}_{\text{person}} = 56 \times (100\ \text{W}) = 5600\ \text{W}$$

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

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

2-64 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.

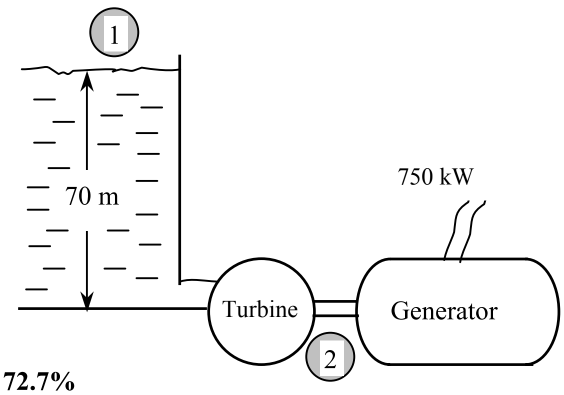
2-65 A hydraulic turbine-generator is generating electricity from the water of a large reservoir. The combined turbine-generator efficiency and the turbine efficiency are to be determined.

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

Analysis We take the free surface of the reservoir to be point 1 and the turbine exit to be point 2. We also take the turbine exit as the reference level ($z_2 = 0$), and thus the potential energy at points 1 and 2 are $\mathrm{pe}_1 = gz_1$ and $\mathrm{pe}_2 = 0$. The flow energy P/ρ 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 ($\mathrm{ke}_1 = \mathrm{ke}_2 = 0$) since the water at point 1 is essentially motionless, and the kinetic energy of water at turbine exit is assumed to be negligible. The potential energy of water at point 1 is

$$pe_1 = gz_1 = (9.81\,\mathrm{m/s^2})(70\,\mathrm{m})\left(\frac{1\,\mathrm{kJ/kg}}{1000\,\mathrm{m^2/s^2}}\right) = 0.687\,\mathrm{kJ/kg}$$

Then the rate at which the mechanical energy of the fluid is supplied to the turbine become



$$\begin{aligned}\left|\Delta\dot{E}_{\mathrm{mech,fluid}}\right| &= \dot{m}(e_{\mathrm{mech,in}} - e_{\mathrm{mech,out}}) = \dot{m}(pe_1 - 0) \\ &= \dot{m}pe_1 \\ &= (1500\,\mathrm{kg/s})(0.687\,\mathrm{kJ/kg}) \\ &= 1031\,\mathrm{kW}\end{aligned}$$

The combined turbine-generator and the turbine efficiency are determined from their definitions,

$$\eta_{\text{turbine-gen}} = \frac{\dot{W}_{\mathrm{elect,out}}}{|\Delta\dot{E}_{\mathrm{mech,fluid}}|} = \frac{750\,\mathrm{kW}}{1031\,\mathrm{kW}} = 0.727 \quad \text{or} \quad \mathbf{72.7\%}$$

$$\eta_{\mathrm{turbine}} = \frac{\dot{W}_{\mathrm{shaft,out}}}{|\Delta\dot{E}_{\mathrm{mech,fluid}}|} = \frac{800\,\mathrm{kW}}{1031\,\mathrm{kW}} = 0.776 \quad \text{or} \quad \mathbf{77.6\%}$$

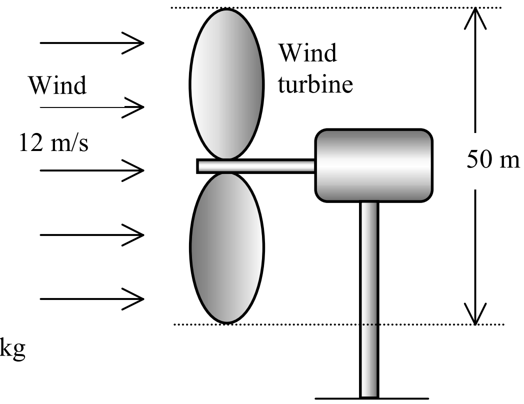
Therefore, the reservoir supplies 1031 kW of mechanical energy to the turbine, which converts 800 kW of it to shaft work that drives the generator, which generates 750 kW of electric power.

Discussion This problem can also be solved by taking point 1 to be 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.

2-66 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 ρ = 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:

$$e_{\text{mech}} = ke = \frac{V^2}{2} = \frac{(12\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 0.072\text{ kJ/kg}$$

$$\dot{m} = \rho VA = \rho V\frac{\pi D^2}{4} = (1.25\text{ kg/m}^3)(12\text{ m/s})\frac{\pi(50\text{ m})^2}{4} = 29{,}450\text{ kg/s}$$

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (29{,}450\text{ kg/s})(0.072\text{ kJ/kg}) = \mathbf{2121\ kW}$$

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

$$\dot{W}_{\text{elect}} = \eta_{\text{wind turbine}}\dot{W}_{\max} = (0.30)(2121\text{ kW}) = \mathbf{636\ kW}$$

Therefore, 636 kW of actual power can be generated by this wind turbine at the stated conditions.

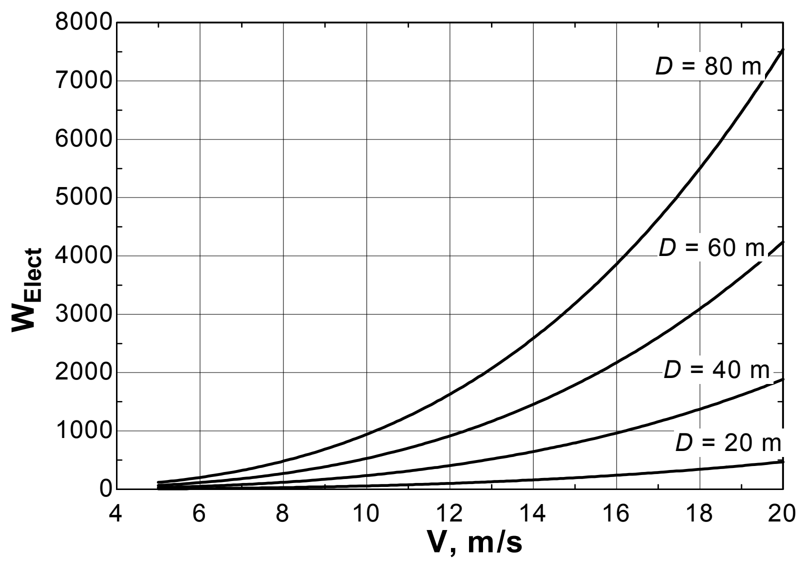
Discussion The power generation of a wind turbine is proportional to the cube of the wind velocity, and thus the power generation will change strongly with the wind conditions.

2-67 EES Problem 2-66 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 80 m in increments of 20 m is to be investigated.

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

```
D1=20 "m"
D2=40 "m"
D3=60 "m"
D4=80 "m"
Eta=0.30
rho=1.25 "kg/m3"
m1_dot=rho*V*(pi*D1^2/4); W1_Elect=Eta*m1_dot*(V^2/2)/1000 "kW"
m2_dot=rho*V*(pi*D2^2/4); W2_Elect=Eta*m2_dot*(V^2/2)/1000 "kW"
m3_dot=rho*V*(pi*D3^2/4); W3_Elect=Eta*m3_dot*(V^2/2)/1000 "kW"
m4_dot=rho*V*(pi*D4^2/4); W4_Elect=Eta*m4_dot*(V^2/2)/1000 "kW"
```

D, m	V, m/s	m, kg/s	W_{elect}, kW
20	5	1,963	7
	10	3,927	59
	15	5,890	199
	20	7,854	471
40	5	7,854	29
	10	15,708	236
	15	23,562	795
	20	31,416	1885
60	5	17,671	66
	10	35,343	530
	15	53,014	1789
	20	70,686	4241
80	5	31,416	118
	10	62,832	942
	15	94,248	3181
	20	125,664	7540



2-68 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

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

(*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

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

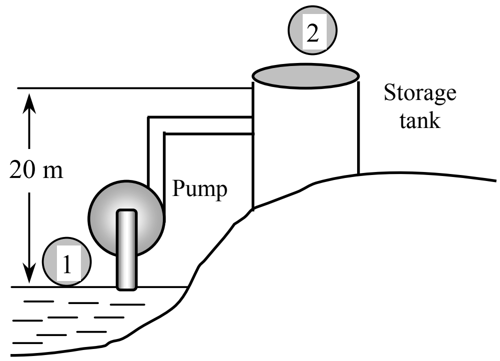
Discussion Note that about one-third of the kinetic energy of the wind is converted to power by the wind turbine, which is typical of actual turbines.

2-69 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 $\mathrm{pe}_1 = 0$ and $\mathrm{pe}_2 = gz_2$. 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 ($\mathrm{ke}_1 = \mathrm{ke}_2 = 0$) 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,

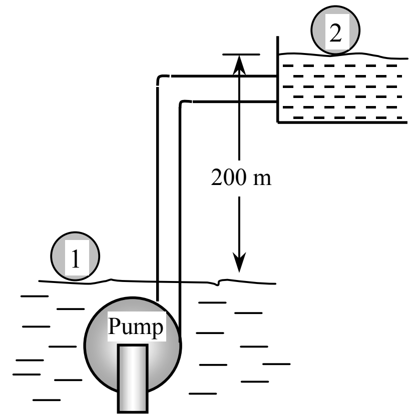
$$\Delta P = \frac{\Delta\dot{E}_{\text{mech,fluid}}}{\dot{V}} = \frac{13.7\ \text{kJ/s}}{0.070\ \text{m}^3/\text{s}}\left(\frac{1\ \text{kPa}\cdot\text{m}^3}{1\ \text{kJ}}\right) = \mathbf{196\ kPa}$$

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.

2-70 Geothermal water is raised from a given depth by a pump at a specified rate. For a given pump efficiency, the required power input to the pump is to be determined.

Assumptions **1** The pump operates steadily. **2** Frictional losses in the pipes are negligible. **3** The changes in kinetic energy are negligible. **4** The geothermal water is exposed to the atmosphere and thus its free surface is at atmospheric pressure.



Properties The density of geothermal water is given to be ρ = 1050 kg/m^3.

Analysis The elevation of geothermal water and thus its potential energy changes, but it experiences no changes in its velocity and pressure. Therefore, the change in the total mechanical energy of geothermal 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,

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

$$= (1050\ \text{kg/m}^3)(0.3\ \text{m}^3/\text{s})(9.81\ \text{m/s}^2)(200\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kW}}{1000\ \text{N}\cdot\text{m/s}}\right) = 618.0\ \text{kW}$$

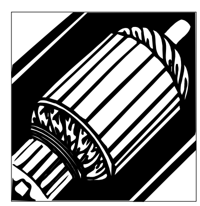
Then the required power input to the pump becomes

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

Discussion The frictional losses in piping systems are usually significant, and thus a larger pump will be needed to overcome these frictional losses.

2-71 An electric motor with a specified efficiency operates in a room. The rate at which the motor dissipates heat to the room it is in when operating at full load and if this heat dissipation is adequate to heat the room in winter are to be determined.

Assumptions The motor operates at full load.



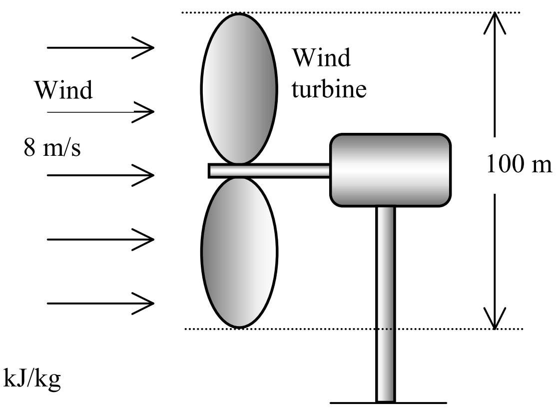
Analysis The motor efficiency represents the fraction of electrical energy consumed by the motor that is converted to mechanical work. The remaining part of electrical energy is converted to thermal energy and is dissipated as heat.

$$\dot{Q}_{\text{dissipated}} = (1-\eta_{\text{motor}})\dot{W}_{\text{in, electric}} = (1-0.88)(20\ \text{kW}) = \mathbf{2.4\ kW}$$

which is larger than the rating of the heater. Therefore, the heat dissipated by the motor alone is sufficient to heat the room in winter, and there is no need to turn the heater on.

Discussion Note that the heat generated by electric motors is significant, and it should be considered in the determination of heating and cooling loads.

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 $\rho = 1.25$ 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

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

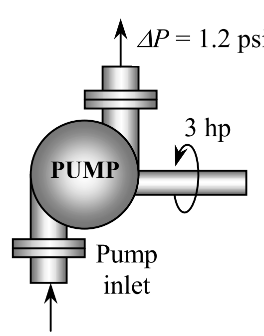
Then the amount of electricity generated per day and its monetary value become

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

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

$$= \dot{\boldsymbol{V}}(P_2 - P_1) = (8\text{ ft}^3/\text{s})(1.2\text{ psi})\left(\frac{1\text{ Btu}}{5.404\text{ psi}\cdot\text{ft}^3}\right) = 1.776\text{ Btu/s} = 2.51\text{ hp}$$

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

$$\eta_{\text{pump}} = \frac{\Delta\dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{pump, shaft}}} = \frac{2.51\text{ hp}}{3\text{ hp}} = 0.838 \quad\text{or}\quad \mathbf{83.8\%}$$

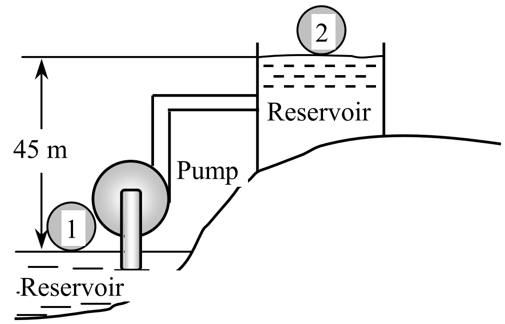
Discussion The overall efficiency of this pump will be lower than 83.8% because of the inefficiency of the electric motor that drives the pump.

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,



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

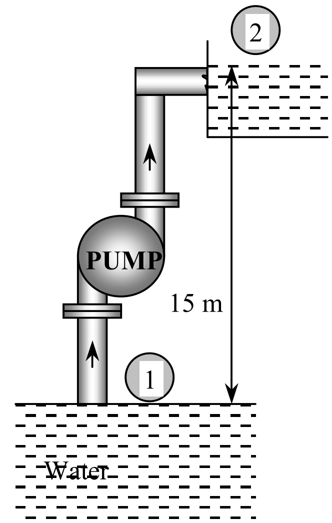
$$= (1000\ \text{kg/m}^3)(0.03\ \text{m}^3/\text{s})(9.81\ \text{m/s}^2)(45\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kW}}{1000\ \text{N}\cdot\text{m/s}}\right) = 13.2\ \text{kW}$$

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 A pump with a specified shaft power and efficiency is used to raise water to a higher elevation. The maximum flow rate of water is to be determined.



Assumptions **1** The flow is steady and incompressible. **2** The elevation difference between the reservoirs is constant. **3** We assume the flow in the pipes to be *frictionless* since the *maximum* flow rate is to be determined,

Properties We take the density of water to be ρ = 1000 kg/m³.

Analysis The useful pumping power (the part converted to mechanical energy of water) is

$$\dot{W}_{\text{pump,u}} = \eta_{\text{pump}}\dot{W}_{\text{pump, shaft}} = (0.82)(7 \text{ hp}) = 5.74 \text{ hp}$$

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,

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

Noting that $\Delta\dot{E}_{\text{mech}} = \dot{W}_{\text{pump,u}}$, the volume flow rate of water is determined to be

$$\dot{V} = \frac{\dot{W}_{\text{pump,u}}}{\rho g z_2} = \frac{5.74 \text{ hp}}{(1000 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(15 \text{ m})}\left(\frac{745.7 \text{ W}}{1 \text{ hp}}\right)\left(\frac{1 \text{ N}\cdot\text{m/s}}{1 \text{ W}}\right)\left(\frac{1 \text{ kg}\cdot\text{m/s}^2}{1 \text{ N}}\right) = \mathbf{0.0291\ m^3/s}$$

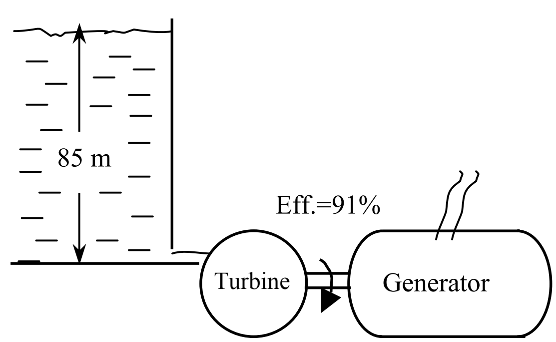
Discussion This is the maximum flow rate since the frictional effects are ignored. In an actual system, the flow rate of water will be less because of friction in pipes.

2-76 The available head of a hydraulic turbine and its overall efficiency are given. The electric power output of this turbine is to be determined.

Assumptions **1** The flow is steady and incompressible. **2** The elevation of the reservoir remains constant.

Properties We take the density of water to be ρ = 1000 kg/m³.

Analysis The total mechanical energy the 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. Therefore, the actual power produced by the turbine can be expressed as



$$\dot{W}_{\text{turbine}} = \eta_{\text{turbine}}\dot{m}gh_{\text{turbine}} = \eta_{\text{turbine}}\rho\dot{V}gh_{\text{turbine}}$$

Substituting,

$$\dot{W}_{\text{turbine}} = (0.91)(1000 \text{ kg/m}^3)(0.25 \text{ m}^3/\text{s})(9.81 \text{ m/s}^2)(85 \text{ m})\left(\frac{1 \text{ N}}{1 \text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1 \text{ kW}}{1000 \text{ N}\cdot\text{m/s}}\right) = \mathbf{190\ kW}$$

Discussion Note that the power output of a hydraulic turbine is proportional to the available elevation difference (turbine head) and the flow rate.

2-77 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.

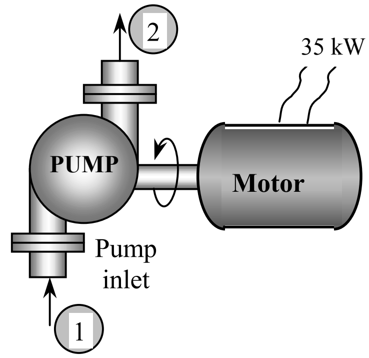
Assumptions **1** The flow is steady and incompressible. **2** The elevation difference across the pump is negligible.

Properties The density of oil is given to be $\rho = 860\ \text{kg/m}^3$.

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.

2-78E 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.

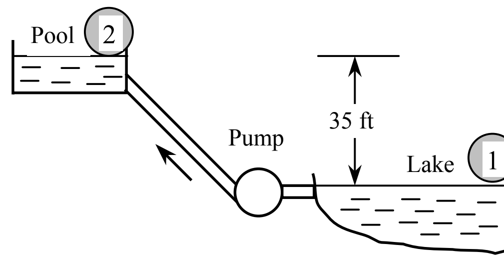
Assumptions **1** The flow is steady and incompressible. **2** The elevation difference between the lake and the free surface of the pool is constant. **3** The average flow velocity is constant since pipe diameter is constant.

Properties We take the density of water to be $\rho = 62.4\ \text{lbm/ft}^3$.

Analysis The useful mechanical pumping power delivered to water is

$$\dot{W}_{\text{pump,u}} = \eta_{\text{pump}}\dot{W}_{\text{pump}} = (0.73)(12\ \text{hp}) = 8.76\ \text{hp}$$

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

$$\Delta\dot{E}_{\text{mech}} = (62.4\ \text{lbm/ft}^3)(1.2\ \text{ft}^3\text{/s})(32.2\ \text{ft/s}^2)(35\ \text{ft})\left(\frac{1\ \text{lbf}}{32.2\ \text{lbm}\cdot\text{ft/s}^2}\right)\left(\frac{1\ \text{hp}}{550\ \text{lbf}\cdot\text{ft/s}}\right) = 4.76\ \text{hp}$$

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

$$\dot{W}_{\text{frict}} = \dot{W}_{\text{pump, u}} - \Delta\dot{E}_{\text{mech}} = 8.76 - 4.76\ \text{hp} = \mathbf{4.0\ hp}$$

Discussion Note that the pump must supply to the water an additional useful mechanical power of 4.0 hp to overcome the frictional losses in pipes.