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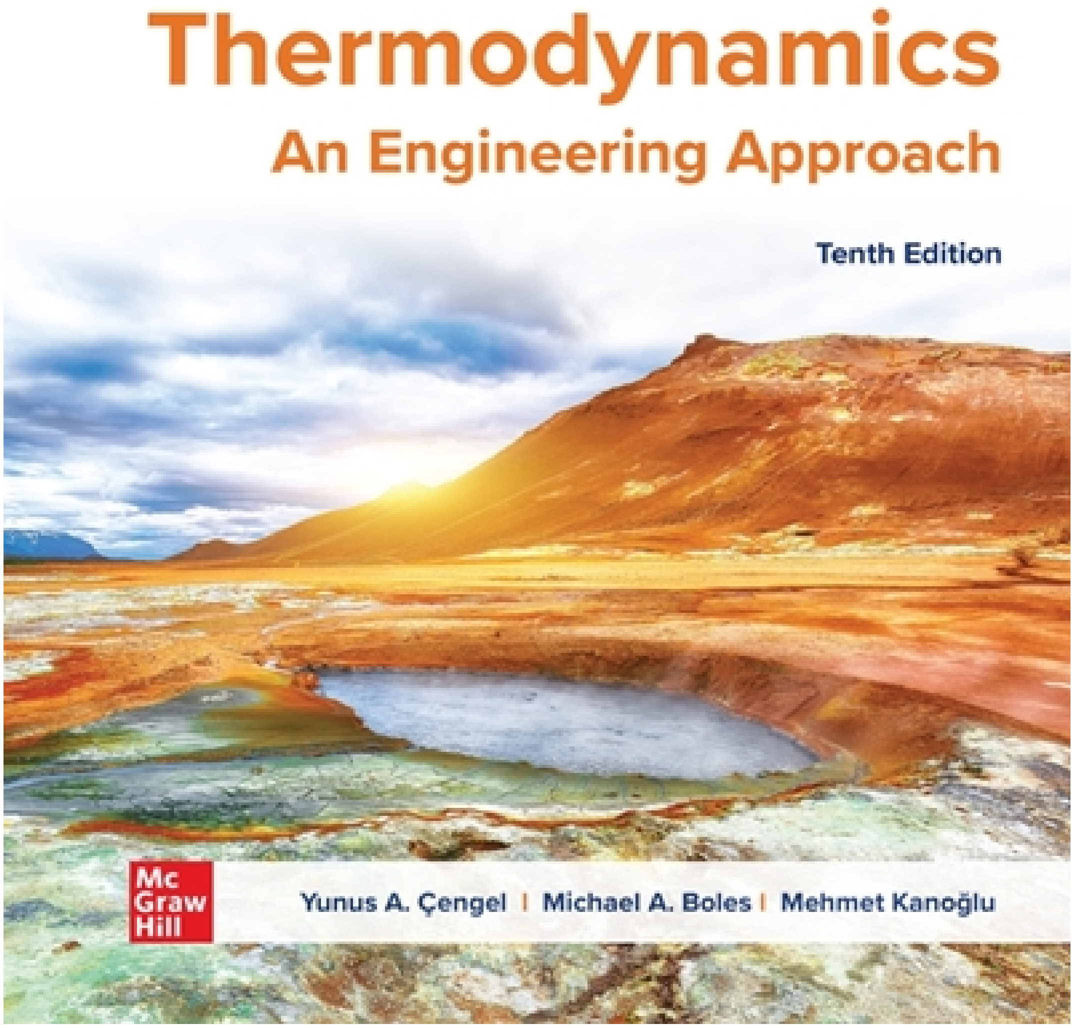

Solutions

SOLUTIONS MANUAL

Thermodynamics: An Engineering Approach

10th Edition

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Chapter 2
ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS

CYU - Check Your Understanding

CYU 2-1 ■ Check Your Understanding

CYU 2-1.1 A refrigerator is placed in the middle of a room. The refrigerator consumes 0.5 kW of electricity while removing heat from the refrigerated space at a rate of 0.6 kW. What is the net effect of operating this refrigerator on the room?
(a) 0.1 kW cooling
(b) 0.6 kW cooling
(c) 0.5 kW heating
(d) 1.1 kW heating
(e) 1.1 kW cooling

Answer: (*c*) 0.5 kW heating

CYU 2-1.2 A fan is operating in an isolated a room. The fan consumes 300 W of electricity and converts 75 percent of this electricity to the kinetic energy of air. What is the heating rate of the room by the fan?
(a) 375 W
(b) 300 W
(c) 225 W
(d) 75 W
(e) 0

Answer: (*b*) 300 W

CYU 2-2 ■ Check Your Understanding

CYU 2-2.1 Select the correct list of energy forms which constitute internal energy:
(a) Potential and kinetic
(b) Sensible, chemical, and kinetic
(c) Sensible and latent
(d) Sensible, chemical, and nuclear
(e) Sensible, latent, chemical, and nuclear

Answer: (*e*) Sensible, latent, chemical, and nuclear

CYU 2-2.2 To what velocity do we need to accelerate a car at rest to increase its kinetic energy by 1kJ/kg?
(a) 1m/s
(b) 1.4m/s
(c) 10m/s

(d) $44.7\,\text{m/s}$
(e) $90\,\text{m/s}$

Answer: (*d*) $44.7\,\text{m/s}$
$ke = V^2/2 \rightarrow 1\,\text{kJ/kg} = V^2/2 \rightarrow 1000\,\text{m2/s2} = V^2/2 \rightarrow V = 44.7\,\text{m/s}$
since $1\,\text{kJ/kg} = 1000\,\text{m}^2/\text{s}^2$

CYU 2-2.3 How many meters do we need to raise a mass of 1 kg to increase its potential energy by 1 kJ?
(a) 1 m
(b) 9.8 m
(c) 49 m
(d) 98 m
(e) 102 m

Answer: (*e*) 102 m
$PE = mgz \rightarrow 1\,\text{kJ} = (1\,\text{kg})(9.8\,\text{m/s}^2)z \rightarrow 1000\,\text{kg m2/s2} = (1\,\text{kg})(9.8\,\text{m/s}^2)z \rightarrow z = 102\,\text{m}$
since $1\,\text{kJ/kg} = 1000\,\text{m}^2/\text{s}^2$

CYU 2-2.4 What is the total energy of a 5-kg object with KE = 10 kJ, PE = 15 kJ, $u = 20\,\text{kJ/kg}$
(a) 20 kJ
(b) 25 kJ
(c) 45 kJ
(d) 125 kJ
(e) 225 kJ

Answer: (*d*) 125 kJ
$E = U + KE + PE = (5\,\text{kg})(20\,\text{kJ/kg}) + 10\,\text{kJ} + 15\,\text{kJ} = 125\,\text{kJ}$

CYU 2-2.5 What is the total mechanical energy of a fluid flowing in a horizontal pipe at a velocity is $10\,\text{m/s}$? The pressure of the fluid is 200 kPa and its specific volume is $0.001\,\text{m}^3/\text{kg}$.
(a) $0.050\,\text{kJ/kg}$
(b) $0.2\,\text{kJ/kg}$
(c) $0.25\,\text{kJ/kg}$
(d) $50\,\text{kJ/kg}$
(e) $50.2\,\text{kJ/kg}$

Answer: (*c*) $0.25\,\text{kJ/kg}$
$e = Pv + ke = Pv + V^2/2 = (200\,\text{kPa})\left(0.001\,\text{m}^3/\text{kg}\right) + (1/1000)(10\,\text{m/s})^2/2 = 0.2 + 0.05 = 0.25\,\text{kJ/kg}$
since $1\,\text{kJ/kg} = 1000\,\text{m}^2/\text{s}^2$

CYU 2-3 ■ Check Your Understanding

CYU 2-3.1 If an energy transfer between a closed system and its surroundings is not heat, it must be
(a) Work
(b) Energy transfer by mass
(c) Work or energy transfer by mass

(d) Mechanical energy
(e) Thermal energy

Answer: (*a*) Work

CYU 2-3.2 Select the wrong statement regarding energy transfer mechanisms.
(a) Heat always flows from high temperature to low temperature.
(b) There cannot be any net heat transfer between two systems that are at the same temperature.
(c) If a system undergoes an adiabatic process, the temperature of the system must remain constant.
(d) Heat transfer is recognized only as it crosses the boundary of a system.

Answer: (*c*) If a system undergoes an adiabatic process, the temperature of the system must remain constant.

CYU 2-3.3 A 2-kg closed system receives 6 kJ heat from a source for a period of 10 min. The rate of heat transfer and the heat transfer per unit mass are
(a) 3 W, 10 kJ / kg
(b) 10 W, 3 kJ / kg
(c) 3 kW, 10 kJ / kg
(d) 0.6 kW, 3 kJ / kg
(e) 0.6 W, 3 kJ / kg

Answer: (*b*) 10 W, 3 kJ / kg

$\dot{Q} = Q / dt = (6000\,J) / (10 \times 60\,s) = 10\,J/s = 10\,W$

$q = Q / m = (6\,kJ) / (2\,kg) = 3\,kJ/kg$

CYU 2-4 ■ Check Your Understanding

CYU 2-4.1 Select the wrong statement regarding heat and work interactions.
(a) Both heat and work are boundary phenomena.
(b) Heat and work are defined at a state of a system.
(c) The magnitudes of heat and work depend on the path followed during a process.
(d) The magnitudes of heat and work depend on the initial and final states of a system.
(e) The temperature of a well-insulated system can be changed by energy transfer as work.

Answer: (*b*) Heat or work is defined at a state.

CYU 2-4.2 Work is done on a 0.5-kg closed system by a rotating shaft in the amount of 10 kJ during a period of 20 s. The work per unit mass and the power are
(a) 10 kJ / kg , 5 kW
(b) 5 kJ / kg , 2 kW
(c) 20 kJ / kg , 0.5 kW
(d) 2000 J / kg , 50 W
(e) 2 kJ / kg , 5 kW

Answer: (*c*) 20 kJ / kg , 0.5 kW

$w = W / m = (10\,kJ) / (0.5\,kg) = 20\,kJ/kg$

$\dot{W} = W / dt = (10\,kJ) / (20\,s) = 0.5\,kJ/s = 0.5\,kW$

CYU 2-5 ■ Check Your Understanding

CYU 2-5.1 Which of the following is not mechanical work?
(a) Spring work
(b) Shaft work
(c) Work for stretching of a liquid film
(d) Work to accelerate a body
(e) Electrical work

Answer: (*e*) Electrical work

CYU 2-5.2 Which of the following are mechanical work?
I Electrical work
II Magnetic work
III Spring work
IV Shaft work
(a) I and II
(b) I and III
(c) III and IV
(d) I, II, and IV
(e) I, III, and IV

Answer: (*c*) III and IV

CYU 2-5.3 The velocity of a 1000-kg car is increased from rest to $72\,\text{km/h}$ in 10 s. What is the required power for acceleration?
(a) 518 kW
(b) 259 kW
(c) 200 kW
(d) 20 kW
(e) 2 kW

Answer: (*d*) 20 kW

$$W = 0.5m\left(V_2^2 - V_1^2\right) = 0.5(1000\,\text{kg})\left[(72/3.6\,\text{m/s})^2 - 0\right] = 200{,}000\,\text{kg}\,\text{m}^2/\text{s}^2 = 200\,\text{kJ}$$

since $1\,\text{kJ/kg} = 1000\,\text{m}^2/\text{s}^2$ and $1\,\text{m/s} = 3.6\,\text{km/h}$

$$\dot{W} = W/dt = (200\,\text{kJ})/(10\,\text{s}) = 20\,\text{kW}$$

CYU 2-6 ■ Check Your Understanding

CYU 2-6.1 Energy can be transferred to or from a system by
I Mass flow
II II. Work
III Heat transfer
(a) I, II, and III
(b) I and II
(c) I and III
(d) II and III
(e) Only III

Answer: (*a*) I, II, and III

CYU 2-6.2 Heat is lost from a system in the amount of 3 kJ. If the energy of the system is decreased by 5 kJ, what is the work interaction?

(a) $W_{in} = 2\,kJ$
(b) $W_{out} = 2\,kJ$
(c) $W_{in} = 8\,kJ$
(d) $W_{out} = 8\,kJ$
(e) $W_{in} = 3\,kJ$

Answer: (*b*) $W_{out} = 2\,kJ$

$$E_{in} - E_{out} = dE_{sys}$$
$$(Q_{in} + W_{in}) - (Q_{out} + W_{out}) = E_2 - E_1$$
$$(0+0) - (3\,kJ + W_{out}) = -5\,kJ$$
$$W_{out} = 2\text{ kJ}$$

CYU 2-6.3 30 kJ of energy enters a well-insulated piston-cylinder device by mass flow while piston rises and does 40 kJ of work. What is the change in the total energy of the system?

(a) 40 J
(b) –70 kJ
(c) 70 kJ
(d) –10 kJ
(e) 10 kJ

Answer: (*d*) –10 kJ

$$E_{in} - E_{out} = dE_{sys}$$
$$(Q_{in} + W_{in} + E_{mass,in}) - (Q_{out} + W_{out} + E_{mass,out}) = E_2 - E_1$$
$$30\text{ kJ} - 40\text{ kJ} = -10\text{ kJ}$$

CYU 2-6.4 Heat is transferred to a closed system in the amount of 13 kJ while 8 kJ electrical work is done on the system. If there are no kinetic and potential energy changes, what is the internal energy change of the system?

(a) 5 kJ
(b) –5 kJ
(c) 21 kJ
(d) –21 kJ
(e) 8 kJ

Answer: (*c*) 21 kJ

$$E_{in} - E_{out} = dE_{sys}$$
$$(Q_{in} + W_{in}) - (Q_{out} + W_{out}) = dE_{sys} = dU$$
$$13\text{kJ} + 8\text{kJ} = 21\text{kJ}$$

CYU 2-6.5 Using the formal sign convention, the heat and work interactions are given as W = –60 J and Q = 35 J. What is the energy change of the system ΔE?

(a) –60 J
(b) –25 J
(c) 25 J
(d) –95 J
(e) 95 J

Answer: (*e*) 95 J

Q - W = dE

35 J - (-60 J) = 95 J

CYU 2-7 ■ Check Your Understanding

CYU 2-7.1 A house is heated by a natural gas heater. During a 1-h period, 0.5 kg natural gas is consumed and 20,000 kJ heat is delivered to the house. The hating value of natural gas is $50,000\,\text{kJ/kg}$. What is the efficiency of the heater?

(a) 0%
(b) 20%
(c) 50%
(d) 80%
(e) 100%

Answer: (*d*) 80%

$Q_{in} = mHV = (0.5\,\text{kg})(50,000\,\text{kJ/kg}) = 25,000\,\text{kJ}$

$\text{eta} = Q_{supplied}/Q_{in} = (20,000\,\text{kJ})/(25,000\,\text{kJ}) = 0.8 = 80\%$

CYU 2-7.2 The overall efficiency of a natural gas power plant is 45 percent. The thermal efficiency is 50 percent and the generator efficiency is 100 percent. What is the efficiency of the natural gas furnace?
(a) 100%
(b) 90%
(c) 45.5%
(d) 22.5%
(e) 10%

Answer: (*b*) 90%

$\text{eta}_{overall} = \text{eta}_{th}\ \text{eta}_{gen}\ \text{eta}_{furnace}$

$0.45 = (0.50)(1)\ \text{eta}_{furnace}$

$\text{eta}_{furnace} = 0.9$

CYU 2-7.3 The motor of a pump consumes 5 kW of electrical power. If the pump efficiency is 80 percent and the motor efficiency is 90 percent, what is the shaft power input to the pump?
(a) 1.4 kW
(b) 3.6 kW
(c) 4 kW
(d) 4.5 kW
(e) 5 kW

Answer: (*d*) 4.5 kW

$\text{Shaft power} = (\text{Electric power})(\text{eta}_{motor}) = (5\text{kW})(0.9) = 4.5\text{kW}$

CYU 2-7.4 A turbine-generator unit has a combined efficiency of 72 percent. The turbine efficiency is 80 percent and the mechanical energy decrease of the fluid across the turbine is 1 MW. The shaft power output from the turbine and the electrical power output from the generator, respectively, are
(a) 0.8 MW, 0.72MW
(b) 0.72 MW, 0.8 MW
(c) 0.9 MW, 0.72 MW
(d) 0.72 MW, 0.9 MW
(e) 0.9 MW, 0.8 MW

Answer: (*a*) 0.8 MW, 0.72 MW

$$\text{Shaft power} = (dE_{mech})(\text{eta}_{turb}) = (1\text{MW})(0.8) = 0.8\text{MW}$$

$$\text{eta}_{overall} = \text{eta}_{turb}\ \text{eta}_{gen} \rightarrow 0.72 = (0.80)\ \text{eta}_{gen} \rightarrow \text{eta}_{gen} = 0.9$$

$$\text{Electric power} = (\text{Shaft power}) / (\text{eta}_{gen}) = (0.8\text{MW})(0.9) = 0.72\text{MW}$$

CYU 2-8 ■ Check Your Understanding

CYU 2-8.1 Which of the emission listed below is not an air pollutant?

(a) Hydrocarbons
(b) Nitrogen oxides
(c) Carbon monoxide
(d) Carbon dioxide
(e) Sulfur dioxide

Answer: (*d*) Carbon dioxide

CYU 2-8.2 Ground-level ozone, which is the primary component of smog, forms when _______ and _______ react in the presence of sunlight on hot, calm days.

(a) CO, NO_x
(b) CO, HC
(c) HC, NO_x
(d) CO, SO_2
(e) SO_2, NO_x

Answer: (*c*) HC, NO_x

CYU 2-8.3 The primary greenhouse gas is

(*a*) Hydrocarbons (*b*) Nitrogen oxides (*c*) Carbon monoxide (*d*) Carbon dioxide
(*e*) Water vapor

Answer: (*d*) Carbon dioxide

PROBLEMS

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 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.

2-4C Thermal energy is the sensible and latent forms of internal energy, and it is referred to as heat in daily life.

2-5C 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.

2-6C In electric heaters, electrical energy is converted to sensible internal energy.

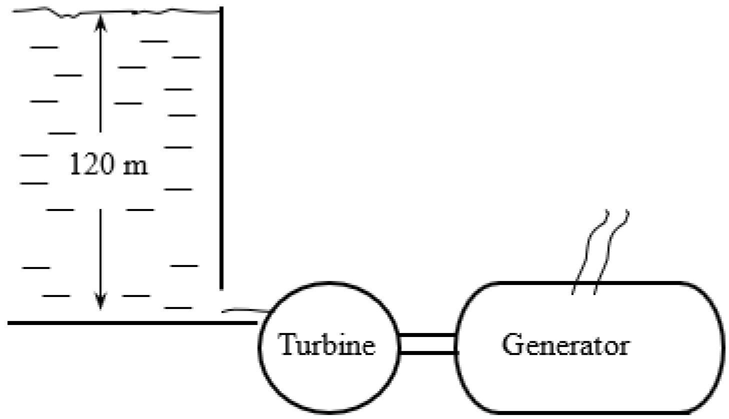
2-7C Hydrogen is also a fuel, since it can be burned, but it is not an energy source since there are no hydrogen reserves in the world. Hydrogen can be obtained from water by using another energy source, such as solar or nuclear energy, and then the hydrogen obtained can be used as a fuel to power cars or generators. Therefore, it is more proper to view hydrogen is an energy carrier than an energy source.

2-8C Initially, the rock possesses potential energy relative to the bottom of the sea. As the rock falls, this potential energy is converted into kinetic energy. Part of this kinetic energy is converted to thermal energy as a result of frictional heating due to air resistance, which is transferred to the air and the rock. Same thing happens in water. Assuming the impact velocity of the rock at the sea bottom is negligible, the entire potential energy of the rock is converted to thermal energy in water and air.

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

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

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
h=120 [m]
m_dot=1500 [kg/s]
"Analysis"
g=9.81 [m/s^2]
e_mech=(g*h)*Convert(m^2/s^2, kJ/kg)
W_dot_max=m_dot*e_mech
```

2-10E The specific kinetic energy of a mass whose velocity is given is to be determined.

Analysis According to the definition of the specific kinetic energy,

$$\text{ke} = \frac{V^2}{2} = \frac{(100 \text{ ft/s})^2}{2}\left(\frac{1 \text{ Btu/lbm}}{25{,}037 \text{ ft}^2/\text{s}^2}\right) = \mathbf{0.200 \text{ Btu/lbm}}$$

EES (Engineering Equation Solver) SOLUTION

"Given"
V=100 [ft/s]
"Analysis"
ke=V^2/2*(1 [Btu/lbm])/(25037 [ft^2/s^2])

2-11 The specific kinetic energy of a mass whose velocity is given is to be determined.

Analysis Substitution of the given data into the expression for the specific kinetic energy gives

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

EES (Engineering Equation Solver) SOLUTION

"Given"
V=30 [m/s]
"Analysis"
ke=V^2/2*(1 [kJ/kg])/(1000 [m^2/s^2])

2-12E 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

$$\text{PE} = mgz = (100 \text{ lbm})(31.7 \text{ ft/s}^2)(-20 \text{ ft})\left(\frac{1 \text{ Btu/lbm}}{25{,}037 \text{ ft}^2/\text{s}^2}\right) = \mathbf{-2.53 \text{ Btu}}$$

EES (Engineering Equation Solver) SOLUTION

"Given"
z=20 [ft]
g=31.7 [ft/s^2]
m=100 [lbm]
"Analysis"
PE=m*g*z*(1 [Btu/lbm])/(25037 [ft^2/s^2])

2-13 The specific potential energy of an object is to be determined.

Analysis The specific potential energy is given by

$$\text{pe} = gz = (9.8 \text{ m/s}^2)(50 \text{ m})\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) = \mathbf{0.49 \text{ kJ/kg}}$$

EES (Engineering Equation Solver) SOLUTION

"Given"
z=50 [m]
g=9.8 [m/s^2]
"Analysis"
pe=g*z*(1 [kJ/kg])/(1000 [m^2/s^2])

2-14 The total potential energy of an object is to be determined.

Analysis Substituting the given data into the potential energy expression gives

$$\text{PE} = mgz = (100\text{ kg})(9.81\text{ m/s}^2)(20\text{ m})\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = \mathbf{19.6\ kJ}$$

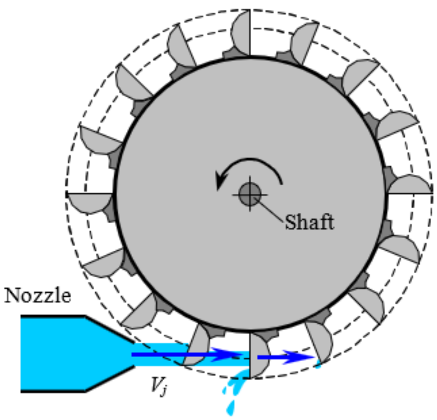
EES (Engineering Equation Solver) SOLUTION

```
"Given"
m=100 [kg]
z=20 [m]
"Analysis"
g=9.81 [m/s^2]
PE=m*g*z*(1 [kJ/kg])/(1000 [m^2/s^2])
```

2-15 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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
V=60 [m/s]
m_dot=120 [kg/s]
"Analysis"
g=9.81 [m/s^2]
e_mech=V^2/2*Convert(m^2/s^2, kJ/kg)
```

W_dot_max=m_dot*e_mech

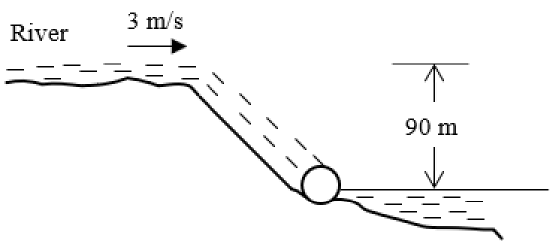
2-16 A river is flowing at a specified velocity, flow rate, and elevation. The total mechanical energy of the river water per unit mass, and the power generation potential of the entire river are to be determined.

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

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



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

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

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

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

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.

EES (Engineering Equation Solver) SOLUTION

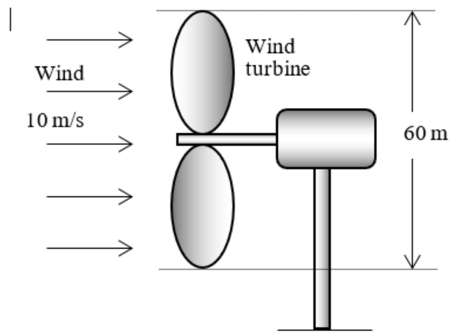
```
"Given"
V=3 [m/s]
V_dot=500 [m^3/s]
h=90 [m]
"Analysis"
g=9.81 [m/s^2]
e_mech=(g*h+V^2/2)*Convert(m^2/s^2, kJ/kg)
rho=1000 [kg/m^3]
m_dot=rho*V_dot
W_dot_max=m_dot*e_mech
```

2-17 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:



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

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

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

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
V=10 [m/s]
D=60 [m]
rho=1.25 [kg/m^3]
"Analysis"
g=9.81 [m/s^2]
e_mech=V^2/2*Convert(m^2/s^2, kJ/kg)
A=pi*D^2/4
m_dot=rho*V*A
W_dot_max=m_dot*e_mech
```

Energy Transfer by Heat and Work

2-18C 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.

2-19C 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.

2-20C Energy can cross the boundaries of a closed system in two forms: heat and work.

2-21C 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.

2-22C The form of energy that crosses the boundary of a closed system because of a temperature difference is heat; all other forms are work.

2-23C

(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.

2-24C It is a work interaction since the electrons are crossing the system boundary, thus doing electrical work.

2-25C It is a heat interaction since it is due to the temperature difference between the sun and the room.

2-26C Compressing a gas in a piston-cylinder device is a work interaction.

2-27 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) $\dot{W} = (5\text{ W})\left(\frac{1\text{ J/s}}{1\text{ W}}\right)\left(\frac{1\text{ N}\cdot\text{m}}{1\text{ J}}\right)\left(\frac{1\text{ kg}\cdot\text{m/s}^2}{1\text{ N}}\right) = \mathbf{5\ kg\cdot m^2/s^3}$

EES (Engineering Equation Solver) SOLUTION

```
"Given"
W_dot=5 [W]
"Analysis"
W_dot_1=W_dot*Convert(W, N-m/s)
W_dot_2=W_dot*Convert(W, kg-m^2/s^3)
```

Mechanical Forms of Work

2-28C The work done (i.e., energy transferred to the car) is the same, but the power is different.

2-29E 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.

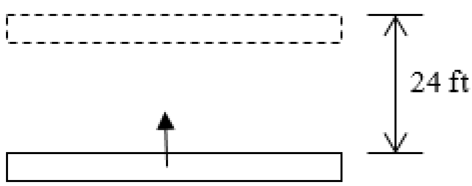
Analysis

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

$$W = mg\Delta z = (3 \times 2000\ \text{lbm})(32.174\ \text{ft/s}^2)\left(\frac{1\ \text{lbf}}{32.174\ \text{lbm}\cdot\text{ft/s}^2}\right)(24\ \text{ft})$$

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

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



(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

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
m=2*3000 [lbm] "1 ton = 2000 lbm"
z=36 [ft]
"Analysis"
g=32.2 [ft/s^2]
W_1=m*g*z*Convert(lbm-ft/s^2, lbf)
W_2=W_1*Convert(lbf-ft, Btu)
```

2-30E The engine of a car develops 225 hp at 3000 rpm. The torque transmitted through the shaft is to be determined.

Analysis The torque is determined from

$$\text{T} = \frac{\dot{W}_{sh}}{2\pi\dot{n}} = \frac{225\ \text{hp}}{2\pi(3000/60)/\text{s}}\left(\frac{550\ \text{lbf}\cdot\text{ft/s}}{1\ \text{hp}}\right) = \mathbf{394\ lbf\cdot ft}$$

EES (Engineering Equation Solver) SOLUTION

```
"Given"
W_dot_sh=225 [hp]
n_dot=3000 [1/min]
"Analysis"
T=W_dot_sh/(2*pi*n_dot)*Convert(min, s)*Convert(hp, lbf-ft/s)
```

2-31E 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,

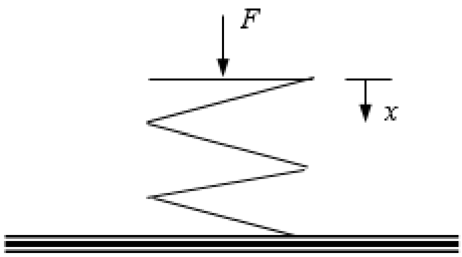
$$W = \int_1^2 F ds = \int_1^2 (F_0 + kx)dx$$

$$= F_0(x_2 - x_1) + \frac{k}{2}(x_2^2 - x_1^2)$$

$$= (100 \text{ lbf})[(1 - 0)\text{in}] + \frac{200 \text{ lbf/in}}{2}(1^2 - 0^2)\text{in}^2$$

$$= 200 \text{ lbf}\cdot\text{in}$$

$$= (200 \text{ lbf}\cdot\text{in})\left(\frac{1 \text{ Btu}}{778.169 \text{ lbf}\cdot\text{ft}}\right)\left(\frac{1 \text{ ft}}{12 \text{ in}}\right) = \mathbf{0.0214\ Btu}$$



EES (Engineering Equation Solver) SOLUTION


```
"Given"
k=200 [lbf/in]
F_0=100 [lbf]
x_2=1 [in]

"Analysis"
x_1=0 [in]
W=(F_0*(x_2-x_1)+k/2*(x_2^2-x_1^2))*Convert(lbf-in, Btu)
```

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

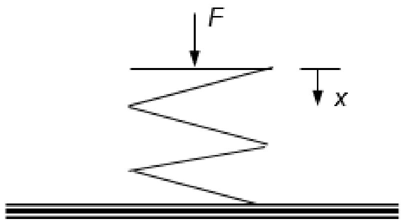
Analysis Since there is no preload, $F = kx$. Substituting this into the work expression gives

$$W = \int_1^2 F ds = \int_1^2 kx dx = k\int_1^2 x dx = \frac{k}{2}(x_2^2 - x_1^2)$$

$$= \frac{300 \text{ kN/m}}{2}\left[(0.03 \text{ m})^2 - 0^2\right]$$

$$= 0.135 \text{ kN}\cdot\text{m}$$

$$= (0.135 \text{ kN}\cdot\text{m})\left(\frac{1 \text{ kJ}}{1 \text{ kN}\cdot\text{m}}\right) = \mathbf{0.135\ kJ}$$



EES (Engineering Equation Solver) SOLUTION

"Given"
k=3 [kN/cm]
F_0=0 [N]
x_2=3 [cm]
"Analysis"
x_1=0 [cm]
W=k/2*(x_2^2-x_1^2)*Convert(kN-cm, kJ)

2-33 A ski lift is operating steadily at $10\,\text{km/h}$. 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 $10\,\text{km/h}$, 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,

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
distance=1000 [m]
DELTAz=200 [m]
space=20 [m]
N_people=3
Vel=10[km/h]*Convert(km/h, m/s)
m_chair=250 [kg]
t=5 [s]
"Properties"
g=9.807 [m/s^2]
"Analysis"
"Power required to operate"
N_chair=distance/space
m=N_chair*m_chair
W_g=m*g*DELTAz*Convert(kg-m^2/s^2, kJ)
DELTAt=distance/Vel
W_dot_g=W_g/DELTAt
"Power required to accelerate"
a=Vel/t
W_a=1/2*m*Vel^2*Convert(kg-m^2/s^2, kJ)
W_dot_a=W_a/t
sin(alpha)=DELTAz/distance
h=1/2*a*t^2*sin(alpha)
W_g_b=m*g*h*Convert(kg-m^2/s^2, kJ)
W_dot_g_b=W_g_b/t
W_dot_total=W_dot_a+W_dot_g_b
```


2-34 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,

$$W_a = \frac{1}{2}m\left(V_2^2 - V_1^2\right) = \frac{1}{2}(1500 \text{ kg})\left(\left(\frac{100{,}000 \text{ m}}{3600 \text{ s}}\right)^2 - 0\right)\left(\frac{1 \text{ kJ}}{1000 \text{ kg}\cdot\text{m}^2/\text{s}^2}\right) = 578.7 \text{ kJ}$$

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
m=1500 [kg]
W_dot_a=75 [kW]
Vel1=0
Vel2=100[km/h]*Convert(km/h, m/s)
"Analysis"
W_a=1/2*m*(Vel2^2-Vel1^2)*Convert(kg-m^2/s^2, kJ)
DELTAt=W_a/W_dot_a
```

2-35 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,

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
m=1200 [kg]
Vel_b=50[km/h]*Convert(km/h, m/s)
alpha=30 [degrees]
Vel1_c=0 [m/s]
Vel2_c=90[km/h]*Convert(km/h, m/s)
t=12 [s]
"Properties"
g=9.807 [m/s^2]
"Analysis"
"(a)"
W_dot_g_a=0
W_dot_a_a=0
W_dot_total_a=W_dot_a_a+W_dot_g_a
"(b)"
W_dot_a_b=0
W_dot_g_b=m*g*Vel_b*sin(alpha)*Convert(kg-m^2/s^2, kJ)
W_dot_total_b=W_dot_a_b+W_dot_g_b
"(c)"
W_dot_g_c=0
W_a_c=1/2*m*(Vel2_c^2-Vel1_c^2)*Convert(kg-m^2/s^2, kJ)
```

W_dot_a_c=W_a_c/t
W_dot_total_c=W_dot_a_c+W_dot_g_c

2-36 As a spherical ammonia vapor bubble rises in liquid ammonia, its diameter increases. The amount of work produced by this bubble is to be determined.

Assumptions

1. The bubble is treated as a spherical bubble.
2. The surface tension coefficient is taken constant.

Analysis Executing the work integral for a constant surface tension coefficient gives

$$W = \sigma \int_1^2 dA = \sigma(A_2 - A_1) = \sigma 4\pi(r_2^2 - r_1^2)$$
$$= 4\pi(0.02 \text{ N/m})\left[(0.015 \text{ m})^2 - (0.005 \text{ m})^2\right]$$
$$= 5.03\times 10^{-5} \text{ N}\cdot\text{m}$$
$$= (5.03\times 10^{-5} \text{ N}\cdot\text{m})\left(\frac{1 \text{ kJ}}{1000 \text{ N}\cdot\text{m}}\right)$$
$$= \mathbf{5.03\times 10^{-8} \text{ kJ}}$$

EES (Engineering Equation Solver) SOLUTION

```
"Given"
D1=0.01 [m]
D2=0.03 [m]
sigma=0.02 [N-m]
"Analysis"
r1=D1/2
r2=D2/2
W=sigma*4*pi*(r2^2-r1^2)*(1 [kJ])/(1000 [N-m])
```


2-37 The work required to stretch a steel rod in a specified 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

$$V_0 = \frac{\pi D^2}{4}L = \frac{\pi(0.005 \text{ m})^2}{4}(10 \text{ m}) = 1.963\times 10^{-4} \text{ m}^3$$

The work required to stretch the rod 3 cm is

$$W = \frac{V_0 E}{2}(e_2^2 - e_1^2)$$
$$= \frac{(1.963\times 10^{-4} \text{ m}^3)(21\times 10^4 \text{ kN/m}^2)}{2}\left[\left(\frac{0.03 \text{ m}}{10 \text{ m}}\right)^2 - 0^2\right]$$
$$= 1.855\times 10^{-4} \text{ kN}\cdot\text{m} = 1.855\times 10^{-4} \text{ kJ} = \mathbf{0.1855 \text{ J}}$$

EES (Engineering Equation Solver) SOLUTION

```
"Given"
D=0.005 [m]
```

```
L=10 [m]
dL=0.03 [m]
E=21E4 [kN/m^2]
"Analysis"
V=pi*D^2/4*L
epsilon_1=0
epsilon_2=dL/L
W=(V*E)/2*(epsilon_2^2-epsilon_1^2)
```

The First Law of Thermodynamics

2-38C Energy can be transferred to or from a control volume as heat, various forms of work, and by mass transport.

2-39C No. This is the case for adiabatic systems only.

2-40C Warmer. Because energy is added to the room air in the form of electrical work.

2-41 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

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

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

$$30 \text{ kJ} + 0.5 \text{ kJ} - 5 \text{ kJ} = U_2 - 12.5 \text{ kJ}$$

$$U_2 = \mathbf{38.0\ kJ}$$

Therefore, the final internal energy of the system is 38.0 kJ.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
Q_in=30 [kJ]
Q_out=5 [kJ]
W_pw_in=500 [N-m]*Convert(N-m, kJ)
E_1=12.5 [kJ]
"Analysis"
E_2-E_1=Q_in+W_pw_in-Q_out
```

2-42 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

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
Vel_1=0 [m/s]
Vel_2=30 [m/s]
"Analysis"
DELTAke=(Vel_2^2-Vel_1^2)/2*Convert(m^2/s^2, kJ/kg)
```

2-43 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.

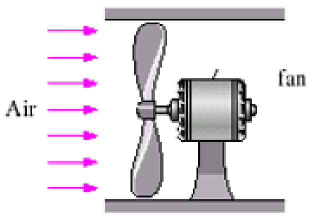
Assumptions The fan operates steadily.

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

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

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

$$\dot W_{\text{sh, in}} = \dot m_{\text{air}}\,\mathrm{ke}_{\text{out}} = \dot m_{\text{air}} \frac{V_{\text{out}}^2}{2}$$



where

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

Substituting, the minimum power input required is determined to be

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

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
V=8 [m/s]
V_dot=9 [m^3/s]
rho=1.18 [kg/m^3]
"Analysis"
m_dot=rho*V_dot
W_dot=m_dot*V^2/2
```

2-44E 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

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

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

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

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

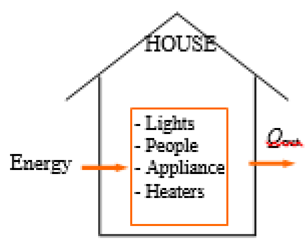
Therefore, the energy content of the system increases by 52 Btu during this process.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
Q_in=65 [Btu]
Q_out=8 [Btu]
W_b_out=5 [Btu]
"Analysis"
Q_in-Q_out-W_b_out=DELTAU
```


2-45E 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

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

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

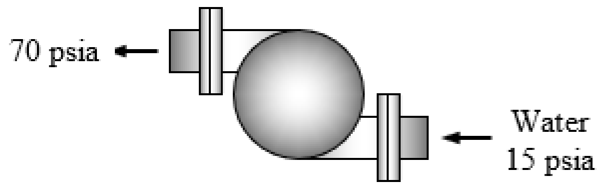
$$\dot{E}_{heater} = 60{,}000 - 6000 = 54{,}000 \text{ Btu/h}\left(\frac{1 \text{ kW}}{3412 \text{ Btu/h}}\right) = \mathbf{15.8\ kW}$$

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
E_dot_out=60000 [Btu/h]
E_dot_gen=6000 [Btu/h]
"Analysis"
E_dot_heater=(E_dot_out-E_dot_gen)*Convert(Btu/h, kW)
```

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



Analysis The power input is determined from

$$\dot{W} = \dot{V}(P_2 - P_1)$$

$$= (0.8\ \text{ft}^3/\text{s})(70 - 15)\text{psia}\left(\frac{1\ \text{Btu}}{5.404\ \text{psia}\cdot\text{ft}^3}\right)\left(\frac{1\ \text{hp}}{0.7068\ \text{Btu/s}}\right)$$

$$= \mathbf{11.5\ hp}$$

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

EES (Engineering Equation Solver) SOLUTION


```
"Given"
P_1=15 [psia]
P_2=70 [psia]
V_dot=0.8 [ft^3/s]
"Analysis"
W_dot=V_dot*(P_2-P_1)*Convert(psia-ft^3, Btu)*Convert(Btu/s, hp)
```

2-47 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

$$\text{Energy Savings} = (\text{Number of lamps})(\text{Lamp wattage})(\text{Reduction of annual operating hours})$$

$$= (24\ \text{lamps})(60\ \text{W/lamp})(3285\ \text{hours/year})$$

$$= \mathbf{4730\ kWh/year}$$

$$\text{Cost Savings} = (\text{Energy Savings})(\text{Unit cost of energy})$$

$$= (4730\ \text{kWh/year})(\$0.11/\text{kWh})$$

$$= \$\mathbf{520/year}$$

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

$$\text{Simple payback period} = \frac{\text{Implementation cost}}{\text{Annual cost savings}} = \frac{\$72}{\$520\,/\,\text{year}} = \mathbf{0.138\ year}\ \ (1.66\ \text{months})$$

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
N_lamp=6*4
E_dot_lamp=60 [W]
CurrentHours=12*365 "[h/year]"
NewHours=3*365 "[h/year]"
Cost_electricity=0.11 [$/kWh]
MaterialCost=32 [$]
LaborCost=40 [$]
"Analysis"
EnergySavings=N_lamp*E_dot_lamp*(CurrentHours-NewHours)*Convert(W, kW)
CostSavings=EnergySavings*Cost_electricity
ImplementationCost=MaterialCost+LaborCost
PaybackPeriod=ImplementationCost/CostSavings
```


2-48 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

$$\text{Unoccupied hours} = (4\ \text{hours / day})(240\ \text{days / year}) = 960\ \text{h / yr}$$

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

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

$$\text{Cost savings} = (\text{Energy savings})(\text{Unit cost of energy}) = (506{,}880\ \text{kWh/yr})(\$0.11/\text{kWh}) = \mathbf{\$55{,}757\ /\ yr}$$

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
N_classroom=200
N_office=400
N_tube_c=12 "tubes/classroom"
N_tube_o=6 "tubes/office"
E_dot_tube=110 [W]
Days=240 [1/year]
Hours=4 [h]
Cost_electricity=0.11 [$/kWh]
"Analysis"
E_dot_classrooms=N_classroom*N_tube_c*E_dot_tube*Convert(W, kW)
E_dot_offices=N_office*N_tube_o*E_dot_tube*Convert(W, kW)
```

```
E_dot_total=E_dot_classrooms+E_dot_offices
UnoccupiedHours=Hours*Days
EnergySavings=E_dot_total*UnoccupiedHours
CostSavings=EnergySavings*Cost_electricity
```

2-49 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.

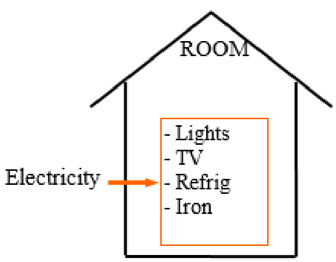
2. All the appliances are kept on.

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

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

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

$$\dot{E}_{\text{in}} = \dot{E}_{\text{lights}} + \dot{E}_{\text{TV}} + \dot{E}_{\text{refrig}} + \dot{E}_{\text{iron}}$$
$$= 40 + 110 + 300 + 1200 \text{ W}$$
$$= 1650 \text{ W}$$



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

$$dE_{\text{room}} / dt = \dot{E}_{\text{in}} = \mathbf{1650\ W}$$

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
T_i=20 [C]
E_dot_lights=40 [W]
E_dot_TV=110 [W]
E_dot_ref=300 [W]
E_dot_iron=1200 [W]
"Analysis"
E_dot_total=E_dot_lights+E_dot_TV+E_dot_ref+E_dot_iron
```

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

$$\text{Mass} = (50\text{ persons})(75\,\text{kg}/\text{person}) = 3750\,\text{kg}$$

The vertical component of escalator velocity is

$$V_{\text{vert}} = V\sin 45° = (0.6\text{ m/s})\sin 45°$$

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

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

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

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

$$\dot{W}_{\text{in}} = mgV_{\text{vert}} = (3750\text{ kg})(9.81\text{ m/s}^2)(0.6\text{ m/s})\sin 45°\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 12.5\text{ kJ/s} = \mathbf{15.6\ kW}$$

When the escalator velocity is doubled to $V = 1.2\,\text{m/s}$, the power needed to drive the escalator becomes

$$\dot{W}_{\text{in}} = mgV_{\text{vert}} = (3750\text{ kg})(9.81\text{ m/s}^2)(1.2\text{ m/s})\sin 45°\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 25.0\text{ kJ/s} = \mathbf{31.2\ kW}$$

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
N_people=50
m_person=75 [kg]
V=0.6 [m/s] "or 1.2 m/s"
theta=45 [degrees]
"Analysis"
m_people=N_people*m_person
V_vert=V*sin(theta)
W_dot_in=m_people*g*V_vert
g=9.81 [m/s^2]
```

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

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

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

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

$$\dot{W}_{in} = m\frac{V_2^2 - V_1^2}{2\Delta t} = (2100 \text{ kg})\frac{(110/3.6 \text{ m/s})^2 - (70/3.6 \text{ m/s})^2}{2(5 \text{ s})}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) = 117 \text{ kJ/s} = \mathbf{117 \text{ kW}}$$

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

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

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
m=2100 [kg]
V_1=70 [km/h]*Convert(km/h, m/s)
V_2=110 [km/h]*Convert(km/h, m/s)
time=5 [s]
"Analysis"
W_dot_in=m*(V_2^2-V_1^2)/(2*time)*Convert(m^2/s^2, kJ/kg)
```


2-52E 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

$$\text{Fuel Savings} = \text{Annual Fuel Consumption}_{\text{High}} - \text{Annual Fuel Consumption}_{\text{Low}}$$

$$= 428.6 \text{ gal/year} - 405.4 \text{ gal/year} = 23.2 \text{ gal/year}$$

$$\text{Cost savings} = (\text{Fuel savings})(\text{Unit cost of fuel}) = (23.2 \text{ gal/year})(\$3.5/\text{gal}) = \mathbf{\$81.1/\text{year}}$$

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
MPG_1=35 [mpg]
MPG_2=37 [mpg]
Miles=15000 [miles]
UnitCost=3.5 [$/gal]
"Analysis"
```

```
AFC_high=Miles/MPG_1
AFC_low=Miles/MPG_2
FuelSavings=AFC_high-AFC_low
CostSavings=FuelSavings*UnitCost
```

Energy Conversion Efficiencies

2-53C *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.

2-54C 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.

2-55C The turbine efficiency, generator efficiency, and *combined turbine-generator efficiency* are defined as follows:

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

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

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

2-56C 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.

2-57 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 electric heater is rated at 2.4 kW. Therefore, the rate of energy consumption by the electric heater is

$$\dot{Q}_{\text{input, electric}} = \mathbf{2.4\ kW}$$

The efficiency of the electric heater is given to be 73 percent. Therefore, a burner that consumes 2.4-kW of electrical energy will supply

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

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

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

since $1\text{kW} = 3412\text{Btu/h}$. Therefore, a gas burner should have a rating of at least $15,700\text{ Btu/h}$ 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

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

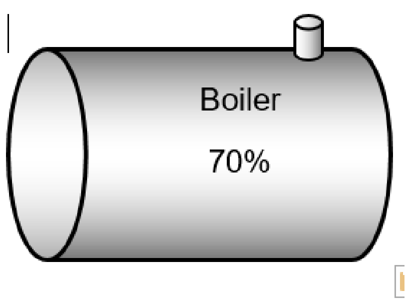
EES (Engineering Equation Solver) SOLUTION

```
"Given"
E_dot=2.4 [kW]
UnitCost_electricity=0.10 [$/kWh]
UnitCost_gas=1.20 [$/therm]
eta_electricity=0.73
eta_gas=0.38
"Analysis"
Q_dot_utilized_electricity=E_dot*eta_electricity
Cost_electricity=UnitCost_electricity/eta_electricity
Q_dot_input_gas=Q_dot_utilized_electricity/eta_gas
Cost_gas=UnitCost_gas/eta_gas*Convert(kWh, therm)
```

2-58E 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 $\dot{Q}_{\text{in, current}} = 5.5 \times 10^6$ Btu/h.

Then the rate of useful heat output of the boiler becomes

$$\dot{Q}_{\text{out}} = (\dot{Q}_{\text{in}} \eta_{\text{furnace}})_{\text{current}} = (5.5 \times 10^6 \text{ Btu/h})(0.7) = 3.85 \times 10^6 \text{ Btu/h}$$

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

$$\dot{Q}_{\text{in, new}} = \dot{Q}_{\text{out}} / \eta_{\text{furnace, new}} = (3.85 \times 10^6 \text{ Btu/h})/0.8 = 4.81 \times 10^6 \text{ Btu/h}$$

$$\dot{Q}_{\text{in, saved}} = \dot{Q}_{\text{in, current}} - \dot{Q}_{\text{in, new}} = 5.5\times 10^6 - 4.81\times 10^6 = 0.69\times 10^6 \text{ Btu/h}$$

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

$$\text{Energy Savings} = \dot{Q}_{\text{in saved}}\text{(Operation hours)}$$
$$= (0.69\times10^6 \text{ Btu/h})(4200 \text{ h/ year}) = \mathbf{2.89\times10^9 \text{ Btu/yr}}$$

$$\text{Cost Savings} = \text{(Energy Savings)(Unit cost of energy)}$$
$$= (2.89\times10^9 \text{ Btu/yr})(\$13/10^6 \text{ Btu}) = \$\mathbf{37,500}\text{/ year}$$

Discussion Notice that tuning up the boiler will save $37,500 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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
Q_dot_in_current=5.5E6 [Btu/h]
eta_furnace_current=0.7
eta_furnace_new=0.8
Hours=4200 [h/year]
UnitCost=13E-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
```


2-59E Problem 2-58E 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 $12 to $14 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 $12, $13, and $14 per million Btu.

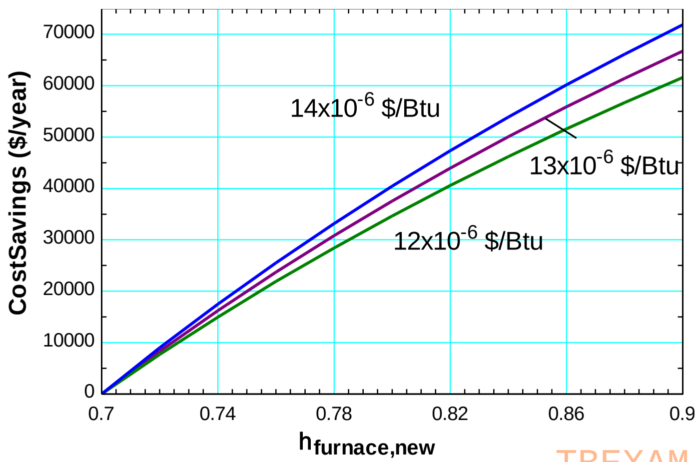
Analysis The problem is solved using EES, and the solution is given below.

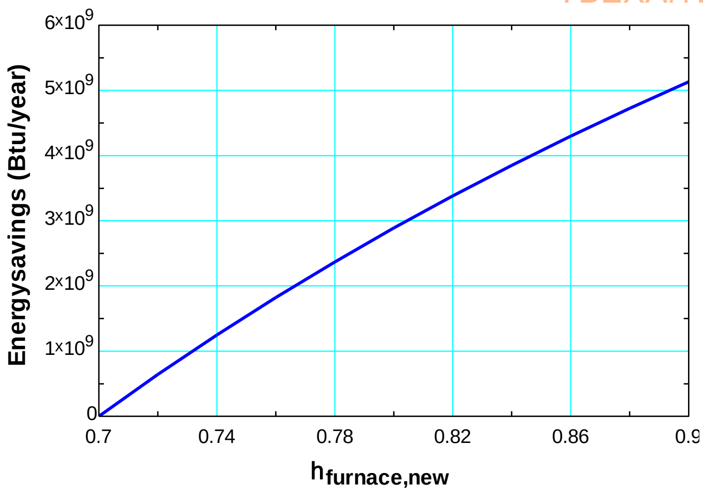
```
"Given"
Q_dot_in_current=5.5E6 [Btu/h]
eta_furnace_current=0.7
eta_furnace_new=0.8
Hours=4200 [h/year]
UnitCost=13E-6 [$/Btu]
"Analysis"
Q_dot_out=Q_dot_in_current*eta_furnace_current
Q_dot_in_new=Q_dot_out/eta_furnace_new
Q_dot_in_saved=Q_dot_in_current-Q_dot_in_new
Energysavings=Q_dot_in_saved*Hours
CostSavings=EnergySavings*UnitCost
```

$\eta_{furnace,new}$	EnergySavings [Btu/year]	CostSavings [$/year]

0.7	0.00E+00	0
0.72	6.42E+08	8342
0.74	1.25E+09	16232
0.76	1.82E+09	23708
0.78	2.37E+09	30800
0.8	2.89E+09	37538
0.82	3.38E+09	43946
0.84	3.85E+09	50050
0.86	4.30E+09	55870
0.88	4.73E+09	61425
0.9	5.13E+09	66733

Table values are for UnitCost=13E-5 [$/Btu]





2-60 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.

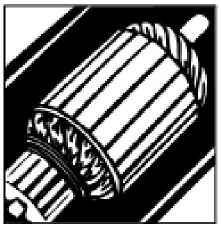
Assumptions

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

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,

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

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



Then the reduction in heat generation becomes

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
W_dot_shaft=75 [hp]
eta_motor_standard=0.91
eta_motor_efficient=0.954
"Analysis"
W_dot_in_standard=W_dot_shaft/eta_motor_standard*Convert(hp, W)
W_dot_in_efficient=W_dot_shaft/eta_motor_efficient*Convert(hp, W)
Q_dot_reduction=W_dot_in_standard-W_dot_in_efficient
```

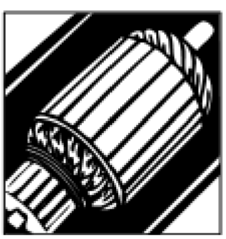

2-61 An electric car is powered by an electric motor mounted in the engine compartment. The rate of heat supply by the motor to the engine compartment at full load conditions is to be determined.

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
W_dot_shaft_out=90 [hp]
eta_motor=0.91
```

```
"Analysis"
W_dot_in_electric=W_dot_shaft_out/eta_motor
Q_dot_generation=(W_dot_in_electric-W_dot_shaft_out)*Convert(hp, W)
```

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 600 W.

Analysis The 6 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 = 745.7 W, the total heat generated by the motors is

$$\dot{Q}_{\text{motors}} = (\text{No. of motors}) \times \dot{W}_{\text{motor}} \times f_{\text{load}} \times f_{\text{usage}} / \eta_{\text{motor}}$$

$$= 7 \times (2.5 \times 746 \text{ W}) \times 0.70 \times 1.0/0.77 = 11{,}870 \text{ W}$$

The heat gain from 14 people is

$$\dot{Q}_{\text{people}} = 14 \times (600 \text{ W}) = 8400 \text{ W}$$

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

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{motors}} + \dot{Q}_{\text{people}} = 11{,}870 + 8400 = \mathbf{20{,}270 \text{ W}}$$

EES (Engineering Equation Solver) SOLUTION

```
"Given"
N_motor=7
W_dot_motor=2.5 [hp]
f_load=0.7
eta_motor=0.77
N_people=14
Q_dot_person=600 [W]
"Analysis"
Q_dot_motors=N_motor*W_dot_motor*f_load/eta_motor*Convert(hp, W)
Q_dot_people=N_people*Q_dot_person
Q_dot_total=Q_dot_motors+Q_dot_people
```

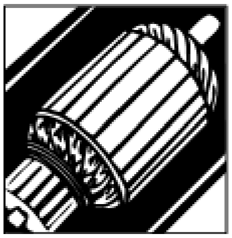

2-63 A room is cooled by circulating chilled water through a heat exchanger, and the air is circulated through the heat exchanger by a fan. The contribution of the fan-motor assembly to the cooling load of the room is to be determined.

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,

$$\dot{Q}_{\text{internal generation}} = \dot{W}_{\text{in, electric}} = \dot{W}_{\text{shaft}} / \eta_{\text{motor}}$$

$$= (0.25 \text{ hp})/0.60 = 0.463 \text{ hp} = \mathbf{311 \text{ W}}$$



since 1 hp = 746 W.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
W_dot_shaft=0.25 [hp]
eta_motor=0.60
"Analysis"
Q_dot_motor=W_dot_shaft/eta_motor*Convert(hp, W)
```

2-64 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.

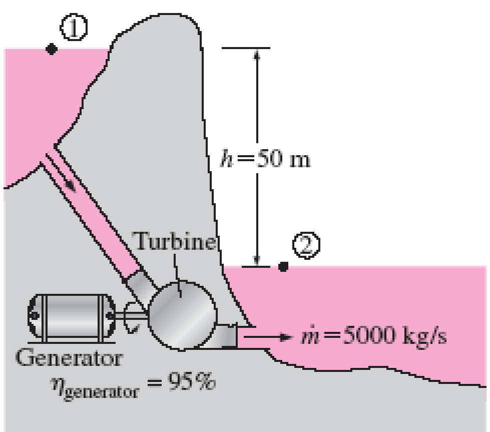
Assumptions

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 $\rho = 1000\ \text{kg/m}^3$. The gravitational acceleration is $g = 9.81\ \text{m/s}^2$

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

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

(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.

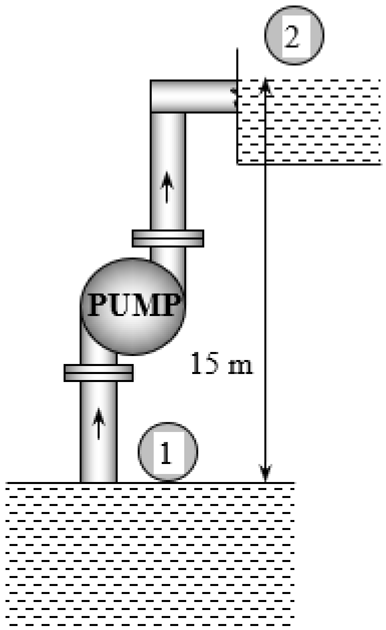
EES (Engineering Equation Solver) SOLUTION

```
"Given"
h=50 [m]
m_dot=5000 [kg/s]
W_dot_elect=1862 [kW]
eta_gen=0.95
"Analysis"
"(a)"
g=9.81 [m/s^2]
DELTAe_mech=g*h*Convert(m^2/s^2, kJ/kg)
DELTAE_dot_mech_fluid=m_dot*DELTAe_mech
eta_turbine_gen=W_dot_elect/DELTAE_dot_mech_fluid
"(b)"
eta_turbine=eta_turbine_gen/eta_gen
"(c)"
W_dot_shaft=eta_turbine*DELTAE_dot_mech_fluid
```


2-65 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 $\rho = 1000\,\text{kg/m}^3$.

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

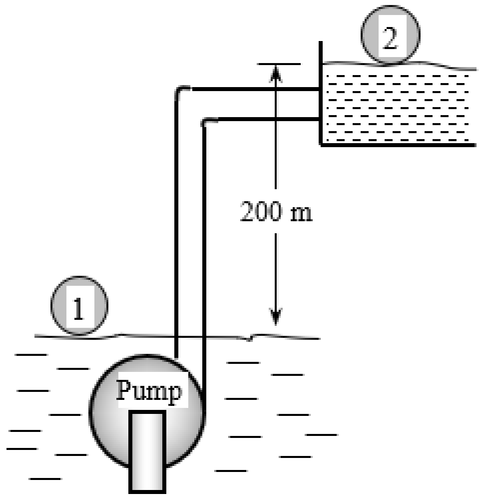
$$\dot{V} = \frac{\dot{W}_{\text{pump,u}}}{\rho g z_2} = \frac{5.74\text{ hp}}{(1000\text{ kg/m}^3)(9.81\text{ m/s}^2)(15\text{ m})}\left(\frac{745.7\text{ W}}{1\text{ hp}}\right)\left(\frac{1\text{ N}\cdot\text{m/s}}{1\text{ W}}\right)\left(\frac{1\text{ kg}\cdot\text{m/s}^2}{1\text{ N}}\right) = \mathbf{0.0291\,m^3/s}$$

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
W_dot_shaft=7 [hp]
z=15 [m]
eta_pump=0.82
"Analysis"
rho=1000 [kg/m^3]
g=9.81 [m/s^2]
W_dot_pump_u=eta_pump*W_dot_shaft*Convert(hp, W)
V_dot=W_dot_pump_u/(rho*g*z)
```

2-66 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 $\rho = 1050\,\text{kg/m}^3$.

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

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

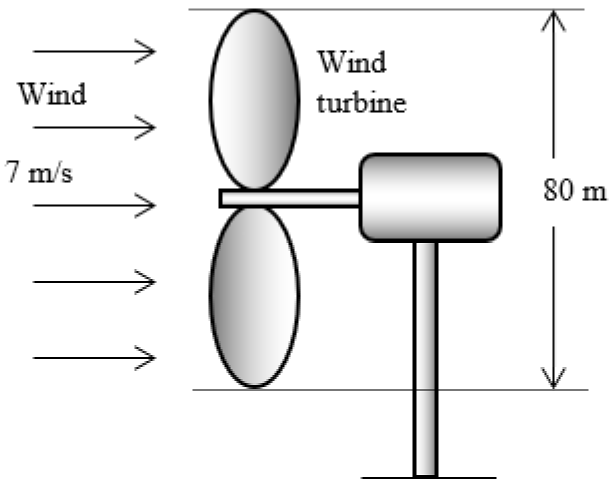
Discussion The frictional losses in piping systems are usually significant, and thus a larger pump will be needed to overcome these frictional losses.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
rho=1050 [kg/m^3]
V_dot=0.3 [m^3/s]
z=200 [m]
eta=0.74
"Analysis"
g=9.81 [m/s^2]
m_dot=rho*V_dot
```

```
DELTAE_dot_mech_fluid=m_dot*g*z*Convert(m^2/s^2, kJ/kg)
W_dot_pump_elect=DELTAE_dot_mech_fluid/eta
```

2-67 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 $\rho = 1.25\ \text{kg/m}^3$.

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:

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

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

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

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

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

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.

EES (Engineering Equation Solver) SOLUTION

```
"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]
```

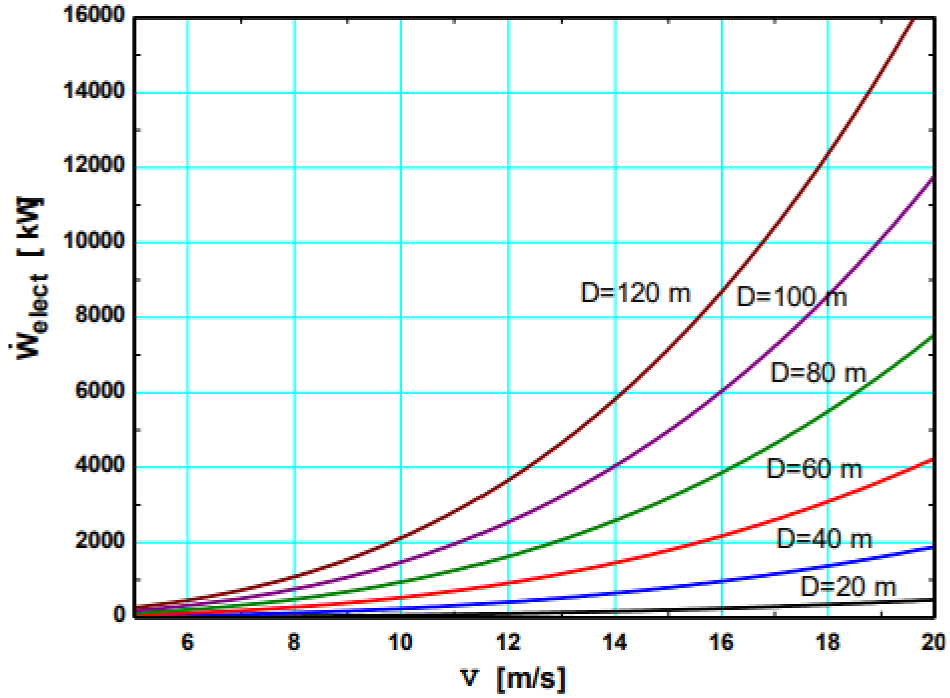
```
A=pi*D^2/4
m_dot=rho*A*V
W_dot_max=m_dot*V^2/2*Convert(m^2/s^2, kJ/kg)
W_dot_elect=eta_overall*W_dot_max
```

2-68 Problem 2-67 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.

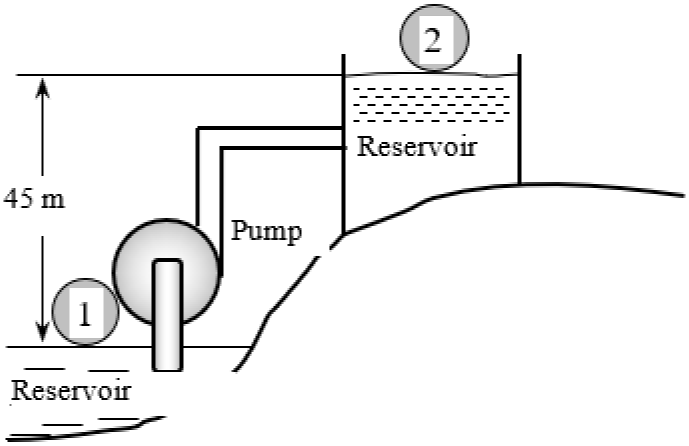
```
"Given"
V=7 [m/s]
D=80 [m]
eta_overall=0.30
rho=1.25 [kg/m^3]
"Analysis"
g=9.81 [m/s^2]
A=pi*D^2/4
m_dot=rho*A*V
W_dot_max=m_dot*V^2/2*Convert(m^2/s^2, kJ/kg)
W_dot_elect=eta_overall*W_dot_max
```

D (m)	V (m/s)	m (kg/s)	W_{elect} (kW)
20	5	1963	7.363
20	10	3927	58.9
20	15	5890	198.8
20	20	7854	471.2
40	5	7854	29.45
40	10	15708	235.6
40	15	23562	795.2
40	20	31416	1885
60	5	17671	66.27
60	10	35343	530.1
60	15	53014	1789
60	20	70686	4241
80	5	31416	117.8
80	10	62832	942.5
80	15	94248	3181
80	20	125664	7540
100	5	49087	184.1
100	10	98175	1473
100	15	147262	4970
100	20	196350	11781
120	5	70686	265.1
120	10	141372	2121
120	15	212058	7157
120	20	282743	16965



16000
14000
12000
10000
8000
6000
4000
2000
0
$\dot{W}_{elect}$ [kW]
6
8
10
12
14
16
18
20
V [m/s]
D=120 m
D=100 m
D=80 m
D=60 m
D=40 m
D=20 m

2-69 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 $\rho = 1000 \text{ kg/m}^3$

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

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

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.

EES (Engineering Equation Solver) SOLUTION

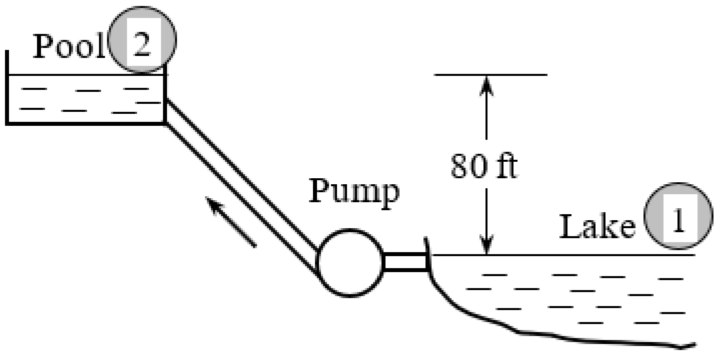
```
"Given"
W_dot_shaft=20 [kW]
z=45 [m]
V_dot=0.03 [m^3/s]
"Analysis"
rho=1000 [kg/m^3]
g=9.81 [m/s^2]
m_dot=rho*V_dot
DELTAE_dot_mech_fluid=m_dot*g*z*Convert(m^2/s^2, kJ/kg)
W_dot_fric=W_dot_shaft-DELTAE_dot_mech_fluid
```

2-70E 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

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

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.

EES (Engineering Equation Solver) SOLUTION

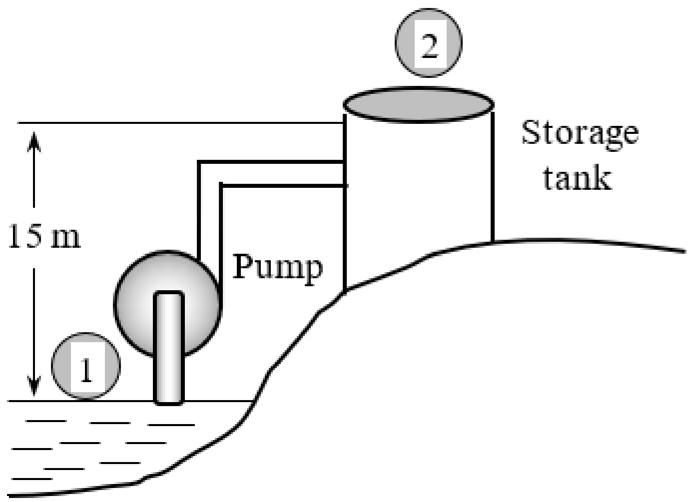
```
"Given"
eta_pump=0.80
W_dot_pump=20 [hp]
V_dot=1.5 [ft^3/s]
z=80 [ft]
"Analysis"
rho=62.4 [lbm/ft^3]
g=32.2 [ft/s^2]
W_dot_pump_u=eta_pump*W_dot_pump
m_dot=rho*V_dot
DELTAE_dot_mech_fluid=m_dot*g*z*Convert(lbm-ft/s^2, lbf)*Convert(lbf-ft/s, hp)
W_dot_fric=W_dot_pump_u-DELTAE_dot_mech_fluid
```

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 $\rho = 1000\,\text{kg/m}^3$.



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 $\text{pe}_1 = 0$ and $\text{pe}_2 = gz_2$. The flow energy at both points is zero since both 1 and 2 are open to the atmosphere $(P_1 = P_2 = P_{\text{atm}})$. Further, the kinetic energy at both points is zero $(\text{ke}_1 = \text{ke}_2 = 0)$ since the water at both locations is essentially stationary. The mass flow rate of water and its potential energy at point 2 are

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

$$pe_2 = gz_2 = (9.81\text{ m/s}^2)(15\text{ m})\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2\text{/s}^2}\right) = 0.1472\text{ kJ/kg}$$

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

$$\Delta\dot{E}_{\text{mech,fluid}} = \dot{m}(e_{\text{mech,out}} - e_{\text{mech,in}}) = \dot{m}(pe_2 - 0) = \dot{m}pe_2 = (70\text{ kg/s})(0.1472\text{ kJ/kg}) = 10.3\text{ kW}$$

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

$$\eta_{\text{pump-motor}} = \frac{\Delta\dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{elect,in}}} = \frac{10.3\text{ kW}}{15.4\text{ kW}} = 0.669 \quad \text{or} \quad \mathbf{66.9\%}$$

(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 10.3 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,

$$\Delta P = \frac{\Delta\dot{E}_{\text{mech,fluid}}}{\dot{V}} = \frac{10.3\text{ kJ/s}}{0.070\text{ m}^3\text{/s}}\left(\frac{1\text{ kPa}\cdot\text{m}^3}{1\text{ kJ}}\right) = \mathbf{147\text{ kPa}}$$

Therefore, the pump must boost the pressure of water by 147 kPa in order to raise its elevation by 15 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.

EES (Engineering Equation Solver) SOLUTION

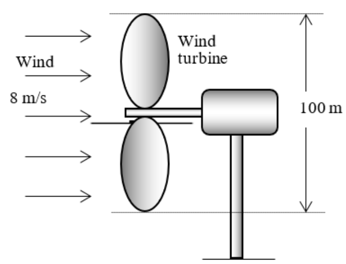
```
"Given"
z=15 [m]
V_dot=0.070 [m^3/s]
W_dot_elect_in=15.4 [kW]
"Analysis"
rho=1000 [kg/m^3]
g=9.81 [m/s^2]
m_dot=rho*V_dot
DELTAE_dot_mech_fluid=m_dot*g*z*Convert(m^2/s^2, kJ/kg)
eta_pump_motor=DELTAE_dot_mech_fluid/W_dot_elect_in
DELTAP=DELTAE_dot_mech_fluid/V_dot
```

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

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

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) = (19,300kWh)($0.09 / kWh) = $**1737** (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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
D=100 [m]
V=8 [m/s]
eta=0.32
rho=1.25 [kg/m^3]
UnitPrice=0.09 [$/kWh]
time=24 [h]
"Analysis"
A=pi*D^2/4
m_dot=rho*A*V
W_dot_max=1/2*m_dot*V^2*Convert(m^2/s^2, kJ/kg)
W_dot_elect=eta*W_dot_max
Amount_Electricity=W_dot_elect*time
Revenues=Amount_Electricity*UnitPrice
```

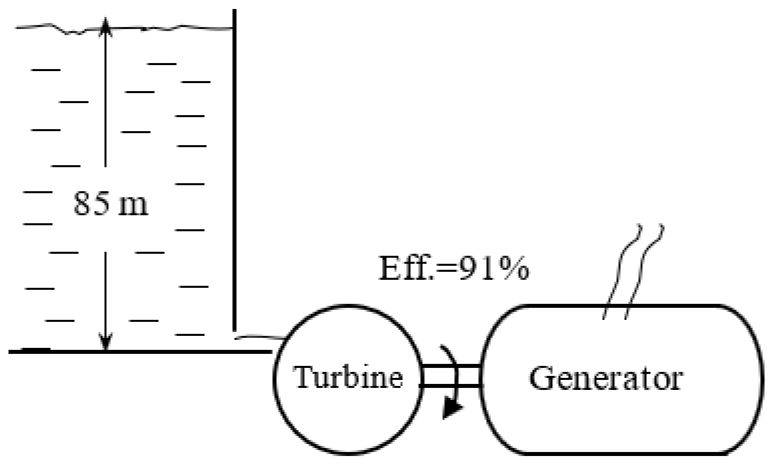

2-73 The available head of a hydraulic turbine and its overall efficiency are given. The electric power output of this turbine is to be determined.

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



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,

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

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
z=85 [m]
V_dot=0.25 [m^3/s]
eta_turb=0.91
"Analysis"
rho=1000 [kg/m^3]
g=9.81 [m/s^2]
m_dot=rho*V_dot
W_dot_turb=eta_turb*m_dot*g*z*Convert(m^2/s^2, kJ/kg)
```

2-74 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

$$\dot{W} = \dot{m}g(z_2 - z_1) \longrightarrow \dot{m} = \frac{\dot{W}}{g(z_2 - z_1)} = \frac{50{,}000 \text{ kJ/s}}{(9.8 \text{ m/s}^2)(206 - 0) \text{ m}\left(\dfrac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)} = \mathbf{24{,}700 \text{ kg/s}}$$

EES (Engineering Equation Solver) SOLUTION

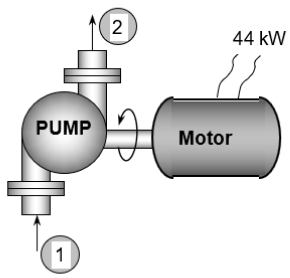
```
"Given"
"Analysis"
z_1=0 [m]
z_2=206 [m]
W_dot=50000 [kW]
eta_turbine=1
g=9.81 [m/s^2]
W_dot=eta_turbine*m_dot*g*(z_2-z_1)*Convert(m^2/s^2, kJ/kg)
```


2-75 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 $e_{mech} = gh + Pv + V^2/2$. 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

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

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

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

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

Substituting, the useful pumping power is determined to be

$$\dot{W}_{\text{pump,u}} = \Delta\dot{E}_{\text{mech,fluid}}$$

$$= (0.1\ \text{m}^3/\text{s})\left(500\ \text{kN/m}^2 + (860\ \text{kg/m}^3)\frac{(8.84\ \text{m/s})^2 - (19.9\ \text{m/s})^2}{2}\left(\frac{1\ \text{kN}}{1000\ \text{kg}\cdot\text{m/s}^2}\right)\right)\left(\frac{1\ \text{kW}}{1\ \text{kN}\cdot\text{m/s}}\right)$$

$$= 36.3\ \text{kW}$$

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

$$\dot{W}_{\text{pump,shaft}} = \eta_{\text{motor}}\dot{W}_{\text{electric}} = (0.90)(44\ \text{kW}) = 39.6\ \text{kW}$$

$$\eta_{\text{pump}} = \frac{\dot{W}_{\text{pump, u}}}{\dot{W}_{\text{pump, shaft}}} = \frac{36.3\ \text{kW}}{39.6\ \text{kW}} = 0.918 = \mathbf{91.8\%}$$

Discussion The overall efficiency of this pump/motor unit is the product of the mechanical and motor efficiencies, which is 0.9 × 0.918 = 0.826.

EES (Engineering Equation Solver) SOLUTION


```
"Given"
W_dot_elect=44 [kW]
rho=860 [kg/m^3]
V_dot=0.1 [m^3/s]
D1=0.08 [m]
D2=0.12 [m]
DELTAP=500 [kPa]
eta_motor=0.90
"Analysis"
A_1=pi*D1^2/4
V_1=V_dot/A_1
A_2=pi*D2^2/4
V_2=V_dot/A_2
W_dot_pump_u=V_dot*(DELTAP+rho*1/2*(V_2^2-V_1^2)*Convert(kg-m/s^2, kN))
W_dot_pump_shaft=eta_motor*W_dot_elect
eta_pump=W_dot_pump_u/W_dot_pump_shaft
```

2-76 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 $1.31\ \text{kg/m}^3$.

Analysis

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

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

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

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

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

Then the conversion efficiency of the turbine becomes

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

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
n_dot=15 [1/min]*Convert(1/min, 1/s)
m_dot=42000 [kg/s]
V_tip=250 [km/h]*Convert(km/h, m/s)
W_dot=180 [kW]
rho=1.31 [kg/m^3]
"Analysis"
D=V_tip/(pi*n_dot)
A=pi*D^2/4
V=m_dot/(rho*A)
KE_dot=1/2*m_dot*V^2*Convert(m^2/s^2, kJ/kg)
eta=W_dot/KE_dot
```


2-77 Liquefied natural gas (LNG) enters a cryogenic turbine at 5000 kPa and –160°C at a rate of 27 kg/s and leaves at 600 kPa. The actual power produced by the turbine is measured to be 240 kW. If the density of LNG is 423.8 kg/m^3, determine the efficiency of the cryogenic turbine.

2-77 Liquefied natural gas (LNG) is expanded in a cryogenic turbine to produce power. The efficiency of the turbine is to be determined.

Assumptions

1. Steady operating conditions exist.

2. Kinetic and potential energy changes are negligible.

Analysis Noting that LNG remains as liquid across the turbine, the ideal or maximum power produced by this cryogenic or hydraulic turbine can be determined from

$$\dot{W}_{max} = \dot{m}\frac{P_1 - P_2}{\rho} = (27 \text{ kg/s})\frac{(5000-600)\text{kPa}}{423.8 \text{ kg/m}^3} = 279.7 \text{ kW}$$

The efficiency of the turbine is defined as the actual power produced divided by the ideal power produced:

$$\eta_{turb} = \frac{\dot{W}_{act}}{\dot{W}_{max}} = \frac{240 \text{ kW}}{279.1 \text{ kW}} = 0.858 = \mathbf{85.8\%}$$

EES (Engineering Equation Solver) SOLUTION

```
T_1=-160 [C]
P_1=4000 [kPa]
P_2=400 [kPa]
m_dot=28 [kg/s]
W_dot_act=185 [kW]
rho_1=density(Methane,T=T_1,P=P_1)
W_dot_rev=m_dot*(P_1-P_2)/rho_1
eta_turbine=W_dot_act/W_dot_rev
```

2-78 A well-established electrical energy storage technology is pumped hydroelectric storage (PHS). The electricity generated from a renewable energy system such as solar panels or wind turbines is used to pump water from a lower reservoir to a higher reservoir during off-peak hours. During peak hours, the water in the higher reservoir is used to drive a water turbine to generate electricity. Consider a PHS system in which $25{,}000 \text{ m}^3$ of water is pumped to an average height of 38 m. Determine the amounts of electricity consumed by the pump and produced by the turbine if the overall efficiency of the pump-motor unit and that of the turbine-generator unit are 75 percent. What is the overall efficiency of this PHS system?

2-78 A pumped hydroelectric storage (PHS) system is considered. The amounts of electricity consumed by the pump and produced by the turbine are to be determined.

Assumptions

1. Frictional losses in piping are negligible.

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

Analysis The total mass of water that is pumped is

$$m = \rho V = (1000 \text{ kg/m}^3)(25{,}000 \text{ m}^3) = 2.50 \times 10^7 \text{ kg}$$

The electricity consumed by the pump is

$$W_{pump,in} = \frac{mgz}{\eta_{pump\text{-}motor}}$$

$$= \frac{(2.50\times10^7 \text{ kg})(9.81 \text{ m/s}^2)(38 \text{ m})}{0.75}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\left(\frac{1 \text{ kWh}}{3600 \text{ kJ}}\right)$$

$$= \mathbf{3452 \text{ kWh}}$$

The electricity produced by the turbine is

$$W_{turb,out} = \eta_{turbine\text{-}gen} mgz$$

$$= (0.75)(2.50\times10^7 \text{ kg})(9.81 \text{ m/s}^2)(38 \text{ m})\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\left(\frac{1 \text{ kWh}}{3600 \text{ kJ}}\right)$$

$$= \mathbf{1942 \text{ kWh}}$$

The overall efficiency of this PHS system is determined from

$$\eta_{overall} = \frac{W_{turb,out}}{W_{pump,in}} = \frac{1942 \text{ kWh}}{3452 \text{ kWh}} = 0.5625 \cong \mathbf{56.3\%}$$

The same result could be obtained by the product of the efficiencies of the pump-motor unit and the turbine-generator unit: 0.75 x 0.75 = 0.5625.

EES (Engineering Equation Solver) SOLUTION

```
V=25000 [m^3]
h=38 [m]
eta_pm=0.75
eta_tg=0.75
rho=1000 [kg/m^3]
g=9.81 [m/s^2]
m=rho*V
W_in=(m*g*h)/eta_pm*convert (J, kWh)
W_out=eta_tg*(m*g*h)*convert (J, kWh)
Eta_overall=W_out/W_in
```

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 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.

2-81C 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.

2-82C 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.

2-83C 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.

2-84E A household uses fuel oil for heating, and electricity for other energy needs. Now the household reduces its energy use by 15%. 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 14,000 kWh of electricity and 900 gallons of fuel oil per year, the amount of CO_2 production this household is responsible for is

$$\begin{aligned}\text{Amount of } CO_2 \text{ produced} &= (\text{Amount of electricity consumed})(\text{Amount of } CO_2 \text{ per kWh}) \\ &\quad + (\text{Amount of fuel oil consumed})(\text{Amount of } CO_2 \text{ per gallon}) \\ &= (14{,}000 \text{ kWh/yr})(1.54 \text{ lbm/kWh}) + (900 \text{ gal/yr})(26.4 \text{ lbm/gal}) \\ &= 45{,}320 \; CO_2 \text{ lbm/year}\end{aligned}$$

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

$$\begin{aligned}\text{Reduction in } CO_2 \text{ produced} &= (0.15)(\text{Current amount of } CO_2 \text{ production}) \\ &= (0.15)(45{,}320 \; CO_2 \text{ kg/year}) \\ &= \mathbf{6798 \; CO_2 \; lbm/year}\end{aligned}$$

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

EES (Engineering Equation Solver) SOLUTION


```
"Given"
E=14000 [kWh/year]
V=900 [gal/year]
m_CO2_fueloil=26.4 [lbm/gal]
m_CO2_electricity=1.54 [lbm/kWh]
f_reduction=0.15
"Analysis"
CO2_produced=E*m_CO2_electricity+V*m_CO2_fueloil
CO2_reduced=f_reduction*CO2_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

$$\begin{aligned}\text{Amount of } CO_2 \text{ produced} &= (\text{Amount of electricity consumed})(\text{Amount of } CO_2 \text{ per kWh}) \\ &= (300{,}000 \text{ household})(700 \text{ kWh/year household})(0.59 \text{ kg/kWh}) \\ &= 1.23 \times 10^8 \; CO_2 \text{ kg/year} \\ &= \mathbf{123{,}000 \; CO_2 \; ton/year}\end{aligned}$$

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

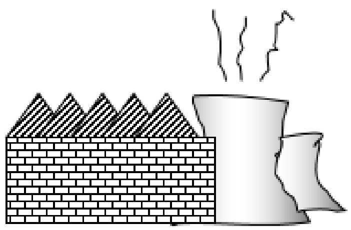
EES (Engineering Equation Solver) SOLUTION

```
"Given"
m_CO2=0.59 [kg/kWh]
E=700 [kWh/year]
N_household=300000
"Analysis"
CO2=N_household*E*m_CO2
```

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

$$\begin{aligned}\text{Amount of } CO_2 \text{ produced} &= (\text{Amount of electricity consumed})(\text{Amount of } CO_2 \text{ per kWh})\\ &= (300{,}000 \text{ household})(700 \text{ kWh/household})(1.1 \text{ kg/kWh})\\ &= 2.31\times 10^8 \; CO_2 \text{ kg/year}\\ &= \mathbf{231{,}000 \; CO_2 \; ton/year}\end{aligned}$$

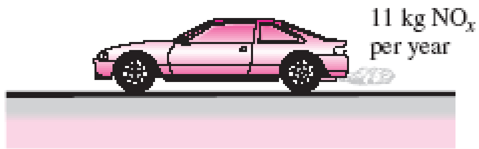
Therefore, the refrigerators in this city are responsible for the production of 231,000 tons of CO_2.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
m_CO2=1.1 [kg/kWh]
E=700 [kWh/year]
N_household=300000
"Analysis"
CO2=N_household*E*m_CO2
```

2-87 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

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

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
mileage=20000 [km/year]
m_NOx_car=11 [kg/year]
m_NOx_naturalgas=0.0043 [kg/therm]
m_NOx_powerplant=0.0071 [kg/kWh]
N_car=2
E=9000 [kWh/year]
Gas=1200 [therm/year]
"Analysis"
NOx=N_car*m_NOx_car+E*m_NOx_powerplant+Gas*m_NOx_naturalgas
```


2-88E 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 850 gallons of gasoline a year compared to 650 gallons for Taurus.

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

$$\begin{aligned}\text{Extra Gasoline} &= (\text{Extra per year})(\text{No. of years})\\ &= (850-650\text{gal/yr})(5\text{yr})\\ &= 1000\text{gal}\end{aligned}$$

$$\begin{aligned}\text{Extra CO}_2\text{ produced} &= (\text{Extra gallons of gasoline used})(\text{CO}_2\text{emission per gallon})\\ &= (1000\text{gal})(19.7\text{lbm/gal})\\ &= \mathbf{19{,}700lbm\ CO_2}\end{aligned}$$

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
V_Taurus=650 [gal/year]
V_Explorer=850 [gal/year]
m_CO2=19.7 [lbm/gal]
DELTAt=5 [year]
```

"Analysis"
ExtraGasoline=(V_Explorer-V_Taurus)*DELTAt
ExtraCO2=ExtraGasoline*m_CO2

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 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.

2-92C 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.

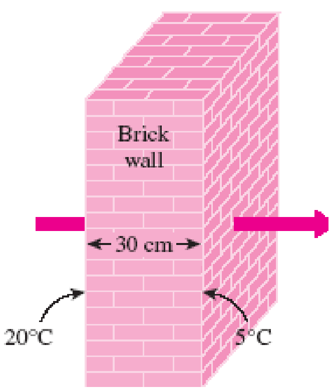
2-93C Emissivity is the ratio of the radiation emitted by a surface to the radiation emitted by a blackbody at the same temperature. Absorptivity is the fraction of radiation incident on a surface that is absorbed by the surface. The Kirchhoff's law of radiation states that the emissivity and the absorptivity of a surface are equal at the same temperature and wavelength.

2-94 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 $k = 0.69\ \text{W/m}\cdot\text{°C}$.

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

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
A=5*6 [m^2]
L=0.30 [m]
k=0.69 [W/m-C]
T1=20 [C]
T2=5 [C]
"Analysis"
Q_dot_cond=k*A*(T1-T2)/L
```

2-95 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

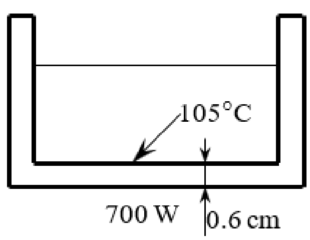
1. Steady operating conditions exist since the surface temperatures of the pan remain constant at the specified values.
2. Thermal properties of the aluminum pan are constant.

Properties The thermal conductivity of the aluminum is given to be $k = 237\ \text{W/m}\cdot\text{°C}$.

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,

$$700\ \text{W} = (237\ \text{W/m}\cdot\text{°C})(0.0314\ \text{m}^2)\frac{T_2 - 105\text{°C}}{0.006\ \text{m}}$$

which gives

$$T_2 = \mathbf{105.6°C}$$

EES SOLUTION

```
"Given"
k=237 [W/m-C]
D=0.20 [m]
L=0.006 [m]
Q_dot_cond=700 [W]
T1=105 [C]
```

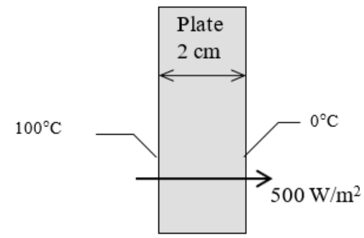
"Analysis"
A=pi*D^2/4
Q_dot_cond=k*A*(T2-T1)/L

2-96 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



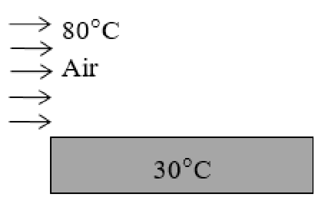
$$\dot{Q} = kA\frac{T_1 - T_2}{L}$$

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

EES (Engineering Equation Solver) SOLUTION

"Given"
L=0.02 [m]
T1=0 [C]
T2=100 [C]
q_cond=500 [W/m^2]
"Analysis"
q_cond=k*(T2-T1)/L

2-97 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

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

EES (Engineering Equation Solver) SOLUTION

"Given"
T_f=80 [C]
A=2[m]*4[m]
T_s=30 [C]
h=55 [W/m^2-C]
"Analysis"
Q_dot_conv=h*A*(T_f-T_s)

2-98 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

$$A = \pi DL = \pi(0.3\text{m})(1.75\text{m}) = 1.649\text{m}^2$$

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

$$\dot{Q}_{\text{conv}} = hA\Delta T = (10\ \text{W/m}^2\cdot{}^\circ\text{C})(1.649\ \text{m}^2)(34-20)^\circ\text{C} = \mathbf{231\,W}$$

EES (Engineering Equation Solver) SOLUTION

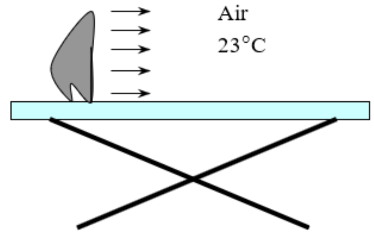
"Given"
D=0.30 [m]
height=1.75 [m]
T_s=34 [C]
h=10 [W/m^2-C]
T_f=20 [C]
"Analysis"
A=pi*D*height
Q_dot_conv=h*A*(T_s-T_f)

2-99 A 1000-W iron is left on the iron board with its base exposed to the air at 23°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 $\varepsilon = 0.4$.



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

$$\dot{Q}_{\text{conv}} = hA\Delta T = (20 \text{ W/m}^2 \cdot \text{K})(0.02 \text{ m}^2)(T_s - 296 \text{ K}) = 0.4(T_s - 296 \text{ K}) \text{ W}$$

and

$$\dot{Q}_{\text{rad}} = \varepsilon\sigma A(T_s^4 - T_o^4) = 0.4(0.02 \text{ m}^2)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)[T_s^4 - (296 \text{ K})^4]$$

$$= 0.04536 \times 10^{-8}[T_s^4 - (296 \text{ K})^4] \text{W}$$

Substituting,

$$1000 \text{ W} = 0.4(T_s - 296 \text{ K}) + 0.04536 \times 10^{-8}[T_s^4 - (296 \text{ K})^4]$$

Solving by trial and error gives

$$T_s = 1106 \text{ K} = \mathbf{833°C}$$

Discussion We note that the iron will dissipate all the energy it receives by convection and radiation when its surface temperature reaches 1106 K.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
E_dot_iron=1000 [W]
T_f=23[C]+273 [K]
h=20 [W/m^2-C]
epsilon=0.4
A=0.02 [m^2]
"Properties"
sigma=5.67E-8 [W/m^2-K^4]
"Analysis"
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
Q_dot_total=E_dot_iron
T_s_C=T_s-273
```

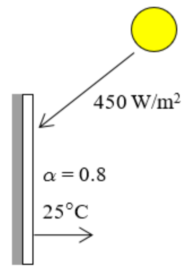
2-100 The backside of the thin metal plate is insulated and the front side is exposed to solar radiation. The surface temperature of the plate is to be determined when it stabilizes.

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

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

EES (Engineering Equation Solver) SOLUTION

```
"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
```

2-101 Prob. 2-100 is reconsidered. Effect of convection heat transfer coefficient on the surface temperature of the plate is to be investigated.

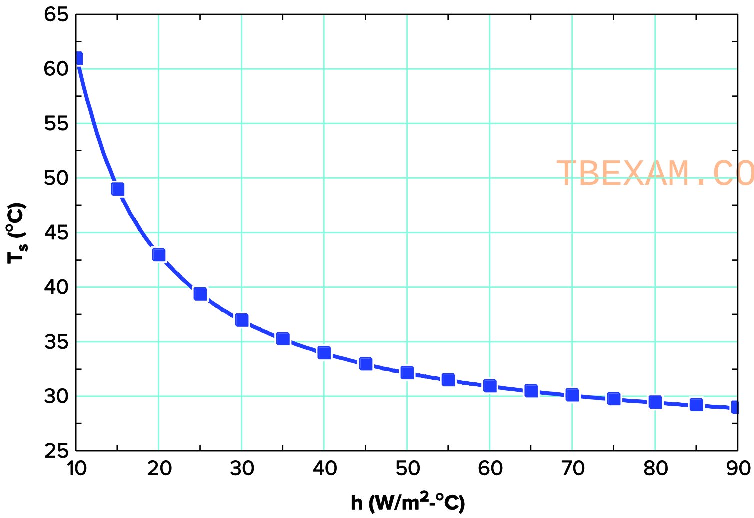
Analysis The problem is solved using EES, and the solution is given below.

```
"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



2-102 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 $k = 80.2\,\text{W/m}\cdot^\circ\text{C}$ (Table 2-3). The heat of fusion of water is at 1 atm is $333.7\,\text{kJ/kg}$.

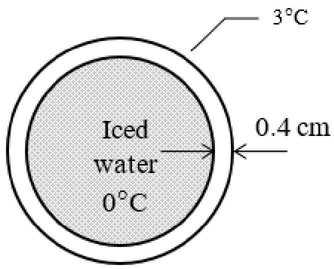
Analysis This spherical shell can be approximated as a plate of thickness 0.4 cm and surface area

$$A = \pi D^2 = \pi(0.4\text{m})^2 = 0.5027\,\text{m}^2$$

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

$$\dot{Q}_{\text{cond}} = kA\frac{\Delta T}{L} = (80.2\text{ W/m}\cdot^\circ\text{C})(0.5027\text{ m}^2)\frac{(3-0)^\circ\text{C}}{0.004\text{ m}} = \mathbf{30,235\text{ W}}$$

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



$$\dot{m}_{\text{ice}} = \frac{\dot{Q}}{h_{if}} = \frac{30.235\text{ kJ/s}}{333.7\text{ kJ/kg}} = \mathbf{0.0906\text{ kg/s}}$$

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* = 39.2 cm) or the mean surface area (*D* = 39.6 cm) in the calculations.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
D=0.40 [m]
L=0.004 [m]
T1=0 [C]
T2=3 [C]
"Properties"
k=80.2 [W/m-K] "from Table A-3"
k_EES=k_('Iron', 2.5) "EES function returns thermal conductivity of iron at 2.5 C"
h_if=333.7 [kJ/kg] "for water from the text"
"Analysis"
A=pi*D^2
Q_dot_cond=k*A*(T2-T1)/L "The curved wall is approximated as a plane wall because of the large diameter to thickness ratio"
m_dot_ice=Q_dot_cond/h_if*Convert(W, kW)
```

Review Problems

2-103 A gravity driven lighting device requires that a sand bag is raised in every 20 minutes. The velocity of the sand bag as it descends and the overall efficiency of the device are to be determined.

Analysis

(a) It takes 20 min for the sand bag to descend from a 2-m height. Then, the velocity is

$$V = \frac{\Delta z}{\Delta t} = \frac{2\text{ m}}{(20\times 60)\text{ s}}\left(\frac{1000\text{ mm}}{1\text{ m}}\right) = \mathbf{1.67\ mm/s}$$

(b) The energy stored in the sand bag at a higher elevation is stored in the form of potential energy, which is equal to energy input to the device. Therefore,

$$E_{\text{in}} = \Delta\text{PE} = mg\Delta z = (10\text{ kg})(9.81\text{ m/s}^2)(2\text{ m})\left(\frac{1\text{ J/kg}}{1\text{ m}^2/\text{s}^2}\right) = 196.2\text{ J}$$

For a time period of 20 min, the input power to the device is

$$\dot{E}_{\text{in}} = \frac{E_{\text{in}}}{\Delta t} = \frac{196.2\text{ J}}{(20\times 60)\text{ s}}\left(\frac{1\text{ W}}{1\text{ J/s}}\right) = 0.1635\text{ W}$$

The LED bulb provides 16 lumens of lighting. For an efficacy of 150 lumens per watt, the corresponding output electric power is

$$\dot{E}_{\text{out}} = \frac{\dot{E}_{\text{lighting}}}{\text{Efficacy}} = \frac{16\text{ lumens}}{150\text{ lumens/W}} = 0.1067\text{ W}$$

The overall efficiency of the device is the ratio of the output power to the input power:

$$\eta_{\text{overall}} = \frac{\dot{E}_{\text{out}}}{\dot{E}_{\text{in}}} = \frac{0.1067\text{ W}}{0.1635\text{ W}} = 0.652 = \mathbf{65.2\ percent}$$

Discussion One can double the amount of lighting from 16 lumens to 32 lumens by doubling the weight of the sand bag. However, this requires lifting of a 20-kg weight by a strong person available on the site.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
E_dot_lighting=16 [lumen]
m=10 [kg]
z=2 [m]
t=(20*60) [s]
Efficacy=150 [lumen/W]
"Analysis"
V=z/t
E_in=m*g*z
g=9.81 [m/s^2]
E_dot_in=E_in/t
E_dot_out=E_dot_lighting/Efficacy
eta=E_dot_out/E_dot_in
```

2-104 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

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

EES (Engineering Equation Solver) SOLUTION

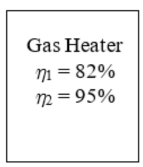
```
"Given"
N_people=56
Q_dot_person=100 [W]
N_lamps=18
Q_dot_lamp=40 [W]
f=1.1
"Analysis"
Q_dot_lighting=f*N_lamps*Q_dot_lamp
Q_dot_people=N_people*Q_dot_person
Q_dot_total=Q_dot_lighting+Q_dot_people
```

2-105 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.

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: $\text{Annual cost of heating} = (\text{Cost of useful heat})/\text{Efficiency} = (\$660/\text{yr})/0.82 = \$805/\text{yr}$

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

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

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

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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
eta_old=0.55
eta_conventional=0.82
eta_highefficiency=0.95
Cost_conventional=1600 [$]
Cost_highefficiency=2700 [$]
CurrentCost=1200 [$/year]
"Analysis"
CostHeat=eta_old*CurrentCost
AnnualCost_conventional=CostHeat/eta_conventional
AnnualCost_highefficiency=CostHeat/eta_highefficiency
PaybackPeriod=(Cost_highefficiency-Cost_conventional)/(AnnualCost_conventional-AnnualCost_highefficiency)
```

2-106 A homeowner 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,

$$\textit{Natural gas heater}: \quad \text{Unit cost of useful energy} = \frac{\$1.24/\text{therm}}{0.87}\left(\frac{1\ \text{therm}}{105{,}500\ \text{kJ}}\right) = \$13.5 \times 10^{-6}/\text{kJ}$$

$$\textit{Heating oil heater}: \quad \text{Unit cost of useful energy} = \frac{\$2.3/\text{gal}}{0.87}\left(\frac{1\ \text{gal}}{138{,}500\ \text{kJ}}\right) = \$19.1 \times 10^{-6}/\text{kJ}$$

$$\textit{Electric heater}: \quad \text{Unit cost of useful energy} = \frac{\$0.12/\text{kWh})}{1.0}\left(\frac{1\ \text{kWh}}{3600\ \text{kJ}}\right) = \$33.3 \times 10^{-6}/\text{kJ}$$

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
UnitCost_electric=0.12 [$/kWh]
UnitCost_gas=1.24 [$/therm]
UnitCost_oil=2.3 [$/gal]
eta_electric=1.0
eta_gas=0.87
eta_oil=0.87
"Analysis"
Cost_UsefulEnergy_gas=UnitCost_gas/eta_gas*1/Convert(therm, kJ)
Cost_UsefulEnergy_oil=UnitCost_oil/eta_oil*1/138500 "[$/kJ], since 1 gal = 138500 kJ"
Cost_UsefulEnergy_electric=UnitCost_electric/eta_electric*1/Convert(kWh, kJ)
```

2-107 It is estimated that 570,000 barrels of oil would be saved per day if the thermostat setting in residences in winter were lowered by 6°F (3.3°C). The amount of money that would be saved per year is to be determined.

Assumptions The average heating season is given to be 180 days, and the cost of oil to be $\$40/\text{barrel}$.

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

$$(570{,}000\ \text{barrel/day})(180\ \text{days/year})(\$55/\text{barrel}) = \mathbf{\$5.64\times10^9}$$

Therefore, the proposed measure will save more than 5.6-billion dollars a year in energy costs.

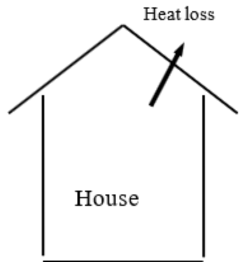
EES (Engineering Equation Solver) SOLUTION

```
"Given"
OilSavings=570000 "[barrel/day]"
DELTAT=3.3 [C]
HeatingSeason=180 [day/year]
UnitCost=55 "[$/barrel]"
"Analysis"
MoneySaved=OilSavings*HeatingSeason*UnitCost
```

2-108 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.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
Cost_energy=1200 [$/year]
f_heat_cool=0.46
reduction_heat_cool=0.30
Cost_insulation=200 [$]
"Analysis"
MoneySaved=Cost_energy*f_heat_cool*reduction_heat_cool
Payback=Cost_insulation/MoneySaved
```

2-109 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 $32\,\text{kg/kmol}$.

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

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

$$\dot{m}_{\text{Sulfur}} = (750 \times 10^{-6})\dot{m}_{\text{fuel}} = (500 \times 10^{-6})(18.67 \text{ kg/h}) = \mathbf{0.00933\ kg/h}$$

The rate of sulfurous acid given off to the environment is

$$\dot{m}_{\text{H2SO3}} = \frac{M_{\text{H2SO3}}}{M_{\text{Sulfur}}}\dot{m}_{\text{Sulfur}} = \frac{2 \times 1 + 32 + 3 \times 16}{32}(0.00933 \text{ kg/h}) = \mathbf{0.0239\ kg/h}$$

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

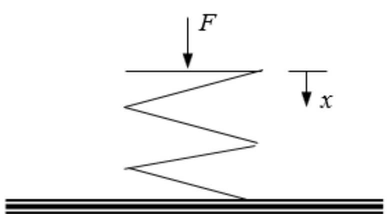
EES (Engineering Equation Solver) SOLUTION

```
"GIVEN"
Vol_engine=0.004 [m^3]
N_dot=2500[1/min]*Convert(1/min, 1/s)
AF=18
Sulfur_PPM=500E-6
m_dot_air=336 [kg/h]
MM_sulfur=32 [kg/kmol]
"PROPERTIES"
MM_O2=MolarMass(O2)
MM_H2=MolarMass(H2)
MM_H2SO3=MM_H2+MM_sulfur+1.5*MM_O2
"ANALYSIS"
m_dot_fuel=m_dot_air/AF
m_dot_sulfur=Sulfur_PPM*m_dot_fuel
m_dot_H2SO3=MM_H2SO3/MM_sulfur*m_dot_sulfur
```


2-110 The work required to compress a spring is to be determined.

Analysis

(a) With the preload, $F = F_0 + kx$. Substituting this into the work integral gives



$$W = \int_1^2 F ds = \int_1^2 (kx + F_0)dx$$

$$= \frac{k}{2}(x_2^2 - x_1^2) + F_0(x_2 - x_1)$$

$$= \frac{300 \text{ N/cm}}{2}\left[(1 \text{ cm})^2 - 0^2\right] + (100 \text{ N})\left[(1 \text{ cm}) - 0\right]$$

$$= 250 \text{ N}\cdot\text{cm} = 2.50 \text{ N}\cdot\text{m} = 2.50 \text{ J} = \mathbf{0.0025 \text{ kJ}}$$

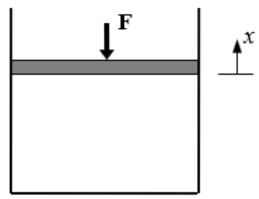
EES (Engineering Equation Solver) SOLUTION

```
"Given"
x2=1 [cm]
k=300 [N/cm]
F0=100 [N]
"Analysis"
x1=0 [cm]
W=k/2*(x2^2-x1^2)+F0*(x2-x1)
W_kJ=W*Convert(N-cm,kJ)
```

2-111 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



$$W = \int_1^2 F ds = \int_1^2 \frac{\text{Constant}}{x^k} dx$$

$$= \frac{\text{Constant}}{1-k}(x_2^{1-k} - x_1^{1-k})$$

$$= \frac{1000 \text{ N}\cdot\text{m}^{1.3}}{1-1.3}\left[(0.3 \text{ m})^{-0.3} - (0.1 \text{ m})^{-0.3}\right]$$

$$= 1867 \text{ N}\cdot\text{m} = 1867 \text{ J} = \mathbf{1.87 \text{ kJ}}$$

EES (Engineering Equation Solver) SOLUTION

```
"Given"
C=1000 [N-m^1.3]
k=1.3
x1=0.1 [m]
x2=0.3 [m]
"Analysis"
W=C/(1-k)*(x2^(1-k)-x1^(1-k))
```

2-112 A TV set is kept on a specified number of hours per day. The cost of electricity this TV set consumes per month is to be determined.

Assumptions

1. The month is 30 days.

2. The TV set consumes its rated power when on.

Analysis The total number of hours the TV is on per month is

$$\text{Operating hours} = (6\,\text{h/day})(30\,\text{days}) = 180\,\text{h}$$

Then the amount of electricity consumed per month and its cost become

$$\text{Amount of electricity} = (\text{Power consumed})(\text{Operating hours}) = (0.120\text{ kW})(180\text{ h}) = 21.6\text{ kWh}$$

$$\text{Cost of electricity} = (\text{Amount of electricity})(\text{Unit cost}) = (21.6\text{kWh})(\$0.12/\text{kWh}) = \$\mathbf{2.59}(\text{per month})$$

Properties Note that an ordinary TV consumes more electricity that a large light bulb, and there should be a conscious effort to turn it off when not in use to save energy.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
E_dot_TV=0.120 [kW]
time=30*6 [h]
UnitCost=0.12 [$/kWh]
"Analysis"
Cost=E_dot_TV*time*UnitCost
```

2-113E 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

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

$$= (62.4\text{ lbm/ft}^3)(200\text{ gal/min})\left(\frac{35.315\text{ ft}^3/\text{s}}{15{,}850\text{ gal/min}}\right)(32.174\text{ ft/s}^2)(300\text{ ft})\left(\frac{1\text{ lbf}}{32.174\text{ lbm}\cdot\text{ft/s}^2}\right)$$

$$= 8342\text{ lbf}\cdot\text{ft/s} = (8342\text{ lbf}\cdot\text{ft/s})\left(\frac{1\text{ kW}}{737.56\text{ lbf}\cdot\text{ft/s}}\right) = \mathbf{11.3\text{ kW}}$$

EES (Engineering Equation Solver) SOLUTION

```
"Given"
z_1=-200 [ft]
z_2=100 [ft]
V_dot=200 [gal/min]*Convert(gal/min, ft^3/s)
"Analysis"
rho=62.4 [lbm/ft^3]
g=32.174 [ft/s^2]
W_dot=rho*V_dot*g*(z_2-z_1)*Convert(lbm-ft/s^2, lbf)
W_dot_kW=W_dot*Convert(lbf-ft/s, kW)
```

2-114 The weight of the cabin of an elevator is balanced by a counterweight. The power needed when the fully loaded cabin is rising, and when the empty cabin is descending at a constant speed are to be determined.

Assumptions

1. The weight of the cables is negligible.

2. The guide rails and pulleys are frictionless.

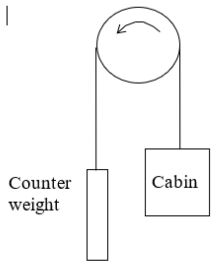
3. Air drag is negligible.

Analysis

(a) When the cabin is fully loaded, half of the weight is balanced by the counterweight. The power required to raise the cabin at a constant speed of 1.2 m/s is

$$\dot{W} = \frac{mgz}{\Delta t} = mgV = (400\text{ kg})(9.81\text{ m/s}^2)(1.2\text{ m/s})\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1\text{ kW}}{1000\text{ N}\cdot\text{m/s}}\right) = \mathbf{4.71\,kW}$$

If no counterweight is used, the mass would double to 800 kg and the power would be 2×4.71 = **9.42 kW**.



(b) When the empty cabin is descending (and the counterweight is ascending) there is mass imbalance of 400-150 = 250 kg. The power required to raise this mass at a constant speed of 1.2 m/s is

$$\dot{W} = \frac{mgz}{\Delta t} = mgV = (250\text{ kg})(9.81\text{ m/s}^2)(1.2\text{ m/s})\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1\text{ kW}}{1000\text{ N}\cdot\text{m/s}}\right) = \mathbf{2.94\,kW}$$

If a friction force of 800 N develops between the cabin and the guide rails, we will need

$$\dot{W}_{\text{friction}} = \frac{F_{\text{friction}}z}{\Delta t} = F_{\text{friction}}V = (800\text{ N})(1.2\text{ m/s})\left(\frac{1\text{ kW}}{1000\text{ N}\cdot\text{m/s}}\right) = 0.96\text{ kW}$$

of additional power to combat friction which always acts in the opposite direction to motion. Therefore, the total power needed in this case is

$$\dot{W}_{\text{total}} = \dot{W} + \dot{W}_{\text{friction}} = 2.94 + 0.96 = \mathbf{3.90\,kW}$$

EES (Engineering Equation Solver) SOLUTION

```
"Given"
m_loaded=800 [kg]
m_empty=150 [kg]
m_counter=400 [kg]
Vel_rise=1.2 [m/s]
Vel_descend=1.2 [m/s]
F_friction=800 [N]
"Properties"
g=9.81 [m/s^2]
"Analysis"
"(a)"
m_a=m_loaded-m_counter
W1_dot_a=m_a*g*Vel_rise*Convert(N-m/s, kW)
W2_dot_a=m_loaded*g*Vel_rise*Convert(N-m/s, kW)
"(b)"
m_b=m_counter-m_empty
W1_dot_b=m_b*g*Vel_descend*Convert(N-m/s, kW)
W_dot_friction=F_friction*Vel_descend*Convert(N-m/s, kW)
W2_dot_b=W1_dot_b+W_dot_friction
```

2-115 The power that could be produced by a water wheel is to be determined.

Properties The density of water is taken to be $1000\,\text{m}^3/\text{kg}$ (Table A-3).

Analysis The power production is determined from

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

$$= (1000\text{ kg/m}^3)(0.480/60\text{ m}^3/\text{s})(9.81\text{ m/s}^2)(14\text{ m})\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)$$

$$= \mathbf{1.10\ kW}$$

EES (Engineering Equation Solver) SOLUTION

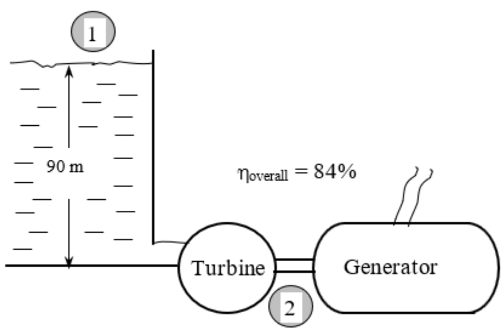
```
"Given"
z_1=0 [m]
z_2=14 [m]
V_dot=480 [L/min]*Convert(L/min, m^3/s)
"Analysis"
rho=1000 [kg/m^3]
g=9.81 [m/s^2]
W_dot=rho*V_dot*g*(z_2-z_1)*Convert(m^2/s^2, kJ/kg)
```


2-116 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 $\rho = 1000\,\text{kg/m}^3 = 1\,\text{kg/L}$.



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

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

Then the maximum and actual electric power generation become

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

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

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.

EES (Engineering Equation Solver) SOLUTION

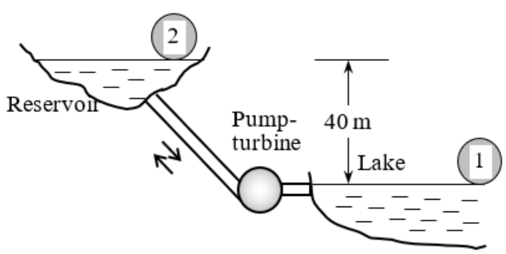
```
"Given"
V_dot=65 [m^3/s]
z=90 [m]
eta=0.84
"Analysis"
rho=1000 [kg/m^3]
g=9.81 [m/s^2]
m_dot=rho*V_dot
W_dot_max=m_dot*g*z*Convert(m^2/s^2, kJ/kg)
W_dot_elect=eta*W_dot_max
```


2-117 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 $\rho = 1000\text{ kg/m}^3$.



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.

$$\dot{W}_{\max,\text{ turbine}} = \dot{W}_{\min,\text{ pump}} = \dot{W}_{\text{ideal}} = \Delta\dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\Delta pe = \dot{m}g\Delta z = \rho\dot{V}g\Delta z$$

$$= (1000\text{ kg/m}^3)(2\text{ m}^3\text{/s})(9.81\text{ m/s}^2)(40\text{ m})\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1\text{ kW}}{1000\text{ N}\cdot\text{m/s}}\right)$$

$$= 784.8\text{ kW}$$

The actual pump and turbine electric powers are

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

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

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

$$\text{Cost} = \dot{W}_{\text{pump, elect}} \text{D} t ´ \text{ Unit price} = (1046 \text{ kW})(365 ´ 10 \text{ h/year})(\$0.05/\text{kWh}) = \$190{,}968/\text{year}$$

$$\text{Revenue} = \dot{W}_{\text{turbine}} \text{D} t ´ \text{ Unit price} = (588.6 \text{ kW})(365 ´ 10 \text{ h/year})(\$0.12/\text{kWh}) = \$257{,}807/\text{year}$$

$$\text{Net income} = \text{Revenue} - \text{Cost} = 257{,}807 - 190{,}968 = \mathbf{\$66{,}839 / year}$$

Discussion It appears that this pump-turbine system has a potential to generate net revenues of about $67,000 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.

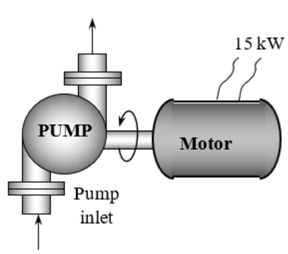
EES (Engineering Equation Solver) SOLUTION

```
"Given"
z=40 [m]
V_dot=2 [m^3/s]
eta_pump_motor=0.75
eta_turb_gen=0.75
time=365*10 [h/year]
UnitPrice_night=0.05 [$/kWh]
UnitPrice_day=0.12 [$/kWh]
"Analysis"
rho=1000 [kg/m^3]
g=9.81 [m/s^2]
m_dot=rho*V_dot
W_dot_max=m_dot*g*z*Convert(m^2/s^2, kJ/kg)
W_dot_pump_elect=W_dot_max/eta_pump_motor
W_dot_turb_elect=W_dot_max*eta_turb_gen
Cost=W_dot_pump_elect*time*UnitPrice_night
Revenue=W_dot_turb_elect*time*UnitPrice_day
NetIncome=Revenue-Cost
```


2-118 The pump of a water distribution system is pumping water at a specified flow rate. The pressure rise of water 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.
2. The elevation difference across the pump is negligible.
3. Water is incompressible.



Analysis From the definition of motor efficiency, the mechanical (shaft) power delivered by the he motor is

$$\dot{W}_{\text{pump, shaft}} = h_{\text{motor}}\dot{W}_{\text{electric}} = (0.90)(15 \text{ kW}) = 13.5 \text{ kW}$$

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

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

$$= (0.050 \text{ m}^3/\text{s})(300\text{-}100 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 10 \text{ kJ/s} = 10 \text{ kW}$$

since $\dot{m} = \rho\dot{V} = \dot{V}/v$ and there is no change in kinetic and potential energies of the fluid. Then the pump efficiency becomes

$$\eta_{\text{pump}} = \frac{\Delta\dot{E}_{\text{mech, fluid}}}{\dot{W}_{\text{pump, shaft}}} = \frac{10 \text{ kW}}{13.5 \text{ kW}} = 0.741 \quad \text{or} \quad \mathbf{74.1\%}$$

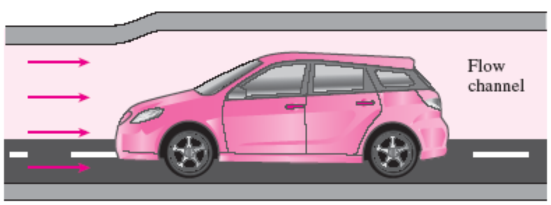
Discussion The overall efficiency of this pump/motor unit is the product of the mechanical and motor efficiencies, which is 0.9×0.741 = 0.667.

EES (Engineering Equation Solver) SOLUTION

```
"Given"
W_dot_elect=15 [kW]
eta_motor=0.90
V_dot=0.050 [m^3/s]
P1=100 [kPa]
P2=300 [kPa]
"Analysis"
rho=1000 [kg/m^3]
W_dot_pump_shaft=eta_motor*W_dot_elect
DELTAE_dot_mech_fluid=V_dot*(P2-P1)
eta_pump=DELTAE_dot_mech_fluid/W_dot_pump_shaft
```

2-119 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

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

The mass flow rate through the control volume is

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

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

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

EES (Engineering Equation Solver) SOLUTION

```
"Given"
A_1=3 [m^2]
Vel_1=90 [km/h]*Convert(km/h, m/s)
P=700 [mmHg]*Convert(mmHg,kPa)
T=(20+273) [K]
Vel_2=82 [km/h]*Convert(km/h, m/s)
"Analysis"
R=0.287 [kJ/kg-K]
v=(R*T)/P
m_dot=(A_1*Vel_1)/v
W_dot=m_dot*(Vel_1^2-Vel_2^2)/2*Convert(m^2/s^2, kJ/kg)
A_2=(m_dot*v)/Vel_2
```

2-120 Wind energy has been used since 4000 BC to power sailboats, grind grain, pump water for farms, and generate electricity. In the United States alone, more than 6 million small windmills, most of them under 5 hp, have been used since the 1850s to pump water. Small windmills have been used to generate electricity since 1900, but the development of modern wind turbines occurred towards the end of the twentieth century in response to the energy crises in the early 1970s. Regions with an average wind speed of above $5\,\text{m/s}$ are potential sites for economical wind power generation. A typical wind turbine has a blade span (or rotor) diameter of about 100 m and generates about 3 MW of power. Recent wind turbines have power capacities above 10 MW and rotor diameters of over 150 m.

Consider a wind turbine with an 80-m-diameter rotor that is rotating at 20 rpm (revolutions per minute) under steady winds at an average velocity of 30 km/h. Assuming the wind turbine has an efficiency of 35 percent (i.e., it converts 35 percent of the kinetic energy of the wind to electricity), determine (*a*) the power produced, in kW; (*b*) the tip speed of the blade, in km/h; and (*c*) the revenue generated by the wind turbine per year if the electric power produced is sold to the utility at $\$1.15/\text{kWh}$. Take the density of air to be $1.20\,\text{kg/m}^3$.

2-120 A wind turbine is rotating at 20 rpm under steady winds of $30\,\text{km/h}$. 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

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

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

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

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

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

$$\text{Revenue generated} = (\text{Electricity produced})(\text{Unit price})$$

$$= (5.351\times 10^6\text{ kWh/year})(\$1.15/\text{kWh})$$

$$= \mathbf{\$6,154,000\ /\ yr}$$

Discussion

(a) If we repeat this problem at a wind velocity of $20\,\text{km/h}$, the power generated, the tip velocity, and the revenue generated become 181 kW, $302\,\text{km/h}$, and $\$1,823,000\ /\text{yr}$, respectively.

Fundamentals of Engineering (FE) Exam Problems

2-121 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
"Some Wrong Solutions with Common Mistakes:"
W1_Etotal=We*time/60 "using minutes instead of s"
W2_Etotal=We "ignoring time"
```

2-122 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 $\$0.13/\text{kWh}$, the electricity cost of this refrigerator per month (30 days) is

(a) \$4.9
(b) \$5.8
(c) \$7.5
(d) \$8.3
(e) \$9.7

Answer (c) \$7.5

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_e=0.320 [kW]
Hours=0.25*(24*30) [h]
price=0.13 [$/kWh]
```

Cost=W_e*Hours*price
"Some Wrong Solutions with Common Mistakes:"
W1_cost= W_e*24*30*price "running continuously"

2-123 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 $\$0.11/\text{kWh}$, the annual electricity cost of this compressor is

(a) $14,300
(b) $15,380
(c) $16,540
(d) $19,180
(e) $22,180

Answer (c) $16,540

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_comp=75 [hp]
Hours=2500 [h/yr]
Eff=0.93
price=0.11 [$/kWh]
W_e=W_comp*Convert(hp, kW)*Hours/Eff
Cost=W_e*price
"Some Wrong Solutions with Common Mistakes:"
W1_cost= W_comp*0.7457*Hours*price*Eff "multiplying by efficiency"
W2_cost= W_comp*Hours*price/Eff "not using conversion"
W3_cost= W_comp*Hours*price*Eff "multiplying by efficiency and not using conversion"
W4_cost= W_comp*0.7457*Hours*price "Not using efficiency"
```


2-124 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).

```
W_fan=0.50*0.7457 [kW]
Eff=0.65
E=W_fan/Eff
"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"
```

2-125 A fan is to accelerate quiescent air to a velocity to 9 m/s at a rate of $3 \text{ m}^3/\text{min}$. If the density of air is 1.15 kg/m^3, the minimum power that must be supplied to the fan is

(a) 41 W
(b) 122 W
(c) 140 W
(d) 206 W
(e) 280 W

Answer (c) 140 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).

```
V=9 [m/s]
V_dot=3 [m^3/s]
rho=1.15 [kg/m^3]
m_dot=rho*V_dot
W_e=m_dot*V^2/2
"Some Wrong Solutions with Common Mistakes:"
W1_W_e=V_dot*V^2/2 "Using volume flow rate"
W2_W_e=m_dot*V^2 "forgetting the 2"
W3_W_e=V^2/2 "not using mass flow rate"
```


2-126 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]
t=4 [s]
Wa=m*((V2/3.6)^2-(V1/3.6)^2)/2000/t
"Some Wrong Solutions with Common Mistakes:"
W1_Wa=((V2/3.6)^2-(V1/3.6)^2)/2/t "Not using mass"
W2_Wa=m*((V2)^2-(V1)^2)/2000/t "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/t "Using velocities"
```

2-127 The elevator of a large building is to raise a net mass of 550 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) 12 kW
(d) 45 kW
(e) (65 kW

Answer (e) 65 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=550 [kg]
V=12 [m/s]
g=9.81 [m/s^2]
W=m*g*V*Convert(kg-m^2/s^3, kW)
"Some Wrong Solutions with Common Mistakes:"
W1_W=m*V "Not using g"
W2_W=m*g*V^2/2000 "Using kinetic energy"
W3_W=m*g/V "Using wrong relation"
```

2-128 Electric power is to be generated in a hydroelectric power plant that receives water at a rate of $70\,\text{m}^3/\text{s}$ 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).


```
V_dot=70 [m^3/s]
z=65 [m]
Eff=0.85
g=9.81 [m/s^2]
rho=1000 [kg/m^3]
We=rho*V_dot*g*z*Eff*Convert(W, MW)
"Some Wrong Solutions with Common Mistakes:"
W1_We=rho*V_dot*z*Eff/10^6 "Not using g"
W2_We=rho*V_dot*g*z/Eff/10^6 "Dividing by efficiency"
W3_We=rho*V_dot*g*z/10^6 "Not using efficiency"
```

2-129 A 2-kW pump is used to pump kerosene ($\rho = 0.820\,\text{kg}/\text{L}$) 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) $8.3\,\text{L}/\text{s}$
(b) $7.2\,\text{L}/\text{s}$
(c) $6.8\,\text{L}/\text{s}$
(d) $12.1\,\text{L}/\text{s}$
(e) $17.8\,\text{L}/\text{s}$

Answer (a) $8.3\,\text{L}/\text{s}$

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/s^2]
W=rho*Vdot*g*z*Convert(W, kW)
"Some Wrong Solutions with Common Mistakes:"
W=W1_Vdot*g*z/1000 "Not using density"
```

2-130 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 [m^3/s]
DP=211 [kPa]
Emech=Vdot*DP
Eff=Emech/We
```


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

2-131 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 $10 \text{ W/m}^2 \times °\text{C}$ 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)
"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"

2-132 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) $43,500\,\text{W/m}^2\cdot°\text{C}$

(b) $137\,\text{W/m}^2\cdot°\text{C}$

(c) $68,330\,\text{W/m}^2\cdot°\text{C}$

(d) $10,038\,\text{W/m}^2\cdot°\text{C}$

(e) $37,540\,\text{W/m}^2\cdot°\text{C}$

Answer (a) $43,500\,\text{W/m}^2\cdot°\text{C}$

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]
We=4100 [W]
Ts=130 [C]
Tf=100 [C] "Boiling temperature of water at 1 atm"
A=pi*D*L
We= h*A*(Ts-Tf)
"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"
```


2-133 A $3-\text{m}^2$ 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 $12\,\text{W/m}^2.°\text{C}$, 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).

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

2-134 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
"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"

2-135 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
"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"

2-136 … 2-144 Design and Essay Problems