CHAPTER 2: THE NATURE OF ENERGY

2.1) A 5.00-kg light fixture is suspended above a theater's stage 15.0 meters above the ground. The local acceleration due to gravity is 9.75 m/s^2. Determine the potential energy of the light fixture.

Given: m = 5.00 kg, z = 15.0 m; g = 9.75 m/s^2

Solution:

PE = mgz = (5.00 kg)(9.75 m/s^2)(15.0 m) = **731 J**

2.2) In 1908, Charles Street of the Washington, D.C., baseball team caught a baseball thrown from the top of the Washington Monument. If the height of the ball before it was thrown was 165 m and the mass of the baseball was 0.145 kg, what was the potential energy of the baseball before it was thrown? Assume that the acceleration due to gravity was 9.81 m/s^2.

Given: m = 0.145 kg, z = 165 m; g = 9.81 m/s^2

Solution:

PE = mgz = (0.145 kg)(9.81 m/s^2)(165 m) = **235 J**

2.3) 10.0 kg of water is about to fall over a cliff in a waterfall. The height of the cliff is 115 m. Determine the potential energy of the mass of water considering standard gravity on earth.

Given: m = 10.0 kg; g = 9.81 m/s^2; z = 115 m

Solution:

PE = mgz = (10.0 kg)(9.81 m/s^2)(115 m) = 11,280 J **= 11.3 kJ**

2.4) A jet airplane is flying at a height of 10,300 m at a velocity of 240 m/s. If the mass of the airplane is 85,000 kg, and if the acceleration due to gravity is 9.70 m/s^2, determine the potential energy and the kinetic energy of the airplane.

Given: m = 85,000 kg; g = 9.70 m/s^2; z = 10,300 m; V = 240 m/s

Solution:

PE = mgz = (85,000 kg)(9.70 m/s^2)(10,300 m) = **8.49 × 10^9 J = 8,490 MJ**

$KE = ½ mV^2 = ½ (85,000 kg)(240 m/s)^2 =$ **2.45×10^9 J = 2,450 MJ**

2.5) A piece of space debris with a mass of 7 kg is falling through the atmosphere towards earth at a height of 4.5 km with a velocity of 230 m/s. Determine the potential and kinetic energy of the object.

Given: m = 7 kg; z = 4500 m; V = 230 m/s

Assume: $g = 9.81 m/s^2$

Solution:

$PE = mgz = (7 kg)(9.81 m/s^2)(4500 m) =$ **309 kJ**
$KE = ½ mV^2 = ½ (7 kg)(230 m/s)^2 =$ **185 kJ**

2.6) A baseball with a mass of 0.145 kg is thrown by a pitcher at a velocity of 42.0 m/s. Determine the kinetic energy of the baseball.

Given: m = 0.145 kg; V = 42.0 m/s

Solution:

$KE = ½ mV^2 = ½ (0.145 kg) (42.0 m/s)^2 =$ **128 J**

2.7) A brick with a mass of 2.50 kg, which was dropped from the roof of a building, is about to hit the ground at a velocity of 27.0 m/s. Determine the kinetic energy of the brick.

Given: m = 2.50 kg; V = 27.0 m/s

Solution:

$KE = ½ mV^2 = ½ (2.50 kg) (27.0 m/s)^2 =$ **911 J**

2.8) An 80.0-kg rock that was hurled by a catapult is about to hit a wall while traveling at 7.50 m/s. What is the kinetic energy of the rock just before contacting the wall?

Given: m = 80.0 kg; V = 7.50 m/s

Solution:

$KE = ½ mV^2 = ½ (80.0 kg) (7.50 m/s)^2 =$ **2250 J = 2.25 kJ**

2.9) Steam flows through a pipe located 4 m above the ground. The velocity of the steam in the pipe is 80.0 m/s. If the specific internal energy of the steam is 2765 kJ/kg, determine the total internal energy, the kinetic energy, and the potential energy of 1.50 kg of steam in the pipe.

Given: m = 1.50 kg; z = 4 m; V = 80.0 m/s; u = 2765 kJ/kg

Assume: $g = 9.81\ m/s^2$

Solution:

U = mu = (1.50 kg) (2765 kJ/kg) = **4,150 kJ**
KE = ½ mV^2 = ½ (1.50 kg)$(80.0\ m/s)^2$ = 4,800 J = **4.80 kJ**
PE = mgz = (1.50 kg)$(9.81\ m/s^2)$(4 m) = 58.9 J **= 0.0589 kJ**

2.10) Now, for problem 2.9 replace the steam with liquid water. If the specific internal energy of the liquid water is 120 kJ/kg, determine the total internal energy, the kinetic energy, and the potential energy of 1.50 kg of water in the pipe.

Given: m = 1.50 kg; z = 4 m; V = 80.0 m/s; u = 120 kJ/kg

Assume: $g = 9.81\ m/s^2$

Solution:

U = mu = (1.50 kg) (120 kJ/kg) = **180 kJ**
KE = ½ mV^2 = ½ (1.50 kg)$(80.0\ m/s)^2$ = 4,800 J = **4.80 kJ**
PE = mgz = (1.50 kg)$(9.81\ m/s^2)$(4 m) = 58.9 J **= 0.0589 kJ**

2.11) Steam, with a specific internal energy of 2803 kJ/kg, is flowing through a pipe located 5 m above the ground. The velocity of the steam in the pipe is 75 m/s. Determine the total internal energy, the kinetic energy, and the potential energy of 1 kg of steam in the pipe.

Given: m = 1 kg; z = 5 m; V = 75 m/s; u = 2803 kJ/kg

Assume: $g = 9.81\ m/s^2$

Solution:

U = mu = (1 kg) (2803 kJ/kg) = **2803 kJ** = **2,803,000 J**
KE = ½ mV^2 = ½ (1 kg)$(75\ m/s)^2$ = **2810 J**
PE = mgz = (1 kg)$(9.81\ m/s^2)$(5 m) **= 49.0 J**

2.12) Replace the steam in Problem 2.11 with liquid water. If the specific internal energy of the liquid water is 105 kJ/kg, determine the total internal energy, the kinetic energy, and the potential energy of 1 kg of water in the pipe.

Given: m = 1 kg; z = 5 m; V = 75 m/s; u = 105 kJ/kg

Assume: $g = 9.81\ m/s^2$

Solution:

U = mu = (1 kg) (105 kJ/kg) = **105 kJ = 105,000 J**
KE = ½ mV^2 = ½ (1 kg)$(75\ m/s)^2$ = **2810 J**
PE = mgz = (1 kg)$(9.81\ m/s^2)$(5 m) **= 49.0 J**

2.13) Determine the specific energy of air at 25°C, traveling at 35.0 m/s at a height of 10.0 m. Consider the specific internal energy of the air to be 212.6 kJ/kg.

Given: T= 25°C; z = 10.0 m; V = 35.0 m/s; u = 212.6 kJ/kg

Assume: $g = 9.81\ m/s^2$

Solution:

e = u + ½ V^2 = gz = 212.6 kJ/kg + ½ $(35.0\ m/s)^2$/(1000 J/kJ) + (10.0 m)$(9.81\ m/s^2)$ / (1000 J/kJ)
e = 213.3 kJ/kg

2.14) Determine the total energy of water vapor with a mass of 2.50 kg, a specific internal energy of 2780 kJ/kg, traveling at a velocity of 56.0 m/s at a height of 3.50 m.

Given: m = 2.50 kg; z = 3.50 m; V = 56.0 m/s; u = 2780 kJ/kg

Assume: $g = 9.81\ m/s^2$

Solution:

E = mu + ½ mV^2 + mgz
= (2.50 kg)[2780 kJ/kg + ½ $(56.0\ m/s)^2$/(1000 J/kJ) + $(9.81\ m/s^2)$(3.50 m)/(1000 J/kJ)]
E = **6950 kJ (6954 kJ)**

2.15) A house has outside walls made of brick with a thermal conductivity of 1.20 W/m·K. The wall thickness is 0.20 m. (a) If the inside temperature of the wall is 20.0°C and the outside temperature of the wall is -10.0°C, determine the heat transfer rate per unit area from conduction (the conductive heat flux) for the wall. (b) For an inside wall temperature of 20.0°C, plot the conductive heat flux through the wall for outside wall temperatures ranging from 30.0°C to -15.0°C. (c) For an outside wall temperature of -10.0°C, plot the conductive heat flux for inside wall temperatures ranging from 15.0°C to 25.0°C. Discuss how this relates to gaining cost savings by heating a home to a lower temperature in the winter.

Given: $\kappa = 1.20$ W/m·K; $\Delta x = 0.20$ m

Solution:

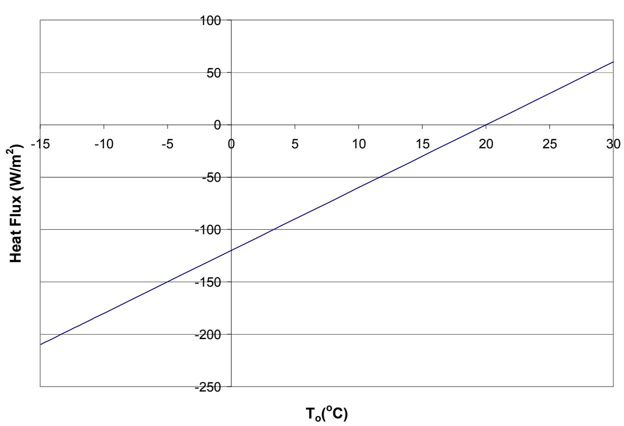
(a) $T_o = -10.0°C$, $T_i = 20.0°C$

$$\dot{Q}_{cond} = -\kappa A \frac{dT}{dx}$$

For the wall, approximate: $\frac{dT}{dx} = \frac{T_i - T_o}{\Delta x} = 150\ ^{o}\text{C/m} = 150 \text{ K/m}$

$\frac{\dot{Q}_{cond}}{A}$ =-(1.20 W/m•K)(150 K/m) = **-180 W/m²**

(b)



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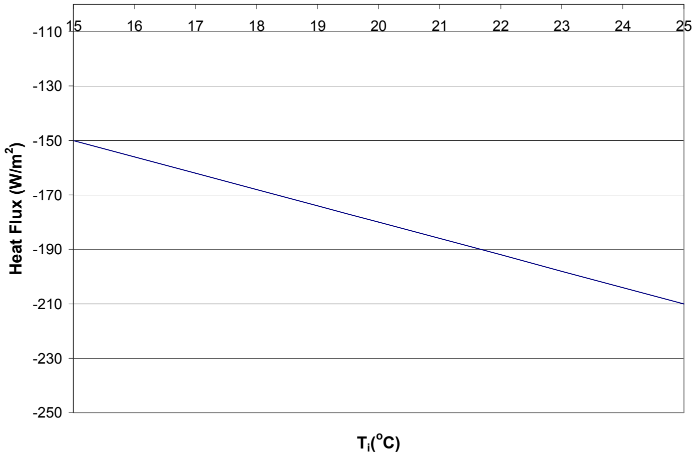


2.16) To reduce heat transfer losses through a glass window, you consider replacing the window with one of three alternatives: a sheet of tin 0.50 cm thick, a layer of brick 8.0 cm thick, and a combination of wood and insulation 4.0 cm thick. The original thickness of the glass is 1.0 cm. Consider the thermal conductivities of each to be the following: glass – 1.40 W/m·K; tin – 66.6 W/m·K; brick – 1.20 W/m·K; wood/insulation combination – 0.09 W/m·K. Considering the inside temperature of the surface to be 20.0°C, and the outside temperature to be -5.0°C, determine the heat conduction rate per unit area for the glass and the three alternatives, and discuss the relative merits of the three alternatives (ignoring material and installation costs).

Given: $T_i = 20.0°C$; $T_o = -5.0°C$

Solution:

For the each material, approximate: $\frac{dT}{dx} = \frac{T_i - T_o}{\Delta x}$

For Glass: κ = 1.40 W/m·K; Δx = 1.0 cm = 0.01 m

$\frac{\dot{Q}_{cond}}{A} = -\kappa \frac{T_i - T_o}{\Delta x}$ **= -3,500 W/m²**

Tin: κ = 66.6 W/m•K; Δx = 0.5 cm = 0.005 m

$\frac{\dot{Q}_{cond}}{A} = -\kappa \frac{T_i - T_o}{\Delta x}$ **= -266,400 W/m²**

Brick: κ = 1.20 W/m•K; Δx = 8.0 cm = 0.08 m

$\frac{\dot{Q}_{cond}}{A} = -\kappa \frac{T_i - T_o}{\Delta x}$ **= -375 W/m²**

Wood/Insulation:

$\kappa = 0.09$ W/m•K; $\Delta x = 4.0$ cm = 0.04 m

$\frac{\dot{Q}_{cond}}{A} = -\kappa \frac{T_i - T_o}{\Delta x}$ = **-56.3 W/m²**

The wood/insulation combination will offer the most resistance to heat flow, followed by the brick. The tin is a worse option than the original glass.

2.17) A factory has a sheet metal wall with a thermal conductivity of 180 W/m·K. The wall thickness is 2.5 cm. (a) If the inside temperature of the wall is 25.0°C and the outside temperature of the wall is -12°C, determine the heat transfer rate per unit area from conduction (the conductive heat flux) for the wall. (b) For an inside wall temperature of 25.0°C, plot the conductive heat flux through the wall for outside wall temperatures ranging from 30°C to -30°C. (c) For an outside wall temperature of -12.0°C, plot the conductive heat flux for inside wall temperatures ranging from 10°C to 30°C. Discuss how this relates to gaining cost savings by heating a building to a lower temperature in the winter.

Given: $\kappa = 180$ W/m·K; $\Delta x = 0.025$ m

Solution:

(a) $T_o = -12$°C, $T_i = 25.0$°C

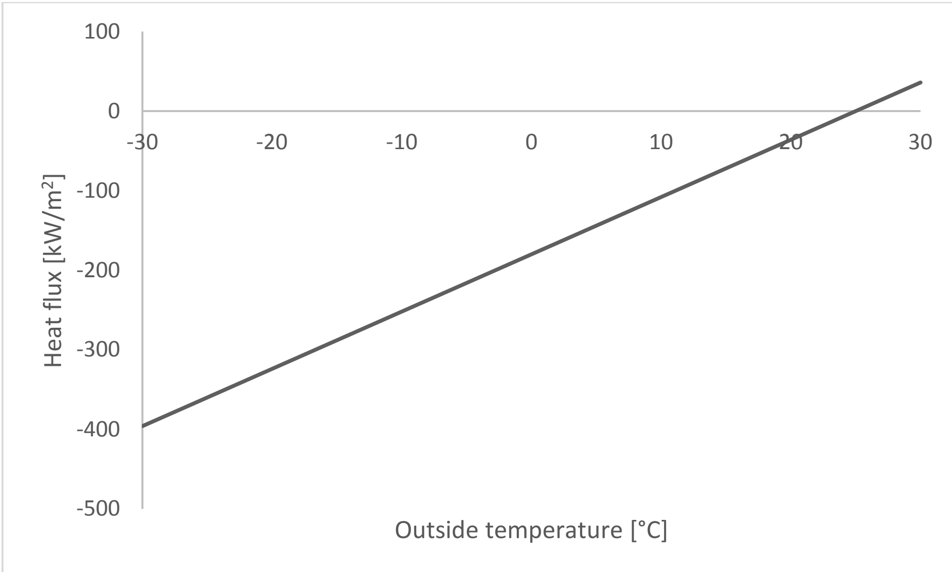
$$\dot{Q}_{cond} = -\kappa A \frac{dT}{dx}$$

For the wall, approximate:

$$\frac{dT}{dx} = \frac{T_i - T_o}{\Delta x} = 1480 \frac{°C}{m}$$

$\frac{\dot{Q}_{cond}}{A}$ = (-180 W/m·K)(1480 °C/m) = **-226 kW/m²**

(b)



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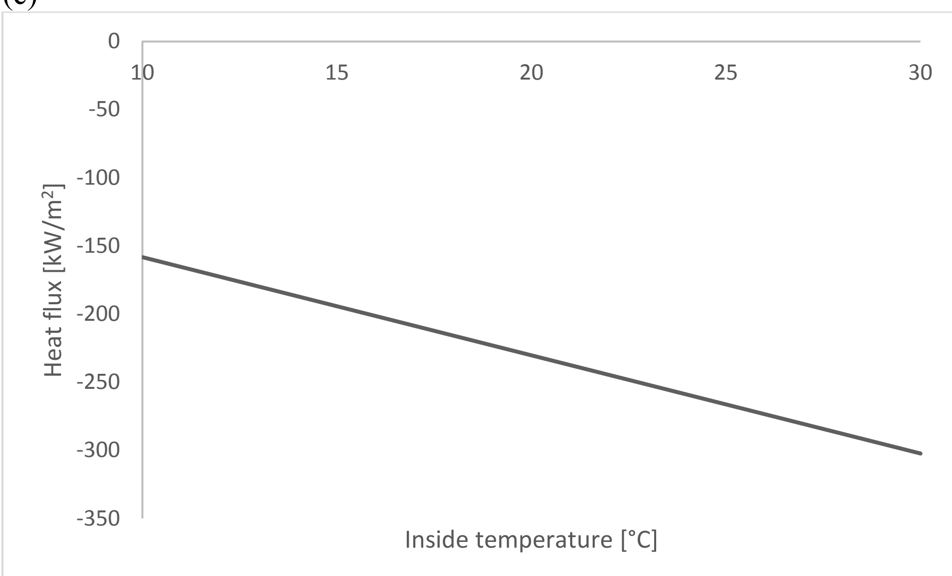


2.18) You are stoking a fire in a furnace, and leave the stoker inside the furnace for several minutes. The end of the stoker inside the furnace reaches a temperature of 300°C, whereas the other end of the stoker in the air is cooled sufficiently to maintain a temperature of 60°C. The length of the stoker between these two ends is 2.0 m. If the cross-sectional area of the stoker is 0.0010 m^2, determine the rate of heat transfer that occurs if (a) the stoker is made of aluminum (κ = 237 W/m·K), (b) iron (κ = 80.2 W/m·K), and (c) granite (κ = 2.79 W/m·K).

<u>Given</u>: T_1 = 300°C; T_2 = 60°C; Δx = 2.0 m; A = 0.0010 m^2

Solution:

For the each material, approximate: $\frac{dT}{dx} = \frac{T_2 - T_1}{\Delta x}$

$$\dot{Q}_{cond} = -\kappa A \frac{dT}{dx} = -\kappa A \frac{T_2 - T_1}{\Delta x}$$

(a) Aluminum: κ = 237 W/m·K

$\dot{Q}_{cond}$ = -(237 W/m·K)(0.0010 m^2)(60°C-300°C)/2.0m = **28.4 W**

(b) Iron: κ = 80.2 W/m·K

$\dot{Q}_{cond}$ = - (80.2 W/m·K)(0.0010 m^2)(60°C-300°C)/2.0m = **9.62 W**

(c) Granite: κ = 2.79 W/m·K

$\dot{Q}_{cond}$ = - (2.79 W/m·K)(0.0010 m^2)(60°C-300°C)/2.0m = **0.335 W**

2.19) A conductive heat transfer of 15 W is applied to a metal bar whose length is 0.50-m. The hot end of the bar is at 80°C. Determine the temperature at the other end of the bar for (a) a copper bar (κ = 401 W/m·K) with a cross-sectional area of 0.0005 m^2, (b) a copper bar (κ = 401 W/m·K) with a cross-sectional area of 0.005 m^2, and (c) a zinc bar (κ = 116 W/m·K) with a cross-sectional area of 0.005 m^2.

Given: $\dot{Q}_{cond}$=150 W; Δx = 0.50 m; T_1 = 80°C

Solution:

From $\dot{Q}_{cond} = -\kappa A \frac{dT}{dx} = -\kappa A \frac{T_2 - T_1}{\Delta x}$

$$T_2 = \frac{\dot{Q}_{cond}}{-kA} \Delta x + T_1$$

(a) Copper, κ = 401 W/m·K, A = 0.0005 m^2

$T_2 = \frac{15W}{-\left(\frac{401W}{m-K}\right)(0.0005m^2)}(0.50m) + 80^oC$ **= 42.6°C**

(b) Copper, κ = 401 W/m·K, A = 0.005 m^2

T_2 = 76.3°C

(c) Zinc, κ = 116 W/m·K, A = 0.005 m^2

T_2 = 54.1°C

Note: A material with a higher thermal conductivity will allow the same amount of heat flow with a smaller temperature difference than a material with a lower thermal conductivity.

2.20) A wind blows over the face of a person on a cold winter day. The temperature of the air is -5.0°C, while the person's skin temperature is 35.0°C. If the convective heat transfer coefficient is 10.0 $W/m^2 \cdot K$ and the exposed surface area of the face is 0.008 m^2, determine the rate of heat loss from the skin via convection.

Given: T_f = -5.0°C; T_s = 35.0°C; h = 10.0 W/m^2-K; A= 0.008 m^2

Solution:

$\dot{Q}_{conv} = hA(T_f - T_s)$ = (10.0 $W/m^2 \cdot K$)(0.008 m^2)(-5°C - 35.0°C) = **-3.2 W**
The heat transfer is from the person to the air.

2.21) Cooling water flows over a hot metal plate with a surface area of 0.5 m^2 in a manufacturing process. The temperature of the cooling water is 15°C, and the metal plate's surface temperature is maintained at 200°C. If the convective heat transfer rate is 68.0 $W/m^2 \cdot K$, determine the rate of convective heat transfer from the plate.

Given: A = 0.5 m^2; T_f = 15°C; T_s = 200°C; h = 68.0 W/m^2-K

Solution:

$\dot{Q}_{conv} = hA(T_f - T_s)$ = (68.0 $W/m^2 \cdot K$)(0.5 m^2)(15°C - 200°C) = **-6,290 W = -6.29 kW**
The heat is transferred from the plate to the water.

2.22) Air passes over a hot metal bar which has a surface area of 0.25 m^2. The temperature of the air is 20°C, and the bar has a temperature maintained at 140°C. If the convective heat transfer coefficient is 23 $W/m^2 \cdot K$, determine the rate of convective heat transfer from the plate.

Given: A = 0.25 m^2; T_f = 20°C; T_s = 140°C; h = 23 $W/m^2 \cdot K$

Solution:

$\dot{Q}_{conv} = hA(T_f - T_s)$ = (23 $W/m^2 \cdot K$)(0.25 m^2)(20°C – 140°C) = **-690 W**
The heat is transferred from the bar to the air.

2.23) A cool early spring breeze passes over the roof of a poorly insulated home. The surface area of the roof is 250 m^2, and the temperature of the roof is maintained at 20°C from heat escaping the house. The air temperature is 5.0°C, and the convective heat transfer coefficient is 12.0 $W/m^2 \cdot K$. Determine the rate of convective heat transfer from the roof.

Given: A = 250 m^2; T_f = 5.0°C; T_s = 20°C; h = 12.0 W/m^2-K

Solution:

$\dot{Q}_{conv} = hA(T_f - T_s)$ = (12.0 W/m^2-K)(250 m^2)(5°C - 20°C) = **-45,000 W = -45.0 kW**
Heat is lost from the roof to the air.

2.24) An electric space heater has a metal coil at a temperature of 250°C and is used to heat a space with an air temperature of 15°C. If the surface area of the space heater is 0.02 m^2 and the emissivity of the heating element is 0.95, what is the rate of radiation heat transfer between the heater and the air?

Given: T_s = 250°C = 523 K; T_{surr} = 15°C = 288 K; A = 0.02 m^2; ε = 0.95

Solution:

$\dot{Q}_{rad} = -\varepsilon\sigma A\left(T_s^4 - T_{surr}^4\right)$ = - (0.95)(5.67x10^{-8} W/m^2-K^4)(0.02m^2)[(523 K)^4 – (288 K)^4] = - **73.2 W**
Heat is transferred from the heater to the air.

2.25) An electrical resistance heater is placed inside a hollow cylinder. The heater has a surface temperature of 260°C, while the inside of the cylinder is maintained at 25°C. If the surface area of the heater is 0.12 m^2, and the emissivity of the heater is 0.90, what is the net rate of radiation heat transfer from the heater?

Given: T_s = 260 °C = 533 K; T_{surr} = 25 °C = 298 K; A = 10.12 m^2; ε = 0.90

Solution:

$\dot{Q}_{rad} = -\varepsilon\sigma A\left(T_s^4 - T_{surr}^4\right)$ = -(0.90)(5.670 × 10^{-8} W/m^2·K^4)(0.12 m^2)[(533 K)^4 – (298 K)^4]
= **-446 W**

2.26) A baker has developed a marvelous cookie recipe that works best if the cookie is cooled in a vacuum chamber through radiation heat transfer alone. The cookie is placed inside the chamber with a surface temperature of 125°C. Assume that the cookie is thin enough that the temperature is uniform throughout during the cooling process. The walls of the chamber are maintained at 10.0°C. If the surface area of the cookie is 0.005 m^2 and if the emissivity of the cookie is 0.80, determine the initial radiation heat transfer rate from the cookie to the walls of the chamber.

Given: T_s = 125°C = 398 K; T_{surr} = 10°C = 283 K; A = 0.005 m^2; ε = 0.80

Solution:

$\dot{Q}_{rad} = -\varepsilon\sigma A\left(T_s^4 - T_{surr}^4\right)$ = - (0.80)(5.67x10^{-8} W/m^2-K^4)(0.005m^2)[(398 K)^4 – (283 K)^4] = - **4.24 W**
Heat is transferred from the cookie to the walls.

2.27) A building is losing heat to the surrounding air. The inside walls of the building are maintained at 22.0°C, and the walls have a thermal conductivity of 0.50 W/m·K. The wall thickness is 0.10 m, and the outside wall temperature is held at 2.0°C. The air temperature is -10.0°C. Consider the emissivity of the outside of the walls to be 0.85. Calculate the conductive heat flux and the radiative heat flux. Considering that the heat flux entering the outside of the wall from the inside must balance the heat flux leaving the outside of the wall via convection and radiation, determine the necessary convective heat transfer coefficient of the air passing over the outside wall.

Given: $T_o = T_s$ = 2°C = 275 K; T_{surr} = -10°C = 263 K; T_i = 22.0°C = 295 K; Δx = 0.10 m; ε = 0.85; κ = 0.50 W/m·K

Solution:

Conduction: $\frac{\dot{Q}_{cond}}{A} = -\kappa\frac{T_i - T_o}{\Delta x}$ = - (0.50W/m·K)(295 K – 275 K)/(0.10 m) = **-100 W/m^2**
Radiation:
$\frac{\dot{Q}_{rad}}{A} = -\varepsilon\sigma\left(T_s^4 - T_{surr}^4\right)$ = - (0.85)(5.67x10^{-8} W/m^2·K^4)[(275 K)^4 – (263 K)^4] = **- 45.1 W/m^2**
Convection:
The difference between the conduction and radiation is the convective heat flux:
$\frac{\dot{Q}_{conv}}{A} = \frac{\dot{Q}_{cond}}{A} - \frac{\dot{Q}_{rad}}{A}$ = -100 W/m^2 – (-45.1 W/m^2) = **-54.9 W/m^2**

2.28) A long cylindrical rod with a diameter of 3.0 cm is placed in the air. The rod is heated by an electrical current so that the surface temperature is maintained at 200°C. The air temperature is 21°C. Air flows over the rod with a convective heat transfer coefficient of 5.0 W/m^2·K. Consider the emissivity of the rod to be 0.92. Ignoring the end effects of the rod, determine the heat transfer rate per unit length of the rod (a) via convection and (b) via radiation.

Given: T_s = 200°C = 473 K; $T_f = T_{surr}$ = 21°C = 294 K; h = 5.0 W/m^2·K; ε =0.92; D = 3.0 cm = 0.03 m

Solution:

The surface area of the cylinder is A = πDL = 0.09425L m^2, where L is the length of the rod.

Convection:

$\frac{\dot{Q}_{conv}}{L} = h\frac{A}{L}(T_f - T_s)$ = (5.0 W/m^2·K)(0.09425 m)(21°C - 200°C) = **-84.4 W/m**

Radiation:

$\frac{\dot{Q}_{rad}}{L} = -\varepsilon\frac{A}{L}\sigma\left(T_s^4 - T_{surr}^4\right)$ = -(0.92)(0.09425 m)(5.67x10^{-8} W/m^2·K^4)[$(473\text{ K})^4 - (294\text{ K})^4$]

= **-209 W/m**

2.29) A weight is attached to a horizontal load through a frictionless pulley. The weight has a mass of 25.0 kg, and the acceleration due to gravity is 9.80 m/s^2. The weight is allowed to fall 2.35 m. What is the work done by the falling weight as it pulls the load on a horizontal plane?

Given: m = 25.0 kg; g = 9.80 m/s^2; Δx = 2.35 m

Solution:

$W = \int_{x_1}^{x_2} F \cdot dx$ = W Δx = (mg) Δx = (25.0 kg)(9.80 m/s^2) (2.35 m) = **576 J**

2.30) How much work is needed to lift a rock with a mass of 58.0 kg a distance of 15.0 m, where the acceleration due to gravity is 9.81 m/s^2?

Given: m = 58.0 kg; Δx = 15.0 m; g = 9.81 m/s^2

Solution:

$W = \int_{x_1}^{x_2} F \cdot dx$ = W Δx = (mg) Δx = (58.0 kg)(9.81 m/s^2) (15.0 m) = **8,530 J = 8.53 kJ**

2.31) How much work is needed to lift a 140 kg rock a distance of 7.5 m, where the acceleration due to gravity is 9.81 m/s^2?

Given: m = 140 kg; Δx = 7.5 m; g = 9.81 m/s^2

Solution:

$W = \int_{x_1}^{x_2} F \cdot dx$ = W Δx = (mg) Δx = (140 kg)(9.81 m/s^2)(7.5 m) = **10.3 kJ**

2.32) A piston-cylinder device is filled with air. Initially, the piston is stabilized such that the length of the cylinder beneath the piston is 0.15 m. The piston has a diameter of 0.10 m. A weight with mass of 17.5 kg is placed on top of the piston, and the piston moves 0.030 m, such that the new length of the air-filled cylinder beneath the piston is 0.12 m. Determine the work done by the newly-added mass.

Given: x_1 = 0.15 m; x_2 = 0.12 m; D = 0.10 m; m = 17.5 kg

Assume: g = 9.81 m/s^2

Solution:

The force exerted by the mass equals the weight of the mass: W= mg = (17.5 kg)(9.81 m/s^2) = 171.7 N

$W = \int_{x_1}^{x_2} F \cdot dx$ = F ($x_2 - x_1$) = (171.7 N) (0.12 m – 0.15 m) = **- 5.15 J**

The negative sign indicates that this is work that is adding energy to the system – the air under the piston in the cylinder.

2.33) 250 kPa of pressure is applied to a piston in a piston-cylinder device. This pressure causes the piston to move 0.025 m. The diameter of the piston is 0.20 m. Determine the work done on the gas inside the piston.

Given: Δx = -0.025 m; P = 250 kPa; D = 0.20 m

Solution:

$W_{mb} = \int_{V_1}^{V_2} P \cdot dV$ = P ΔV

ΔV = (πD^2/4)Δx = -0.000785 m^3

W_{mb} = (250 kPa) (-0.000785 m^3) = -0.196 kN-m = -0.196 kJ = **-196 J**

2.34) A piston-cylinder device is filled with 5 kg of liquid water at 150°C. The specific volume of the liquid water is 0.0010905 m^3/kg. Heat is added to the water until some of the water boils, giving a liquid-vapor mixture with a specific volume of 0.120 m^3/kg. The pressure of the water is 475.8 kPa. How much work was done by the expanding water vapor?

Given: m = 5 kg; v_1 = 0.0010905 m^3/kg; v_2 = 0.120 m^3/kg; P = 475.8 kPa

Solution:

The water boils at constant pressure

$W_{mb} = \int_{V_1}^{V_2} P \cdot dV = mP(v_2 - v_1) = (5\text{ kg})(475.8\text{ kPa})(0.120\text{ m}^3/\text{kg} - 0.0010905\text{ m}^3/\text{kg})$

= **283 kJ**

In this case, work is being done on the surroundings by the expanding water, so the work represents energy out of the system.

2.35) Air at 700 kPa and 25°C fills a piston-cylinder assembly to a volume of 0.015 m^3. The air expands, in a constant-temperature process, until the pressure is 205 kPa. (The constant-temperature process with a gas can be modeled as a polytropic process with *n* = 1.) Determine the work done by the air as it expands.

Given: P_1 = 700 kPa; V_1 = 0.015 m^3; P_2 = 205 kPa

Solution:

PV^1 = constant, so $P_1V_1 = P_2V_2$

$V_2/V_1 = P_1/P_2$

$W_{mb} = P_1V_1 \ln\frac{V_2}{V_1} = P_1V_1 \ln(P_1/P_2) = (700\text{ kPa})(0.015\text{ m}^3)\ln(700\text{ kPa}/205\text{ kPa})$

= **12.9 kJ**

2.36) Air at 450 kPa and 20°C fills a piston-cylinder assembly to a volume of 0.075 m^3. The air expands, in a constant-temperature process, until the pressure is 150 kPa. (The constant-temperature process with a gas can be modeled as a polytropic process with n=1.) Determine the work done by the air as it expands.

Given: P_1 = 450 kPa; V_1 = 0.075 m^3; P_2 = 150 kPa

Solution:

PV^1 = constant, so $P_1V_1 = P_2V_2$

$V_2/V_1 = P_1/P_2$

$W_{mb} = P_1V_1 \ln\frac{V_2}{V_1}$ = $P_1V_1\ln(P_1/P_2)$ = (450 kPa) (0.075 m^3) ln ((450 kPa/150 kPa)) = **37.1 kJ**

2.37) 1.5 kg of water vapor at 500 kPa fills a balloon. The specific volume of the water vapor is 0.3749 m^3/kg. The water vapor condenses at constant pressure until a liquid-vapor mixture with a specific volume of 0.0938 m^3/kg is present. Determine the work done in the process.

Given: m = 1.5 kg; P = 500 kPa; v_1 = 0.3749 m^3/kg; v_2 = 0.0938 m^3/kg

Solution:

The water condenses at constant pressure

$W_{mb} = \int_{V_1}^{V_2} P \cdot dV$ = mP ($v_2 - v_1$) = (1.5 kg)(500 kPa)(0.0938 m^3/kg – 0.3749 m^3/kg)
= **-211 kJ**

2.38) Air at 1200 kPa and 250°C fills a balloon with a volume of 2.85 m^3. The balloon cools and expands until the pressure is 400 kPa. The pressure and volume follow a relationship given by $PV^{1.3}$ = constant. Determine the work done by the air as it expands, and the final temperature of the air.

Given: P_1 = 1200 kPa; T_1 = 250°C = 523 K; V_1 = 2.85 m^3; P_2 = 400 kPa; $PV^{1.3}$ = constant

Solution:

From the ideal gas law, $m = P_1V_1/RT_1$
For air, R = 0.287 kJ/kg-K, so m = 22.78 kg

$V_2 = V_1 \sqrt[1.3]{\frac{P_1}{P_2}}$ = 6.635 m^3

The moving boundary work for a polytropic process with n ≠ 1:

$$W_{mb} = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{(400\,kPa)(6.635\,m^3) - (1200\,kPa)(2.85\,m^3)}{1-1.3}$$ = **2550 kJ**

From the ideal gas law:
$T_2 = P_2V_2/mR$ = **406 K = 133°C**

2.39) Oxygen gas expands in a flexible container following a relationship of $PV^{1.15}$ = constant. The mass of the oxygen is 750 g, and initially the pressure and temperature of the oxygen are 1 MPa and 65°C, respectively. The expansion continues until the volume is double the original volume. Determine the final pressure and temperature of the oxygen, and determine the work done by the oxygen during the expansion.

<u>Given</u>: m = 700 g; T_1 = 65°C = 338 K; P_1 = 1 MPa; $V_2 = 2V_1$; $PV^{1.15}$ = constant.

<u>Solution</u>:

$P_2 = P_1(V_1/V_2)^{1.15} = (1\text{ MPa})(1/2)^{1.15}$ = **451 kPa**
For O_2, R = 0.260 kJ/kg·K
From the ideal gas law: $V_1 = mRT_1/P_1 = 0.066\text{ m}^3$
Then, $V_2 = 2V_1 = 0.132\text{ m}^3$
From the ideal gas law: $T_2 = P_2V_2/mR$ = **304 K**
For the moving boundary work:

$$W_{mb} = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{(451\text{ kPa})(0.132\text{ m}^3) - (1000\text{ kPa})(0.066\text{ m}^3)}{1-1.15} = \mathbf{43.1\text{ kJ}}$$

2.40) Nitrogen gas is compressed in a flexible container following a relationship of $PV^{1.2}$ = constant. The mass of the nitrogen is 1.5 kg, and initially the pressure and temperature of the nitrogen are 120 kPa and 15°C, respectively. The compression continues until the volume reaches 0.10 m^3. Determine the final pressure and temperature of the nitrogen, and determine the work done on the nitrogen in the process.

<u>Given</u>: m = 1.5 kg; P_1 =120 kPa; T_1 = 15°C = 288 K; $PV^{1.2}$ = constant; $V_2 = 0.10\text{ m}^3$

<u>Solution</u>:

For N_2, R = 0.2968 kJ/kg-K
Using the ideal gas law: $V_1 = mRT_1/P_1 = 1.068\text{ m}^3$
For a polytropic process with n = 1.2: $P_1V_1^{1.2} = P_2V_2^{1.2}$
So, **P_2 = 2060 kPa**
From the ideal gas law, $T_2 = P_2V_2/mR$ = **462 K = 189 °C**
For the moving boundary work:

$$W_{mb} = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{(2058\,kPa)(0.1m^3) - (120\,kPa)(1.068\,m^3)}{1-1.20} = \mathbf{-388\text{ kJ}}$$

2.41) Air expands in an isothermal process from a volume of 0.5 m^3 and a pressure of 850 kPa, to a volume of 1.2 m^3. The temperature of the air is 25°C. Determine the work done by the air in this expansion process.

Given: $T_1 = T_2 = 25°C$; $V_1 = 0.5\ m^3$; $P_1 = 850$ kPa; $V_2 = 1.2\ m^3$

Solution:

An isothermal process involving an ideal gas can be modeled as a polytropic process with n = 1.
Therefore,

$W_{mb} = P_1V_1 \ln\frac{V_2}{V_1}$ = (850 kPa)(0.5 m^3) ln (1.2 m^3 / 0.5 m^3) = **372 kJ**

2.42) 3.0 kg of air is initially at 200 kPa and 10°C. The air is compressed in a polytropic process, following the relationship PV^n = constant. The air is compressed until the volume is 0.40 m^3. Determine the work done and the final temperature of the air for values of n of 1.0, 1.1, 1.2, 1.3, and 1.4, and plot the work as a function of n.

Given: m = 3.0 kg; $P_1 = 200$ kPa; $T_1 = 10°C = 283$ K; $V_2 = 0.40\ m^3$

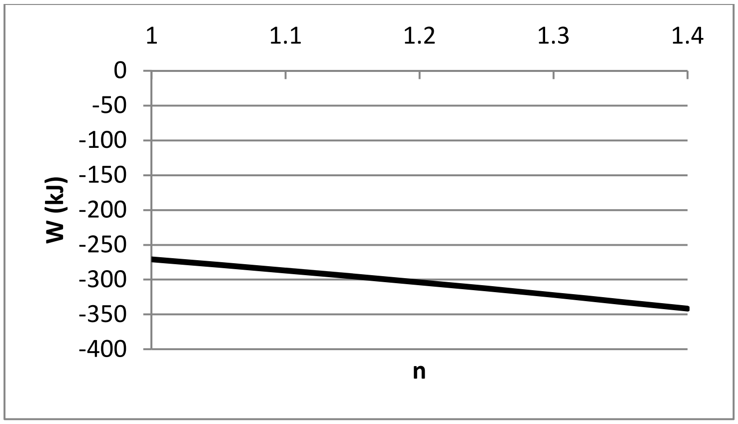
Solution:

For air, R = 0.287 kJ/kg-K
From the ideal gas law, $V_1 = mRT_1/P_1 = 1.218\ m^3$
For a polytropic process with n = 1: $W_{mb} = P_1V_1 \ln\frac{V_2}{V_1}$ = **- 271 kJ**

For a polytropic process with n ≠ 1: $W_{mb} = \frac{P_2V_2 - P_1V_1}{1-n}$

To solve for P_2, use $P_2 = P_1 (V_1/V_2)^n$
The following values can be found from these two equations:

n	P_2 (kPa)	W_{mb} (kJ)
1.1	681	-287
1.2	761	-304
1.3	851	-322
1.4	951	-342



2.43) A torque of 250 N-m is applied to a rotating shaft. Determine the work delivered for one revolution of the shaft.

Given: T = 250 N-m

Solution:

1 revolution involves a rotation through 2π radians. So, the rotating shaft work is

$W_{rs} = \int_{\theta_1}^{\theta_2} T \cdot d\theta$ = 2πT = 1571 J = **1.57 kJ**

2.44) A torque of 510 N-m is applied to a rotating shaft. Determine the power used if the shaft rotates at 1500 revolutions per minute.

Given: T = 510 N-m, $\dot{N}$ = 1500 rpm = 25 rps

Solution:

The rotating shaft power can be found from

$\dot{W}_{rs} = \int_{\theta_1}^{\theta_2} T \cdot d\dot{\theta}$=2πT $\dot{N}$ = 80,100 J/s = **80.1 kW**

2.45) An engine delivers 55 kW of power to a rotating shaft. If the shaft rotates at 2500 revolutions per minute, determine the torque exerted on the shaft by the engine.

Given: $\dot{W}_{rs} = 55\text{ kW}; \dot{N} = 2500\text{ rpm} = 41.67\text{ rps}$

Solution:

From Problem 2.44, $T = \frac{\dot{W}_{rs}}{2\pi\dot{N}}$ = **210 J**

2.46) A steam turbine operates at 1800 revolutions per minute (rpm). The turbine delivers 65.0 MW of power to the shaft of an electrical generator. Determine the torque on the steam turbine's shaft.

Given: $\dot{W}_{rs} = 65.0\text{ MW} = 65{,}000{,}000\text{ W}; \dot{N} = 1800\text{ rpm} = 30\text{ rps}$

Solution:

From Problem 2.44, $T = \frac{\dot{W}_{rs}}{2\pi\dot{N}}$ = 345,000 N-m = **345 kN-m**

2.47) A room fan operates on 120 V and draws a current of 1.5 A. What is the power used by the fan?

Given: E = 120 V; I = 1.5 A

Solution:

$\dot{W}_e = -\text{E}I$ = **-180 W**

2.48) A 23 W CFL bulb is plugged into a 120 V source. What is the current drawn by the bulb?

Given: $\dot{W}_e$ = -23 W; E = 120 V

Solution:

$I = -\frac{\dot{W}_e}{E}$ = **0.192 A**

2.49) An air compressor is plugged into a 208 V outlet, and requires 10 kW of power to complete its compression process. What is the current drawn by the air compressor?

Given: $\dot{W}_e$ = -10 kW = -10,000 W; E = 208 V

Solution:

$I = -\frac{\dot{W}_e}{E}$ = **48.1 A**

2.50) You are placed in an unfamiliar environment, with many odd pieces of electrical equipment using nonstandard plugs. You need to determine the voltage of a particular outlet. The information on the machine plugged into the outlet reveals that the machine uses 2.50 kW of power and draws a current of 20.8 A. What is the voltage of the outlet?

Given: $\dot{W}_e$ = -2.50 kW = -2,500 W; I = 20.8 A

Solution:

$E = -\frac{\dot{W}_e}{I}$ = **120 V**

2.51) A linear elastic spring with a spring constant of 250 N/m is compressed from a length of 0.25 m to a length of 0.17 m. Determine the work done in this compression process.

Given: k = 250 N/m; x_1 = 0.25 m; x_2 = 0.17 m

Solution:

For a spring with a constant spring constant:

$W_{spring} = \int_{x_1}^{x_2} F \cdot dx = \int_{x_1}^{x_2} kx \cdot dx = \frac{1}{2}k(x_2^2 - x_1^2)$ = ½ (250 N/m) [(0.17 m)^2 – (0.25 m)^2] = **- 4.2 J**

2.52) A linear elastic spring has a spring constant of 300 N/m is compressed from a length of 45 cm to a length of 40 cm. Determine the work done in this compression process.

Given: k = 300 N/m; x_1 = 45 cm; x_2 = 40 cm

Solution:

For a spring with a constant spring constant:

$W_{spring} = \int_{x_1}^{x_2} F \cdot dx = \int_{x_1}^{x_2} kx \cdot dx = \frac{1}{2}k(x_2^2 - x_1^2)$ = ½ (300 N/m) [(0.40 m)^2 – (0.45 m)^2] = **-6.38 J**

2.53) A linear elastic spring with a spring constant of 1.25 kN/m is initially at a length of 0.25 m. The spring expands, doing 40 J of work in the process. What is the final length of the spring?

Given: $k = 1{,}250$ N/m; $x_1 = 0.25$ m; $W_{spring} = 40$ J

Solution:

For a spring with a constant spring constant:

$$W_{spring} = \int_{x_1}^{x_2} F \cdot dx = \int_{x_1}^{x_2} kx \cdot dx = \frac{1}{2}k(x_2^2 - x_1^2)$$

$$x_2 = \sqrt{\frac{2W_{spring}}{k} + x_1^2} = \mathbf{0.356\ m}$$

2.54) Air, with a mass flow rate of 8.0 kg/s, enters a gas turbine. The enthalpy of the air entering the turbine is 825 kJ/kg, the velocity of the air is 325 m/s, and the height of the air above the ground is 2.5 m. The acceleration due to gravity is 9.81 m/s^2. Determine the rate at which energy is being transferred into the gas turbine via mass flow by this air.

Given: $\dot{m} = 8.0$ kg/s; $h = 825$ kJ/kg; $V = 325$ m/s; $z = 2.5$ m; $g = 9.81$ m/s^2

Solution:

$$\dot{E}_{massflow} = \dot{m}\left(h + \frac{1}{2}V^2 + gz\right)$$

= (8.0 kg/s)[825 kJ/kg + ½ (325 m/s)^2/(1000 J/kJ) + (9.81 m/s^2)(2.5 m)/(1000 J/kJ)] = **7,023 kW = 7.02 MW**

2.55) A jet of liquid water with a velocity of 42 m/s and an enthalpy of 62 kJ/kg enters a system at a mass flow rate of 210 kg/s. The potential energy of the water is negligible. What is the rate of energy transfer to the system via mass flow for the water jet?

Given: $\dot{m} = 210$ kg/s; $h = 62$ kJ/kg; $V = 42$ m/s; $z = 0$ m;

Solution:

$$\dot{E}_{massflow} = \dot{m}\left(h + \frac{1}{2}V^2 + gz\right)$$

= (210 kg/s)[62 kJ/kg + ½ (42 m/s)^2/(1000 J/kJ) + 0] = **13,210 kW = 13.2 MW**

2.56) Steam enters a steam turbine at a volumetric flow rate of 3 m^3/s. The enthalpy of the steam is 3070 kJ/kg, and the specific volume of the steam is 0.162 m^3/kg. The velocity of the steam as it enters the steam turbine is 75 m/s, and the height of the entrance above the ground is 3 m. The acceleration due to gravity is 9.81 m/s^2. Determine the rate at which energy is being transferred via mass flow for the steam.

Given: $\dot{V} = 3\ m^3/s$; h = 3070 kJ/kg; v = 0.162 m^3/kg; V = 75 m/s; z = 3 m; g = 9.81 m/s^2

Solution:

First, finding the mass flow: $\dot{m} = \frac{\dot{V}}{v} = 18.5$ kg/s

$$\dot{E}_{massflow} = \dot{m}\left(h + \frac{1}{2}V^2 + gz\right)$$

= (18.5 kg/s)[3070 kJ/kg + ½(75 m/s)^2 + (9.81 m/s^2)(3 m)] = **109.4 MW**

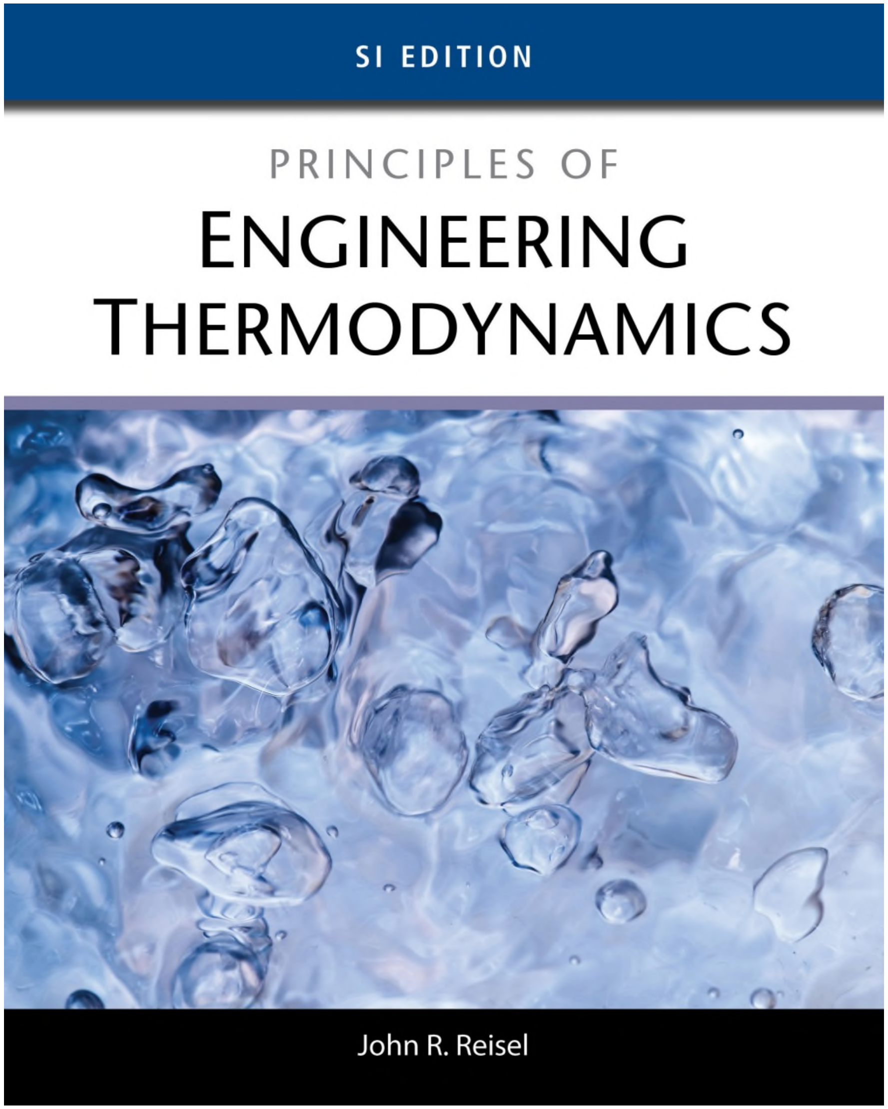
2.57) You can use available steam to add energy to a system via mass flow. The enthalpy of the steam is 2750 kJ/kg, and the velocity of the steam is 120 m/s. The potential energy of the steam is negligible. If you must add 33.1 MW of energy to the system with this steam, what is the required mass flow rate of steam entering the system?

Given: $\dot{E}_{massflow}$ = 33,100 kW; h = 2750 kJ/kg; V = 120 m/s; z = 0 m;

Solution:

$$\dot{E}_{massflow} = \dot{m}\left(h + \frac{1}{2}V^2 + gz\right), \text{ so}$$

$$\dot{m} = \frac{\dot{E}_{massflow}}{h + \frac{1}{2}V^2 + gz} = \frac{33{,}100\ \text{kW}}{2750\,\frac{\text{kJ}}{\text{kg}} + \frac{(\frac{120\ \text{m}}{\text{s}})^2}{2} + 0} = \mathbf{12.0\ kg/s}$$



Chapter 2

The Nature of Energy

Learning Objectives

Upon completion of Chapter 2, you will:

- Understand the nature of energy and the different forms that energy can take;
- Know the methods for transporting energy in or out of a system;
- Recognize the three modes of heat transfer;

Learning Objectives

- Understand the many modes of work;
- Have an approach and framework for solving thermodynamics problems.

What Is Energy?

- *Oxford English Dictionary:*
  - *Energy is the "ability or capacity to produce an effect."*
- SI Units:
  - 1 J = 1 N · 1 m, 1 Joule = 1 Newton · 1 meter.
  - 1 kJ = 1,000 J 1 MJ = 1,000 kJ
- Rate of energy use or change:
  - 1 W = 1 J/s
  - 1 kW = 1,000 W 1MW = 1,000 kW

What Is Energy?

- Units:
  - Standard SI unit of energy is the Joule, equal to a Newton-meter:
  - $1\ J = 1\ N \cdot 1\ m$
- Rate of energy use or change (power):
  - Standard SI unit is the Watt, which equals a Joule per second:
  - $1\ W = 1\ J/s$

Types of Energy

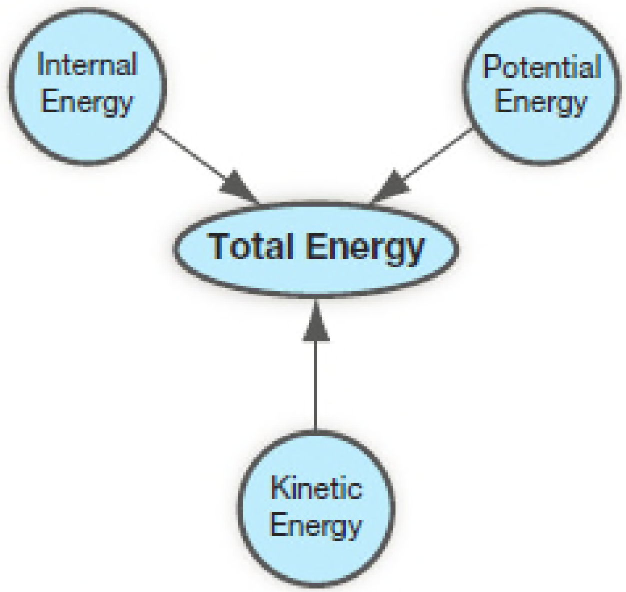


FIGURE 2.1 The total energy of a system is the combination of the system's internal energy, kinetic energy, and potential energy.

Types of Energy

- **Potential energy**

  Potential energy is the energy in a system resulting from the system being in a gravitational field, and is due to the mass of the system being higher than some reference point.

- $PE = m \cdot g \cdot Z$
  - *m: mass of the system*
  - *g: acceleration* due to gravity
  - *z: height of the system* above a reference point

Types of Energy

- **Kinetic Energy**
- Kinetic energy is the energy present in an object as a result of its motion.

$$KE = 1/2mV^2$$

  - *V*: Velocity of the system
- The faster an object is moving, the greater the kinetic energy.

Types of Energy

- Example

Determine the potential energy and the kinetic energy of a 2 kg rock that is falling from a cliff when the rock is 20 m above the ground and traveling at 15 m/s. Assume the cliff is located at sea level.

- Given: $m = 2\ kg,\ z = 20\ m,\ V = 15\ m/s,\ g = 9.81\ m/s^2$
- Solution:

$$PE = mgz = (2\ kg)(9.81\ m/s^2)(20\ m) = 392\ J$$

$$KE = ½\ mV^2 = ½\ (2\ kg)(15\ m/s)^2 = 225\ J$$

Types of Energy

Internal Energy

- The internal energy of a substance is all of the energy present at the molecular level.
- This energy will increase as the temperature of a substance increases.
- Total energy of systems:
  - Extensive: $$E = U + KE + PE = U + \tfrac{1}{2}mV^2 + mgz$$
  - Intensive: $$e = E/m = u + \tfrac{1}{2}V^2 + gz$$
    - where *u* is the specific internal energy. ($u=U/m$)

Types of Energy

- Consider 1 kg of liquid water at 20ºC moving at 50 m/s through a pipe 20 m above the ground. (*u* = 83.9 kJ/kg)
- Contributions of each type of energy:

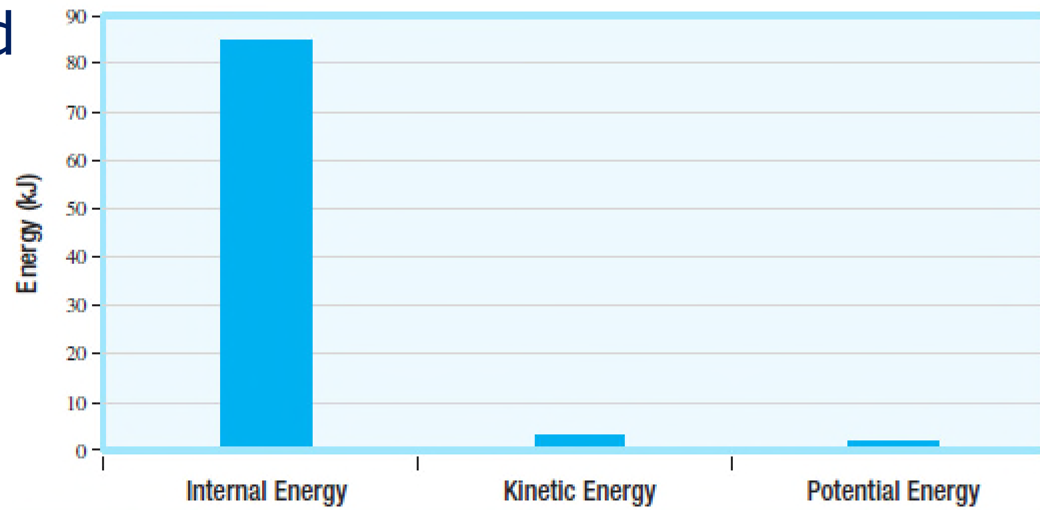


FIGURE 2.5 The internal energy of an object is usually much larger than its kinetic energy or potential energy.

$$U = mu = (1\ \text{kg})(83.9\ \text{kJ/kg}) = 83.9\ \text{kJ}$$

$$KE = \tfrac{1}{2} mV^2 = (0.5)(1\text{kg})(50\text{m/s})^2 = 1250\text{J} = 1.25\text{kJ}$$

$$PE = mgz = (1\ \text{kg})(9.81\ \text{m/s}^2)(20\ \text{m}) = 196\ \text{J} = 0.196\ \text{kJ}$$

Transport of Energy

- If we direct that steam into a turbine, as shown in the figure, the steam can push on the turbine blades, causing the turbine's rotor to spin and produce an effect.

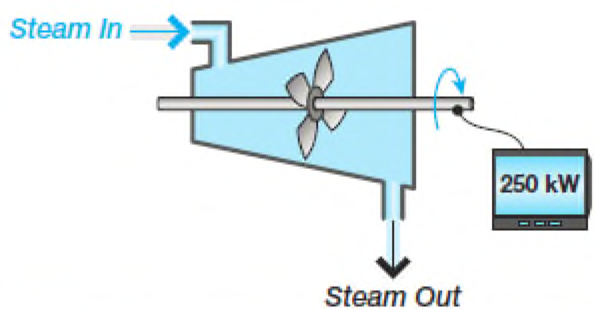


FIGURE 2.7 Flowing steam can cause a turbine shaft to spin as it impinges on the turbine's blades.

- Three general ways of energy transport:
  - Heat transfer,
  - Work,
  - Mass transfer.

Heat Transfer

- The transport of energy via heat transfer is the movement of energy caused by a temperature difference between two systems.

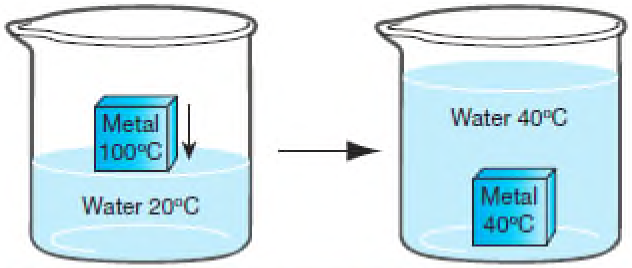


FIGURE 2.8 The placement of a hot object into cool water causes energy to be transferred in the form of heat from the hot object to the water, until thermal equilibrium is reached.

- Q = amount of heat transfer
- $\dot{Q}$ = rate of heat transfer

Heat Transfer

- Modes of heat transfer:
  - Conduction
  - Convection
  - Radiation
- Conduction:
- Conduction is the process of transferring energy from one atom or molecule directly to another atom or molecule.
- What is needed for conduction:
  - a temperature difference between the molecules
  - direct contact between the molecules

Heat Transfer

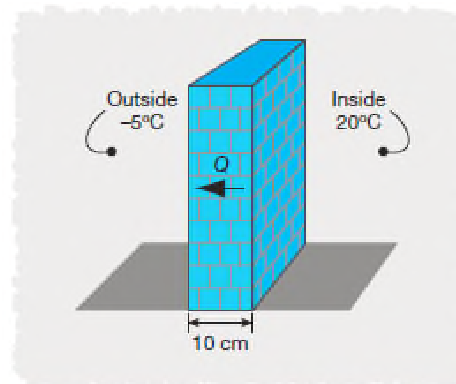


FIGURE 2.11 Heat will transfer via conduction through a wall from an area with a higher temperature to an area with a cooler temperature.

$$\dot{Q}_{cond} = -\kappa A \frac{dT}{dx}$$

Example:

Given:

$T_1 = 20°C$, $T_2 = -5°C$, $x_2 - x_1 = 10$ cm $= 0.10$ m, $A = 8$ m^2, $k = 0.70$ W/m.°C

- Solution:

$$\dot{Q}_{cond} = -\kappa A \frac{dT}{dx} \qquad \frac{dT}{dx} = \frac{T_2 - T_1}{x_2 - x_1} = 250°C/m$$

$$\dot{Q}_{cond} = (-0.70\ W/m \cdot °C)(8\ m^2)(250°C/m) = -1400\ W = -1.40\ kW$$

Heat Transfer

- **Heat Convection**
- In convection, energy is transferred between a solid surface and a moving fluid that is in contact with the surface.
- Processes of heat convection:
  - Heat conduction between the molecules in the moving fluid and the solid surface,
  - Advection from the motions of the fluid.

$$\dot{Q}_{conv} = hA(T_f - T_s)$$

Heat Transfer

- Example:

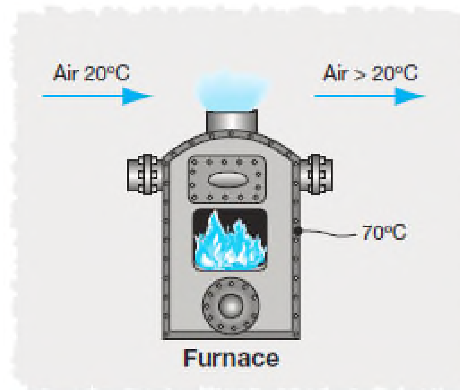


FIGURE 2.13 Cool air will heat up as it flows over a warm surface, via heat convection.

Given:

$$T_f = 20°C,\ T_s = 70°C,\ h = 155\ W/m^2 \cdot K,\ A = 3.5\ m^2$$

Solution:

$$\dot{Q}_{conv} = hA(T_f - T_s)$$

$$\dot{Q}_{conv} = (155\ W/m^2 \cdot K)(3.5\ m^2)(20 - 70)°C = -27{,}100\ W = -27.1\ kW$$

The negative sign indicates that heat is leaving the surface.

Heat Transfer

- **Radiation Heat Transfer**
  - Energy is transferred via photons (or electromagnetic waves).
- As shown in Stefan-Boltzmann law, it is highly dependent on temperature.

$$\dot{Q}_{emit} = \sigma A T_s^4$$

$$\sigma = 5.67 \times 10^{-8}\ W/m^2 \cdot K^4$$

$$\dot{Q}_{rad} = -\ \varepsilon \sigma A (T_s^4 - T_{surr}^4)$$

Heat Transfer

- Example:

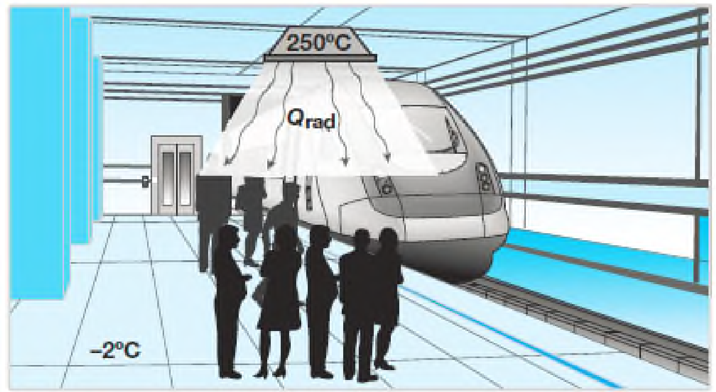


FIGURE 2.15 Heat lamps use radiative heat transfer to keep people warm in outdoor settings in winter.

Given:

$$A = 0.25\,m^2,\ T_s = 250°C = 523\,K,\ T_{surr} = -2°C = 271\,K,\ \varepsilon = 0.92$$

Solution:

$$\dot{Q}_{rad} = -\varepsilon\sigma A(T_s^4 - T_{surr}^4)$$

$$\dot{Q}_{rad} = -(0.92)(5.67 \times 10^{-8}\ \text{W/m}^2.\text{K}^4)(0.25\ \text{m}^2)((523\ \text{K})^4 - (271\ \text{K})^4) = -905\ \text{W}$$

The negative sign indicates that heat is leaving the lamp.

Heat Transfer

- The total amount of heat transfer experienced by a system is the sum of the contributions from the three heat transfer mechanisms.

$$\dot{Q} = \dot{Q}_{cond} + \dot{Q}_{conv} + \dot{Q}_{rad}$$

- Important note!

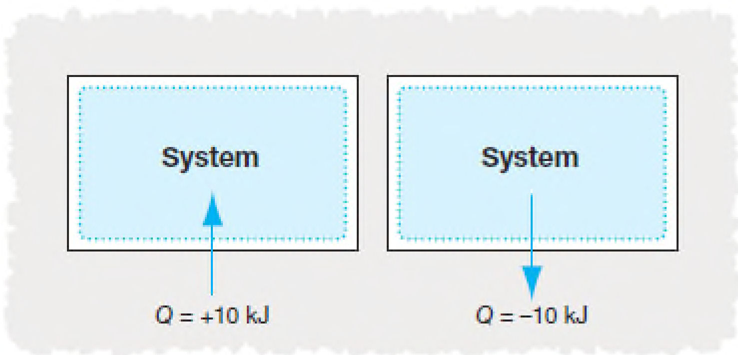


FIGURE 2.17 The sign convention for heat transfer is that heat transfer into a system is positive, and heat transfer out of a system is negative.

Work Transfer

- Work, *W*, is a force, *F*, acting through a displacement, *dx*:

$$W = \int F.dx$$

- The rate at which work is done is called the **power:**

$$\dot{W} = \frac{\delta W}{\delta t}$$

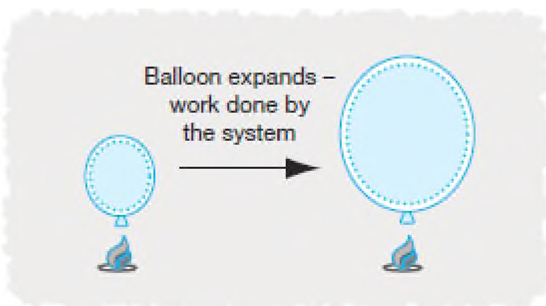


FIGURE 2.18 The change of the volume of a system is a form of work—moving boundary work.

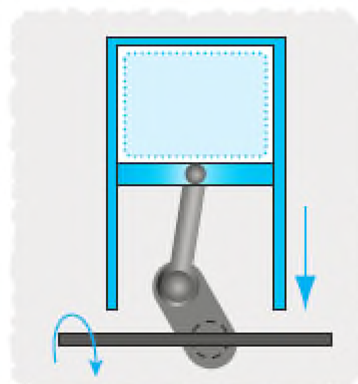


FIGURE 2.19 Through mechanical linkages, the moving boundary work in a piston–cylinder device can be converted to rotating shaft work.

Work Transfer

- For a one-dimensional displacement, such as in a piston–cylinder device, the moving boundary work can be found by:

$$W_{mb} = \int_{x_1}^{x_2} F \cdot dx = \int_{V_1}^{V_2} P \cdot dV$$

$$= p(V_2 - V_2) \qquad (P\text{: constant})$$

$$= P_1 V_1 \ln \frac{V_2}{V_1} \qquad (PV^n = \text{constant}, n = 1)$$

$$= \frac{P_2 V_2 - P_1 V_1}{1 - n} \qquad (PV^n = \text{constant}, n \neq 1)$$

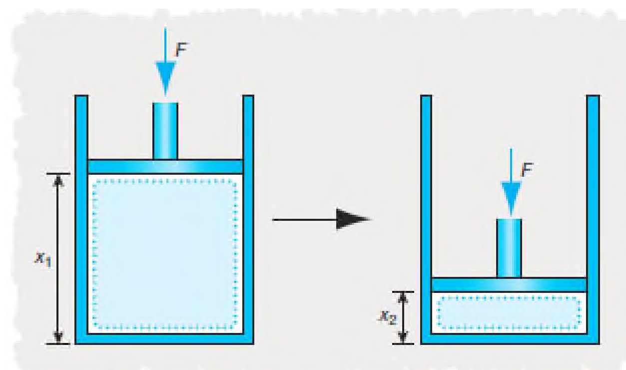


FIGURE 2.20 The force applied on the system by the piston causes the volume to decrease, requiring an input of energy through moving boundary work.

Work Transfer

- Shaft work transfer:
- Example: Rotor on a turbine

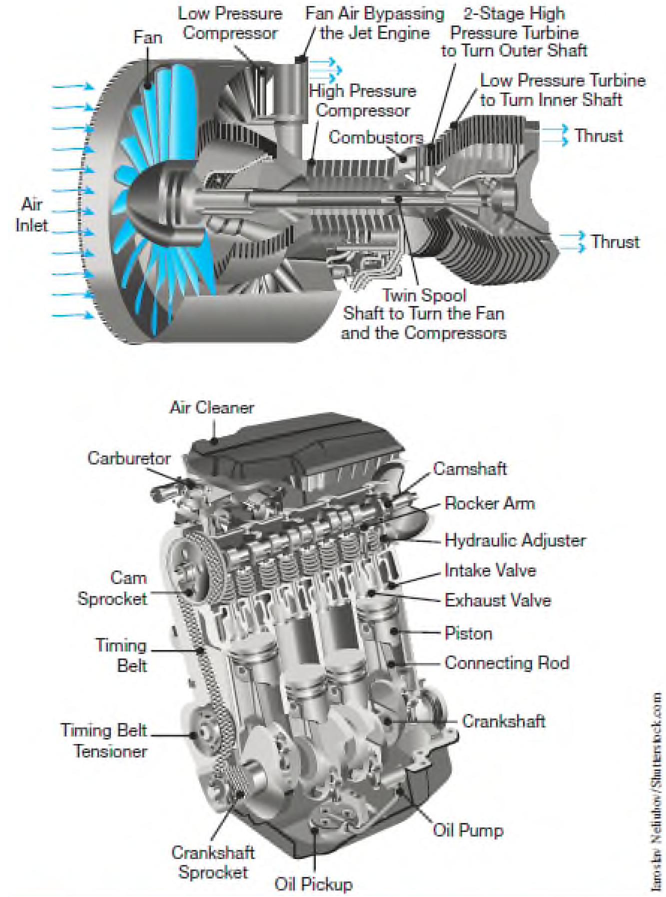


FIGURE 2.22 Rotating shaft work can be found in many devices, including a turbine and the crankshaft of a reciprocating engine.

Work Transfer

Electrical work

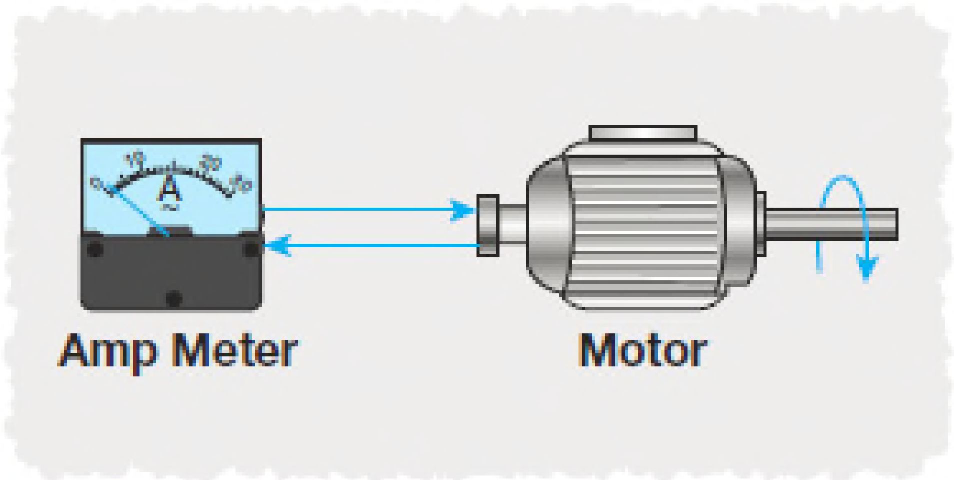


FIGURE 2.23 Electrical work can be converted by motors into rotating shaft work.

Work Transfer

Spring work

$$W_{spring} = \int_{x_1}^{x_2} F \cdot dx$$

$$= \int_{x_1}^{x_2} kx.dx = \frac{1}{2} k (x_2^2 - x_1^2)$$

- There are some additional work modes!

Work Transfer

- Important notes:
  - It may seem odd that the sign convention for the work is opposite that of the heat transfer!

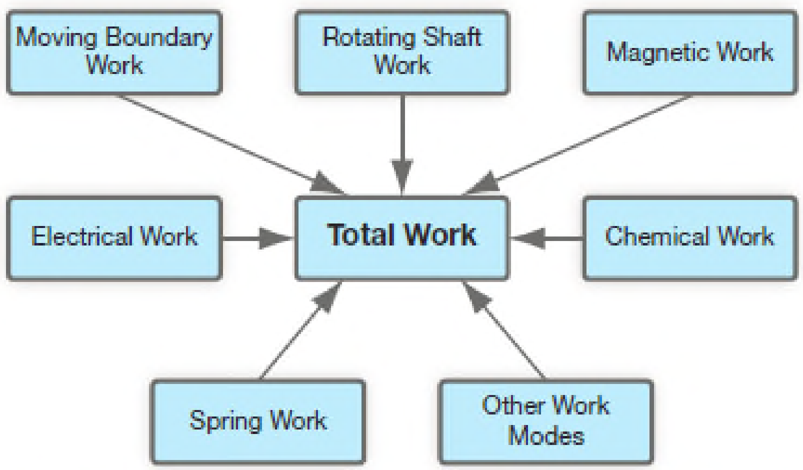


FIGURE 2.24 The total work experienced by a system is the sum of the contributions from all possible work modes.

Work Transfer

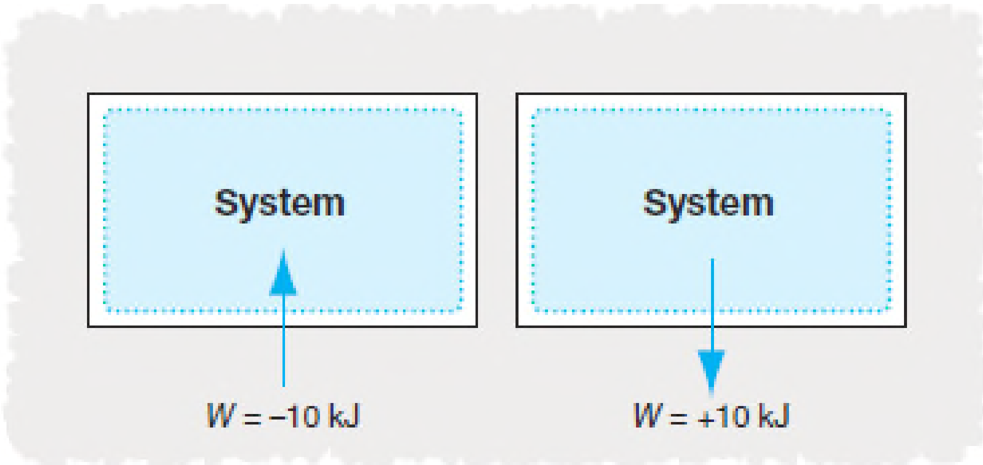


FIGURE 2.25 The sign convention for work is that work into a system is negative and work out of a system is positive.

Energy Transfer via Mass Transfer

- If a substance flows into or out of a system, it carries the substance's energy along with it.

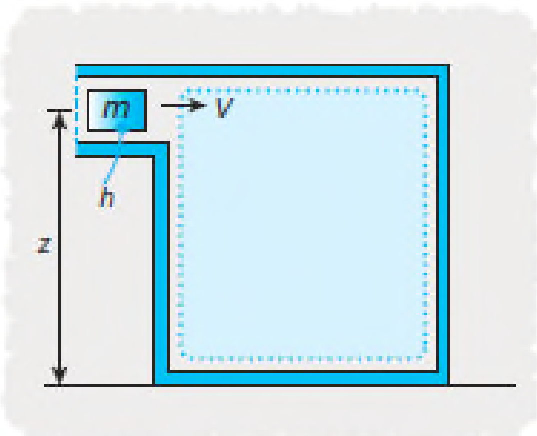


FIGURE 2.28 The enthalpy of the mass flowing into the system is the sum of its internal energy and the flow work.

$$h = H/m = u + Pv$$

$$E_{massflow} = m\left(h + \frac{1}{2}V^2 + gz\right)$$

$$\dot{E}_{massflow} = \dot{m}\left(h + \frac{1}{2}V^2 + gz\right)$$

Analyzing Thermodynamics Systems and Processes

- *Suggested Problem Analysis and Solution Procedure:*

1. Carefully read the problem statement.
2. List all the information that is known about the device or process.
3. List the quantities that are sought in the analysis.
4. Draw a schematic diagram of the device and indicate the system chosen for analysis.
5. Determine whether the thermodynamic system is open, closed, or isolated. Determine the type of substance to be analyzed and what equations of state describe the behavior of the substance.

Analyzing Thermodynamics Systems and Processes

6. Write the appropriate general equations that describe the type of system to be analyzed.
7. Determine what simplifying assumptions are appropriate for this particular analysis.
8. Apply the equations of state to connect the given thermodynamic property data to the properties required in the modified equations.
9. Solve the equations for the desired quantities.
10. Thoughtfully consider the results to determine if the answers make sense from an engineering viewpoint.

Summary

We learned about:

- Different forms of energy that are present in substances
- Three methods of transferring energy into or out of a system
  - Heat transfer
  - Work
  - Energy transfer via mass transfer