Otto Cycle

VI.1. In an ideal gasoline engine, the inlet air pressure and temperature are 95 kPa and 300 K. The engine has a compression ratio of 8 and requires 1500 kJ/kg of heat per cycle.

- Determine the maximal temperature for this cycle.

- Determine its thermal efficiency and the corresponding Carnot efficiency.

VI . 1

Computation of the maximal T° (T_3)

$$T_3 = T_2 + \frac{q_{in}}{c_v}$$

with $T_2 = T_1 \left(\frac{v_1}{v_2}\right)^{k-1}$

$$= 300\,(8)^{1.4-1} = 689.2\,K.$$

Then $T_3 = 689.2 + \frac{1500}{0.717}$

$$T_3 = 2781\ K$$

Thermal efficiency

$$\eta_{otto} = 1 - \frac{1}{r^{k-1}} = 0.56 \text{ or } 56\%.$$

$$\eta_{Carnot} = 1 - \frac{T_1}{T_3} = 0.89 \text{ or } 98\%.$$

VI.2. A four stroke, four cylinders gasoline engine running at 2000 rpm has a compression ratio of 10. The total displacement volume is 2.5 L. Air enters the engine at a pressure of 70 kPa and a temperature of 280 K. 1800 kJ/kg of heat is added per cycle, through a combustion process.

- Determine the power produced by the engine.

IV Determination of the power produced by the engine

We have: $\eta_{otto} = 1 - \frac{1}{r^{k-1}} = 1 - \frac{1}{10^{1.4-1}}$

$\eta_{otto} = 0.602$

Then, $w_{net} = q_{in}\, \eta_{otto}$

$= 1800 \times 0.602$

$w_{net} = 1083.6 \text{ kJ/kg}$

We also have:

$\dot{W} = P_{eff}\, V_{disp}\, \frac{rpm}{60}\, \frac{1}{2}$

We have then to compute the mean effective pressure P_{eff}

$P_{eff} = \frac{w_{net}}{v_1 - v_2} = \frac{w_{net}}{v_1\left(1 - \frac{1}{r}\right)}$

with $v_1 = \frac{RT_1}{P_1} = 0.287\ \frac{280}{70} = 1.148\ \frac{m^3}{kg}$

Then $P_{eff} = \dfrac{1083.6}{1.148\left(1 - \frac{1}{10}\right)} = 1048.8$ kPa.

and

$\dot{W} = 1048.8 \times 0.0025 \; \dfrac{2000}{60} \; \dfrac{1}{2}$

$\dot{W} = 43.7$ kW

Diesel Cycle

1. A diesel engine has a compression ratio of 20:1 with an inlet of 95 kPa, 290 K, state 1, with volume 0.5 L. The maximum cycle temperature is 1800 K. Find the maximum pressure, the net specific work and the thermal efficiency.

Solution:

Compression process (isentropic) from Eqs.8.33-34

$$T_2 = T_1(v_1 / v_2)^{k-1} = 290 \times 20^{0.4} = 961 \text{ K}$$

$$P_2 = 95 \times (20)^{1.4} = 6297.5 \text{ kPa} ; \qquad v_2 = v_1/20 = RT_1/(20\, P_1) = 0.043805$$

$$-{}_1w_2 = u_2 - u_1 \approx C_{vo}(T_2 - T_1) = 0.717\,(961 - 290) = 481.1 \text{ kJ/kg}$$

Combustion at constant P which is the maximum presssure

$$P_3 = P_2 = \mathbf{6298\ kPa} ; \qquad v_3 = v_2\, T_3 / T_2 = 0.043805 \times 1800/961 = 0.08205$$

$${}_2w_3 = P\,(v_3 - v_2) = 6298 \times (0.08215 - 0.043805) = 241.5 \text{ kJ/kg}$$

$${}_2q_3 = u_3 - u_2 + {}_2w_3 = h_3 - h_2 = C_{po}(T_3 - T_2) = 1.004(1800 - 961) = 842.4$$

Expansion process (isentropic) from Eq.8.33

$$T_4 = T_3(v_3 / v_4)^{0.4} = 1800\,(0.08205 / 0.8761)^{0.4} = 698 \text{ K}$$

$${}_3w_4 = u_3 - u_4 \approx C_{vo}(T_3 - T_4) = 0.717\,(1800 - 698) = 790.1 \text{ kJ/kg}$$

Cycle net work and efficiency

$$w_{net} = {}_2w_3 + {}_3w_4 + {}_1w_2 = 241.5 + 790.1 - 481.1 = \mathbf{550.5\ kJ/kg}$$

$$\eta = w_{net} / q_H = 550.5 / 842.4 = \mathbf{0.653}$$

2. At the beginning of compression in a diesel cycle $T = 300$ K, $P = 200$ kPa and after combustion (heat addition) is complete $T = 1500$ K and $P = 7.0$ MPa. Find the compression ratio, the thermal efficiency and the mean effective pressure.

Solution:

Standard Diesel cycle. See P-v and T-s diagrams for state numbers.

Compression process (isentropic) from Eqs.8.33-8.34

$$P_2 = P_3 = 7000 \text{ kPa} \;\Rightarrow\; v_1 / v_2 = (P_2/P_1)^{1/k} = (7000 / 200)^{0.7143} = \mathbf{12.67}$$

$$T_2 = T_1(P_2 / P_1)^{(k-1)/k} = 300(7000 / 200)^{0.2857} = 828.4 \text{ K}$$

Expansion process (isentropic) first get the volume ratios

$$v_3 / v_2 = T_3 / T_2 = 1500 / 828.4 = 1.81$$

$$v_4 / v_3 = v_1 / v_3 = (v_1 / v_2)(v_2 / v_3) = 12.67 / 1.81 = 7$$

The exhaust temperature follows from Eq.8.33

$$T_4 = T_3(v_3 / v_4)^{k-1} = (1500 / 7)^{0.4} = 688.7 \text{ K}$$

$$q_L = C_{vo}(T_4 - T_1) = 0.717(688.7 - 300) = 278.5 \text{ kJ/kg}$$

$$q_H = h_3 - h_2 \approx C_{po}(T_3 - T_2) = 1.004(1500 - 828.4) = 674 \text{ kJ/kg}$$

Overall performance

$$\eta = 1 - q_L / q_H = 1 - 278.5 / 674 = \mathbf{0.587}$$

$$w_{net} = q_{net} = q_H - q_L = 674 - 278.5 = 395.5 \text{ kJ/kg}$$

$$v_{max} = v_1 = R\,T_1 / P_1 = 0.287 \times 300 / 200 = 0.4305 \text{ m}^3\text{/kg}$$

$$v_{min} = v_{max} / (v_1 / v_2) = 0.4305 / 12.67 = 0.034 \text{ m}^3\text{/kg}$$

$$P_{meff} = \frac{w_{net}}{v_{max} - v_{min}} = 395.5 / (0.4305 - 0.034) = \mathbf{997\ kPa}$$

9–61 Repeat Prob. 9–60 using nitrogen as the working fluid.

9–62 An air-standard dual cycle has a compression ratio of 18 and a cutoff ratio of 1.1. The pressure ratio during constant-volume heat addition process is 1.1. At the beginning of the compression, P_1 = 90 kPa, T_1 = 18°C, and V_1 = 0.003 m³. How much power will this cycle produce when it is executed 4000 times per minute? Use constant specific heats at room temperature.

9–63 Repeat Prob. 9–62 if the isentropic compression efficiency is 85 percent and the isentropic expansion efficiency is 90 percent. *Answer:* 9.26 kW

9–64 An ideal dual cycle has a compression ratio of 15 and a cutoff ratio of 1.4. The pressure ratio during constant-volume heat addition process is 1.1. The state of the air at the beginning of the compression is P_1 =98 kPa and T_1 = 24°C. Calculate the cycle's net specific work, specific heat addition, and thermal efficiency. Use constant specific heats at room temperature.

9–65 Develop an expression for the thermal efficiency of a dual cycle when operated such that $r_c = r_p$ where r_c is the cutoff ratio and r_p is the pressure ratio during the constant-volume heat addition process. What is the thermal efficiency of such engine when the compression ratio is 20 and $r_p = 2$?

9–66 How can one change r_p in Prob. 9–65 so that the same thermal efficiency is maintained when the compression ratio is reduced?

9–67 A six-cylinder, four-stroke, 4.5-L compression-ignition engine operates on the ideal diesel cycle with a compression ratio of 17. The air is at 95 kPa and 55°C at the beginning of the compression process and the engine speed is 2000 rpm. The engine uses light diesel fuel with a heating value of 42,500 kJ/kg, an air–fuel ratio of 24, and a combustion efficiency of 98 percent. Using constant specific heats at 850 K, determine (*a*) the maximum temperature in the cycle and the cutoff ratio (*b*) the net work output per cycle and the thermal efficiency, (*c*) the mean effective pressure, (*d*) the net power output, and (*e*) the specific fuel consumption, in g/kWh, defined as the ratio of the mass of the fuel consumed to the net work produced. *Answers:* (*a*) 2383 K, 2.7 (*b*) 4.36 kJ, 0.543 (*c*) 969 kPa, (*d*) 72.7 kW, (*e*) 159 g/kWh

Stirling and Ericsson Cycles

9–68C Consider the ideal Otto, Stirling, and Carnot cycles operating between the same temperature limits. How would you compare the thermal efficiencies of these three cycles?

9–69C Consider the ideal Diesel, Ericsson, and Carnot cycles operating between the same temperature limits. How would you compare the thermal efficiencies of these three cycles?

9–70C What cycle is composed of two isothermal and two constant-volume processes?

9–71C How does the ideal Ericsson cycle differ from the Carnot cycle?

9–72 Consider an ideal Ericsson cycle with air as the working fluid executed in a steady-flow system. Air is at 27°C and 120 kPa at the beginning of the isothermal compression process, during which 150 kJ/kg of heat is rejected. Heat transfer to air occurs at 1200 K. Determine (*a*) the maximum pressure in the cycle, (*b*) the net work output per unit mass of air, and (*c*) the thermal efficiency of the cycle. *Answers:* (*a*) 685 kPa, (*b*) 450 kJ/kg, (*c*) 75 percent

9–73 An ideal Stirling cycle operates with 1 kg of air between thermal energy reservoirs at 27°C and 527°C. The maximum cycle pressure is 2000 kPa and the minimum cycle pressure is 100 kPa. Determine the net work produced each time this cycle is executed, and the cycle's thermal efficiency.

9–74 Determine the external rate of heat input and power produced by the Stirling cycle of Prob. 9–73 when it is repeated 500 times per minute. *Answers:* 3855 kW, 2409 kW

9–75 An air-standard Stirling cycle operates with a maximum pressure of 4200 kPa and a minimum pressure of 70 kPa. The maximum volume of the air is 10 times the minimum volume. The temperature during the heat rejection process is 37°C. Calculate the specific heat added to and rejected by this cycle, as well as the net specific work produced by the cycle. Use constant specific heats at room temperature.

9–76 How much heat is stored (and recovered) in the regenerator of Prob. 9–75?

9–77 An Ericsson cycle operates between thermal energy reservoirs at 627°C and 7°C while producing 500 kW of power. Determine the rate of heat addition to this cycle when it is repeated 2000 times per minute. *Answer:* 726 kW

9–78 If the cycle of Prob. 9–77 is repeated 3000 times per minute while the heat added per cycle remains the same, how much power will the cycle produce?

Ideal and Actual Gas-Turbine (Brayton) Cycles

9–79C Why are the back work ratios relatively high in gas-turbine engines?

9–80C What four processes make up the simple ideal Brayton cycle?

9–81C For fixed maximum and minimum temperatures, what is the effect of the pressure ratio on (*a*) the thermal efficiency and (*b*) the net work output of a simple ideal Brayton cycle?

9–82C What is the back work ratio? What are typical back work ratio values for gas-turbine engines?

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9–83C How do the inefficiencies of the turbine and the compressor affect (*a*) the back work ratio and (*b*) the thermal efficiency of a gas-turbine engine?

9–84 A simple ideal Brayton cycle with air as the working fluid has a pressure ratio of 10. The air enters the compressor at 290 K and the turbine at 1100 K. Accounting for the variation of specific heats with temperature, determine (*a*) the air temperature at the compressor exit, (*b*) the back work ratio, and (*c*) the thermal efficiency.

9–85 A simple Brayton cycle using air as the working fluid has a pressure ratio of 8. The minimum and maximum temperatures in the cycle are 310 and 1160 K. Assuming an isentropic efficiency of 75 percent for the compressor and 82 percent for the turbine, determine (*a*) the air temperature at the turbine exit, (*b*) the net work output, and (*c*) the thermal efficiency.

9–86 Reconsider Prob. 9–85. Using EES (or other) software, allow the mass flow rate, pressure ratio, turbine inlet temperature, and the isentropic efficiencies of the turbine and compressor to vary. Assume the compressor inlet pressure is 100 kPa. Develop a general solution for the problem by taking advantage of the diagram window method for supplying data to EES software.

9–87 Repeat Prob. 9–86 using constant specific heats at room temperature.

9–88 A simple ideal Brayton cycle operates with air with minimum and maximum temperatures of 27°C and 727°C. It is designed so that the maximum cycle pressure is 2000 kPa and the minimum cycle pressure is 100 kPa. Determine the net work produced per unit mass of air each time this cycle is executed and the cycle's thermal efficiency. Use constant specific heats at room temperature.

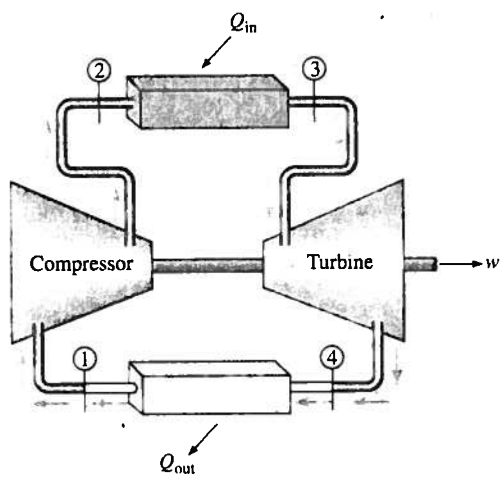

FIGURE P9–88

9–89 Repeat Prob. 9–88 when the isentropic efficiency of the turbine is 90 percent.

9–90 Repeat Prob. 9–88 when the isentropic efficiency of the turbine is 90 percent and that of the compressor is 80 percent.

9–91 Repeat Prob. 9–88 when the isentropic efficiencies of the turbine and compressor are 90 percent and 80 percent, respectively, and there is a 50-kPa pressure drop across the combustion chamber. *Answers:* 7.3 kJ, 3.8 percent

9–92 Air is used as the working fluid in a simple ideal Brayton cycle that has a pressure ratio of 12, a compressor inlet temperature of 300 K, and a turbine inlet temperature of 1000 K. Determine the required mass flow rate of air for a net power output of 70 MW, assuming both the compressor and the turbine have an isentropic efficiency of (*a*) 100 percent and (*b*) 85 percent. Assume constant specific heats at room temperature. *Answers:* (*a*) 352 kg/s, (*b*) 1037 kg/s

9–93 A stationary gas-turbine power plant operates on a simple ideal Brayton cycle with air as the working fluid. The air enters the compressor at 95 kPa and 290 K and the turbine at 760 kPa and 1100 K. Heat is transferred to air at a rate of 35,000 kJ/s. Determine the power delivered by this plant (*a*) assuming constant specific heats at room temperature and (*b*) accounting for the variation of specific heats with temperature.

9–94 Air enters the compressor of a gas-turbine engine at 300 K and 100 kPa, where it is compressed to 700 kPa and 580 K. Heat is transferred to air in the amount of 950 kJ/kg before it enters the turbine. For a turbine efficiency of 86 percent, determine (*a*) the fraction of the turbine work output used to drive the compressor and (*b*) the thermal efficiency. Assume variable specific heats for air.

9–95 Repeat Prob. 9–94 using constant specific heats at room temperature.

9–96 An aircraft engine operates on a simple ideal Brayton cycle with a pressure ratio of 10. Heat is added to the cycle at a rate of 500 kW; air passes through the engine at a rate of 1 kg/s; and the air at the beginning of the compression is at 70 kPa and 0°C. Determine the power produced by this engine and its thermal efficiency. Use constant specific heats at room temperature.

9–97 Repeat Prob. 9–96 for a pressure ratio of 15.

9–98 A gas-turbine power plant operates on the simple Brayton cycle between the pressure limits of 100 and 1200 kPa. The working fluid is air, which enters the compressor at 30°C at a rate of 150 m^3/min and leaves the turbine at 500°C. Using variable specific heats for air and assuming a compressor isentropic efficiency of 82 percent and a turbine isentropic efficiency of 88 percent, determine (*a*) the net power output, (*b*) the back work ratio, and (*c*) the thermal efficiency. *Answers:* (*a*) 659 kW, (*b*) 0.625, (*c*) 0.319

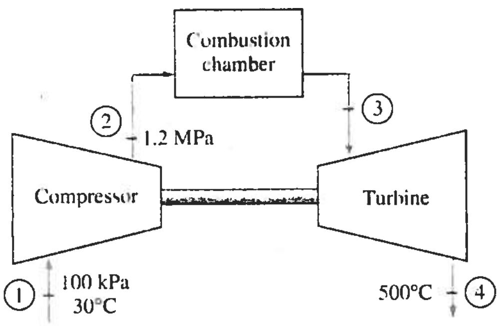

FIGURE P9–98

Brayton Cycle with Regeneration

9–99C How does regeneration affect the efficiency of a Brayton cycle, and how does it accomplish it?

9–100C Somebody claims that at very high pressure ratios, the use of regeneration actually decreases the thermal efficiency of a gas-turbine engine. Is there any truth in this claim? Explain.

9–101C Define the effectiveness of a regenerator used in gas-turbine cycles.

9–102C In an ideal regenerator, is the air leaving the compressor heated to the temperature at (*a*) turbine inlet, (*b*) turbine exit, (*c*) slightly above turbine exit?

9–103C In 1903, Aegidius Elling of Norway designed and built an 11-hp gas turbine that used steam injection between the combustion chamber and the turbine to cool the combustion gases to a safe temperature for the materials available at the time. Currently there are several gas-turbine power plants that use steam injection to augment power and improve thermal efficiency. For example, the thermal efficiency of the General Electric LM5000 gas turbine is reported to increase from 35.8 percent in simple-cycle operation to 43 percent when steam injection is used. Explain why steam injection increases the power output and the efficiency of gas turbines. Also, explain how you would obtain the steam.

9–104 A gas turbine for an automobile is designed with a regenerator. Air enters the compressor of this engine at 100 kPa and 20°C. The compressor pressure ratio is 8; the maximum cycle temperature is 800°C; and the cold air stream leaves the regenerator 10°C cooler than the hot air stream at the inlet of the regenerator. Assuming both the compressor and the turbine to be isentropic, determine the rates of heat addition and rejection for this cycle when it produces 150 kW. Use constant specific heats at room temperature. *Answers:* 303 kW, 153 kW

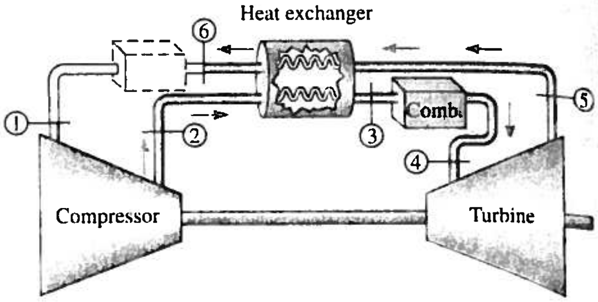

FIGURE P9–104

9–105 Rework Prob. 9–104 when the compressor isentropic efficiency is 87 percent and the turbine isentropic efficiency is 93 percent.

9–106 A gas turbine engine operates on the ideal Brayton cycle with regeneration, as shown in Fig. P9–104. Now the regenerator is rearranged so that the air streams of states 2 and 5 enter at one end of the regenerator and streams 3 and 6 exit at the other end (i.e., parallel flow arrangement of a heat exchanger). Consider such a system when air enters the compressor at 100 kPa and 20°C; the compressor pressure ratio is 7; the maximum cycle temperature is 727°C; and the difference between the hot and cold air stream temperatures is 6°C at the end of the regenerator where the cold stream leaves the regenerator. Is the cycle arrangement shown in the figure more or less efficient than this arrangement? Assume both the compressor and the turbine are isentropic, and use constant specific heats at room temperature.

9–107 An ideal regenerator ($T_3 = T_5$) is added to a simple ideal Brayton cycle (see Fig. P9–104). Air enters the compressor of this cycle at 90 kPa and 10°C; the pressure ratio is 8; and the maximum cycle temperature is 815°C. What is the thermal efficiency of this cycle? Use constant specific heats at room temperature. What would the thermal efficiency of the cycle be without the regenerator?

9–108 Develop an expression for the thermal efficiency of an ideal Brayton cycle with an ideal regenerator of effectiveness 100 percent. Use constant specific heats at room temperature.

9–109 The idea of using gas turbines to power automobiles was conceived in the 1930s, and considerable research was done in the 1940s and 1950s to develop automotive gas turengines by major automobile manufacturers such as the Chrysler and Ford corporations in the United States and Rover in the United Kingdom. The world's first gas-turbine-powered automobile, the 200-hp Rover Jet 1, was built in 1950 in the United Kingdom. This was followed by the production of the Plymouth Sport Coupe by Chrysler in 1954 under the leadership of G. J. Huebner. Several hundred gas-turbine-powered Plymouth cars were built in the early 1960s for demonstration purposes and were loaned to a select group of people to gather field experience. The users had no complaints other than slow acceleration. But the cars were never mass-produced because of the high production (especially material) costs and the failure to satisfy the provisions of the 1966 Clean Air Act.

A gas-turbine-powered Plymouth car built in 1960 had a turbine inlet temperature of 927°C, a pressure ratio of 4, and a regenerator effectiveness of 0.9. Using isentropic efficiencies of 80 percent for both the compressor and the turbine, determine the thermal efficiency of this car. Also, determine the mass flow rate of air for a net power output of 70 kW. Assume the ambient air to be at 300 K and 100 kPa.

9–110 The 7FA gas turbine manufactured by General Electric is reported to have an efficiency of 35.9 percent in the simple-cycle mode and to produce 159 MW of net power. The pressure ratio is 14.7 and the turbine inlet temperature is 1288°C. The mass flow rate through the turbine is 1,536,000 kg/h. Taking the ambient conditions to be 20°C and 100 kPa, determine the isentropic efficiency of the turbine and the compressor. Also, determine the thermal efficiency of this gas turbine if a regenerator with an effectiveness of 80 percent is added.

9–111 Reconsider Prob. 9–110. Using EES (or other) software, develop a solution that allows different isentropic efficiencies for the compressor and turbine and study the effect of the isentropic efficiencies on net work done and the heat supplied to the cycle. Plot the *T-s* diagram for the cycle.

9–112 A Brayton cycle with regeneration using air as the working fluid has a pressure ratio of 7. The minimum and maximum temperatures in the cycle are 310 and 1150 K. Assuming an isentropic efficiency of 75 percent for the compressor and 82 percent for the turbine and an effectiveness of 65 percent for the regenerator, determine (*a*) the air temperature at the turbine exit, (*b*) the net work output, and (*c*) the thermal efficiency. *Answers: (a) 783 K, (b) 108.1 kJ/kg, (c) 22.5 percent*

9–113 A stationary gas-turbine power plant operates on an ideal regenerative Brayton cycle (ϵ = 100 percent) with air as the working fluid. Air enters the compressor at 95 kPa and 290 K and the turbine at 760 kPa and 1100 K. Heat is transferred to air from an external source at a rate of 75,000 kJ/s. Determine the power delivered by this plant (*a*) assuming constant specific heats for air at room temperature and (*b*) accounting for the variation of specific heats with temperature.

9–114 Air enters the compressor of a regenerative gas-turbine engine at 300 K and 100 kPa, where it is compressed to 800 kPa and 580 K. The regenerator has an effectiveness of 72 percent, and the air enters the turbine at 1200 K. For a turbine efficiency of 86 percent, determine (*a*) the amount of heat transfer in the regenerator and (*b*) the thermal efficiency. Assume variable specific heats for air. *Answers: (a) 152.5 kJ/kg, (b) 36.0 percent*

9–115 Repeat Prob. 9–114 using constant specific heats at room temperature.

9–116 Repeat Prob. 9–114 for a regenerator effectiveness of 70 percent.

Brayton Cycle with Intercooling, Reheating, and Regeneration

9–117C Under what modifications will the ideal simple gas-turbine cycle approach the Ericsson cycle?

9–118C The single-stage compression process of an ideal Brayton cycle without regeneration is replaced by a multistage compression process with intercooling between the same pressure limits. As a result of this modification,

(*a*) Does the compressor work increase, decrease, or remain the same?

(*b*) Does the back work ratio increase, decrease, or remain the same?

(*c*) Does the thermal efficiency increase, decrease, or remain the same?

9–119C The single-stage expansion process of an ideal Brayton cycle without regeneration is replaced by a multistage expansion process with reheating between the same pressure limits. As a result of this modification,

(*a*) Does the turbine work increase, decrease, or remain the same?

(*b*) Does the back work ratio increase, decrease, or remain the same?

(*c*) Does the thermal efficiency increase, decrease, or remain the same?

9–120C A simple ideal Brayton cycle without regeneration is modified to incorporate multistage compression with intercooling and multistage expansion with reheating, without changing the pressure or temperature limits of the cycle. As a result of these two modifications,

(*a*) Does the net work output increase, decrease, or remain the same?

(*b*) Does the back work ratio increase, decrease, or remain the same?

(*c*) Does the thermal efficiency increase, decrease, or remain the same?

(*d*) Does the heat rejected increase, decrease, or remain the same?

9–121C A simple ideal Brayton cycle is modified to incorporate multistage compression with intercooling, multistage expansion with reheating, and regeneration without changing the pressure limits of the cycle. As a result of these modifications,

(*a*) Does the net work output increase, decrease, or remain the same?

(*b*) Does the back work ratio increase, decrease, or remain the same?

(*c*) Does the thermal efficiency increase, decrease, or remain the same?

(*d*) Does the heat rejected increase, decrease, or remain the same?

9–122C For a specified pressure ratio, why does multistage compression with intercooling decrease the compressor work, and multistage expansion with reheating increase the turbine work?

9–123C In an ideal gas-turbine cycle with intercooling, reheating, and regeneration, as the number of compression and expansion stages is increased, the cycle thermal efficiency approaches (*a*) 100 percent, (*b*) the Otto cycle efficiency, or (*c*) the Carnot cycle efficiency.

9–124 Consider an ideal gas-turbine cycle with two stages of compression and two stages of expansion. The pressure ratio across each stage of the compressor and turbine is 3. The air enters each stage of the compressor at 300 K and each stage of the turbine at 1200 K. Determine the back work ratio and the thermal efficiency of the cycle, assuming (*a*) no regenerator is used and (*b*) a regenerator with 75 percent effectiveness is used. Use variable specific heats.

9–125 Repeat Problem 9–124, assuming an efficiency of 80 percent for each compressor stage and an efficiency of 85 percent for each turbine stage.

9–126 Air enters a gas turbine with two stages of compression and two stages of expansion at 100 kPa and 17°C. This system uses a regenerator as well as reheating and intercooling. The pressure ratio across each compressor is 4; 300 kJ/kg of heat are added to the air in each combustion chamber; and the regenerator operates perfectly while increasing the temperature of the cold air by 20°C. Determine this system's thermal efficiency. Assume isentropic operations for all compressor and the turbine stages and use constant specific heats at room temperature.

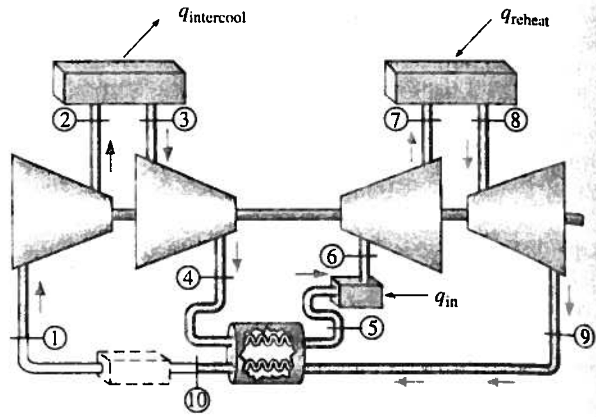

FIGURE P9–126

9–127 Repeat Prob. 9–126 for the case of three stages of compression with intercooling and three stages of expansion with reheating. *Answer: 40.1 percent*

9–128 How much would the thermal efficiency of the cycle in Prob. 9–126 change if the temperature of the cold-air stream leaving the regenerator is 40°C lower than the temperature of the hot-air stream entering the regenerator?

Jet-Propulsion Cycles

9–129C What is propulsive power? How is it related to thrust?

9–130C What is propulsive efficiency? How is it determined?

9–131C Is the effect of turbine and compressor irreversibilities of a turbojet engine to reduce (*a*) the net work, (*b*) the thrust, or (*c*) the fuel consumption rate?

9–132 A turboprop-aircraft propulsion engine operates where the air is at 55 kPa and −23°C, on an aircraft flying at a speed of 180 m/s. The Brayton cycle pressure ratio is 10 and the air temperature at the turbine inlet is 505°C. The propeller diameter is 3 m and the mass flow rate through the propeller is 20 times that through the compressor. Determine the thrust force generated by this propulsion system. Assume ideal operation for all components and constant specific heats at room temperature.

9–133 How much change would result in the thrust of Prob. 9–132 if the propeller diameter were reduced to 2.4 m while maintaining the same mass flow rate through the compressor. Note: the mass flow rate ratio will no longer be 20.

9–134 A turbofan engine operating on an aircraft flying at 200 m/s at an altitude where the air is at 50 kPa and −20°C, is to produce 50,000 N of thrust. The inlet diameter of this engine is 2.5 m; the compressor pressure ratio is 12; and the mass flow rate ratio is 8. Determine the air temperature at the fan outlet needed to produce this thrust. Assume ideal operation for all components and constant specific heats at room temperature. *Answer:* 233 K

9–135 A pure jet engine propels an aircraft at 300 m/s through air at 60 kPa and 0°C. The inlet diameter of this engine is 2 m, the compressor pressure ratio is 10, and the temperature at the turbine inlet is 450°C. Determine the velocity at the exit of this engine's nozzle and the thrust produced. Assume ideal operation for all components and constant specific heats at room temperature.

9–136 A turbojet aircraft is flying with a velocity of 320 m/s at an altitude of 9150 m, where the ambient conditions are 32 kPa and −32°C. The pressure ratio across the compressor is 12, and the temperature at the turbine inlet is 1400 K. Air enters the compressor at a rate of 60 kg/s, and the jet fuel has a heating value of 42,700 kJ/kg. Assuming ideal operation for all components and constant specific heats for air at room temperature, determine (*a*) the velocity of the exhaust gases, (*b*) the propulsive power developed, and (*c*) the rate of fuel consumption.

9–137 Repeat Prob. 9–136 using a compressor efficiency of 80 percent and a turbine efficiency of 85 percent.

9–138 Consider an aircraft powered by a turbojet engine that has a pressure ratio of 12. The aircraft is stationary on the ground, held in position by its brakes. The ambient air is at 27°C and 95 kPa and enters the engine at a rate of 10 kg/s. The jet fuel has a heating value of 42,700 kJ/kg, and it is burned completely at a rate of 0.2 kg/s. Neglecting the effect of the diffuser and disregarding the slight increase in mass at the engine exit as well as the inefficiencies of engine components, determine the force that must be applied on the brakes to hold the plane stationary. *Answer:* 9089 N

9–139 EES Reconsider Prob. 9–138. In the problem statement, replace the inlet mass flow rate by an inlet volume flow rate of 9.063 m^3/s. Using EES (or other) software, investigate the effect of compressor inlet temperature in the range of −20 to 30°C on the force that must be applied to the brakes to hold the plane stationary. Plot this force as a function of compressor inlet temperature.

9–140 Air at 7°C enters a turbojet engine at a rate of 16 kg/s and at a velocity of 300 m/s (relative to the engine). Air is heated in the combustion chamber at a rate 15,000 kJ/s and it leaves the engine at 427°C. Determine the thrust produced by this turbojet engine. (*Hint:* Choose the entire engine as your control volume.)

Second-Law Analysis of Gas Power Cycles

9–141 Calculate the exergy destruction associated with each of the processes of the Brayton cycle described in Prob. 9–85, assuming a source temperature of 1600 K and a sink temperature of 310 K.

9–142 Determine the exergy destruction for each of the processes of the gas turbine cycle in Prob. 9–105. The temperature of the hot reservoir is the same as the maximum cycle temperature and the temperature of the cold reservoir is the same as the minimum cycle temperature.

9–143 Determine the total exergy destruction associated with the Brayton cycle described in Prob. 9–112, assuming a source temperature of 1800 K and a sink temperature of 310 K. Also, determine the exergy of the exhaust gases at the exit of the regenerator.

9–144 EES Reconsider Prob. 9–143. Using EES (or other) software, investigate the effect of varying the cycle pressure ratio from 6 to 14 on the total exergy destruction for the cycle and the exergy of the exhaust gas leaving the regenerator. Plot these results as functions of pressure ratio. Discuss the results.

9–145 Calculate the lost work potential for each process of Prob. 9–128. The temperature of the hot reservoir is the same as the maximum cycle temperature and the temperature of the cold reservoir is the same as the minimum cycle temperature.

9–146 A gas-turbine power plant operates on the simple Brayton cycle between the pressure limits of 100 and 700 kPa. Air enters the compressor at 30°C at a rate of 12.6 kg/s and leaves at 260°C. A diesel fuel with a heating value of 42,000 kJ/kg is burned in the combustion chamber with an air–fuel ratio of 60 and a combustion efficiency of 97 percent. Combustion gases leave the combustion chamber and enter the turbine whose isentropic efficiency is 85 percent. Treating the combustion gases as air and using constant specific heats at 500°C, determine (*a*) the isentropic efficiency of the compressor, (*b*) the net power output and the back work ratio, (*c*) the thermal efficiency, and (*d*) the second-law efficiency.

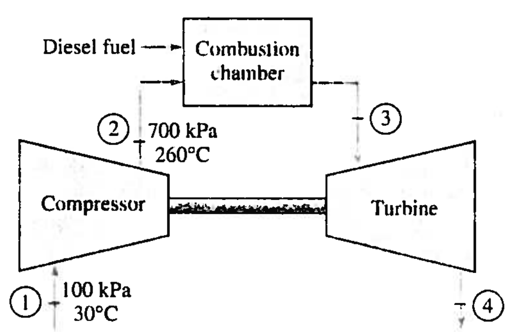

FIGURE P9–146

9–147 A four-cylinder, four-stroke, 2.8-liter modern, high-speed compression-ignition engine operates on the ideal dual cycle with a compression ratio of 14. The air is at 95 kPa and 55°C at the beginning of the compression process and the engine speed is 3500 rpm. Equal amounts of fuel are burned at constant volume and at constant pressure. The maximum allowable pressure in the cycle is 9 MPa due to material strength limitations. Using constant specific heats at 850 K, determine (*a*) the maximum temperature in the cycle, (*b*) the net work output and the thermal efficiency, (*c*) the mean effective pressure, and (*d*) the net power output. Also, determine (*e*) the second-law efficiency of the cycle and the rate of exergy output with the exhaust gases when they are purged. *Answers: (a) 3254 K, (b) 1349 kJ/kg, 0.587, (c) 1466 kPa, (d) 120 kW, (e) 0.546, 50.4 kW*

Review Problems

9–148 A four-stroke turbocharged V-16 diesel engine built by GE Transportation Systems to power fast trains produces 3500 hp at 1200 rpm. Determine the amount of power produced per cylinder per (*a*) mechanical cycle and (*b*) thermodynamic cycle.

9–149 Consider a simple ideal Brayton cycle operating between the temperature limits of 300 and 1500 K. Using constant specific heats at room temperature, determine the pressure ratio for which the compressor and the turbine exit temperatures of air are equal.

9–150 An air-standard cycle with variable specific heats is executed in a closed system with 0.003 kg of air, and it consists of the following three processes:

1-2 Isentropic compression from 100 kPa and 27°C to 700 kPa

2-3 P = *constant* heat addition to initial specific volume

3-1 v = *constant* heat rejection to initial state

(*a*) Show the cycle on P-v and T-s diagrams.

(*b*) Calculate the maximum temperature in the cycle.

(*c*) Determine the thermal efficiency.

Answers: (b) 2100 K, (c) 15.3 percent

9–151 Repeat Prob. 9–150 using constant specific heats at room temperature.

9–152 A four-cylinder spark-ignition engine has a compression ratio of 8, and each cylinder has a maximum volume of 0.6 L. At the beginning of the compression process, the air is at 98 kPa and 17°C, and the maximum temperature in the cycle is 1800 K. Assuming the engine to operate on the ideal Otto cycle, determine (*a*) the amount of heat supplied per cylinder, (*b*) the thermal efficiency, and (*c*) the number of revolutions per minute required for a net power output of 60 kW. Assume variable specific heats for air.

9–153 Reconsider Prob. 9–152. Using EES (or other) software, study the effect of varying the compression ratio from 5 to 11 on the net work done and the efficiency of the cycle. Plot the P-v and T-s diagrams for the cycle, and discuss the results.

9–154 An ideal gas Carnot cycle uses helium as the working fluid and rejects heat to a lake at 15°C. Determine the pressure ratio, compression ratio, and minimum temperature of the heat source for this cycle to have a thermal efficiency of 50 percent. *Answers: 5.65, 2.83, 576 K*

9–155 Repeat Prob. 9–154 when the lake is at 10°C and the Carnot cycle's thermal efficiency is to be 60 percent.

9–156 A typical hydrocarbon fuel produces 42,000 kJ/kg of heat when used in a spark-ignition engine. Determine the compression ratio required for an ideal Otto cycle to use 0.043 grams of fuel to produce 1 kJ of work. Use constant specific heats at room temperature. *Answer: 7.52*

9–157 The cutoff ratio, r_c and the pressure ratio during constant-volume heat addition process, r_p, determine the amount of heat added to the dual cycle. Develop an equation for $q_{in}/(c_v T_1 r^{k-1})$ in terms of k, r_c and r_p. Use constant specific heats at room temperature.

9–158 An ideal Otto cycle has a compression ratio of 9.2 and uses air as the working fluid. At the beginning of the compression process, air is at 98 kPa and 27°C. The pressure is doubled during the constant-volume heat-addition process. Accounting for the variation of specific heats with temperature, determine (*a*) the amount of heat transferred to the air, (*b*) the net work output, (*c*) the thermal efficiency, and (*d*) the mean effective pressure for the cycle.

9–159 Repeat Prob. 9–158 using constant specific heats at room temperature.

9–160 Consider an engine operating on the ideal Diesel cycle with air as the working fluid. The volume of the cylinder is 1200 cm³ at the beginning of the compression process, 75 cm³ at the end, and 150 cm³ after the heat-addition process. Air is at 17°C and 100 kPa at the beginning of the compression process. Determine (*a*) the pressure at the beginning of the heat-rejection process, (*b*) the net work per cycle, in kJ, and (*c*) the mean effective pressure.

9–161 Repeat Prob. 9–160 using argon as the working fluid.

9–162 An ideal dual cycle has a compression ratio of 12 and uses air as the working fluid. At the beginning of the compression process, air is at 100 kPa and 32°C, and occupies a volume of 1230 cm³. During the heat-addition process, 0.3 kJ of heat is transferred to air at constant volume and 1.1 kJ at constant pressure. Using constant specific heats evaluated at room temperature, determine the thermal efficiency of the cycle.

9-163 Consider an ideal Stirling cycle using air as the working fluid. Air is at 350 K and 200 kPa at the beginning of the isothermal compression process, and heat is supplied to air from a source at 1800 K in the amount of 900 kJ/kg. Determine (*a*) the maximum pressure in the cycle and (*b*) the net work output per unit mass of air. *Answers:* (*a*) 5873 kPa, (*b*) 725 kJ/kg

9-164 Consider a simple ideal Brayton cycle with air as the working fluid. The pressure ratio of the cycle is 6, and the minimum and maximum temperatures are 300 and 1300 K, respectively. Now the pressure ratio is doubled without changing the minimum and maximum temperatures in the cycle. Determine the change in (*a*) the net work output per unit mass and (*b*) the thermal efficiency of the cycle as a result of this modification. Assume variable specific heats for air. *Answers:* (*a*) 41.5 kJ/kg, (*b*) 10.6 percent

9-165 Repeat Prob. 9-164 using constant specific heats at room temperature.

9-166 A gas-turbine engine with regeneration operates with two stages of compression and two stages of expansion. The pressure ratio across each stage of the compressor and turbine is 3.5. The air enters each stage of the compressor at 300 K and each stage of the turbine at 1200 K. The compressor and turbine efficiencies are 78 and 86 percent, respectively, and the effectiveness of the regenerator is 72 percent. Determine the back work ratio and the thermal efficiency of the cycle, assuming constant specific heats for air at room temperature. *Answers:* 53.2 percent, 39.2 percent

9-167 EES Reconsider Prob. 9-166. Using EES (or other) software, study the effects of varying the isentropic efficiencies for the compressor and turbine and regenerator effectiveness on net work done and the heat supplied to the cycle for the variable specific heat case. Let the isentropic efficiencies and the effectiveness vary from 70 percent to 90 percent. Plot the *T-s* diagram for the cycle.

9-168 Repeat Prob. 9-166 using helium as the working fluid.

9-169 Consider an ideal gas-turbine cycle with one stage of compression and two stages of expansion and regeneration. The pressure ratio across each turbine stage is the same. The high-pressure turbine exhaust gas enters the regenerator and then enters the low-pressure turbine for expansion to the compressor inlet pressure. Determine the thermal efficiency of this cycle as a function of the compressor pressure ratio and the high-pressure turbine to compressor inlet temperature ratio. Compare your result with the efficiency of the standard regenerative cycle.

9-170 A gas-turbine plant operates on the regenerative Brayton cycle with two stages of reheating and two-stages of intercooling between the pressure limits of 100 and 1200 kPa. The working fluid is air. The air enters the first and the second stages of the compressor at 300 K and 350 K, respectively, and the first and the second stages of the turbine at 1400 K and 1300 K, respectively. Assuming both the compressor and the turbine have an isentropic efficiency of 80 percent and the regenerator has an effectiveness of 75 percent and using variable specific heats, determine (*a*) the back work ratio and the net work output, (*b*) the thermal efficiency, and (*c*) the second-law efficiency of the cycle. Also determine (*d*) the exergies at the exits of the combustion chamber (state 6) and the regenerator (state 10) (See Fig. 9–43 in the text). *Answers:* (*a*) 0.523, 317 kJ/kg, (*b*) 0.553, (*c*) 0.704, (*d*) 931 kJ/kg, 129 kJ/kg

9-171 Compare the thermal efficiency of a two-stage gas turbine with regeneration, reheating and intercooling to that of a three-stage gas turbine with the same equipment when (*a*) all components operate ideally, (*b*) air enters the first compressor at 100 kPa and 10°C, (*c*) the total pressure ratio across all stages of compression is 16, and (*d*) the maximum cycle temperature is 600°C.

9-172 The specific impulse of an aircraft-propulsion system is the force produced per unit of thrust-producing mass flow rate. Consider a jet engine that operates in an environment at 70 kPa and −1°C and propels an aircraft cruising at 360 m/s. Determine the specific impulse of this engine when the compressor pressure ratio is 9 and the temperature at the turbine inlet is 370°C. Assume ideal operations for all components and constant specific heats at room temperature.

9-173 A Brayton cycle with a pressure ratio of 15 operates with air entering the compressor at 70 kPa and 0°C, and the turbine at 600°C. Calculate the net specific work produced by this cycle treating the air as an ideal gas with (*a*) constant specific heats, and (*b*) variable specific heats.

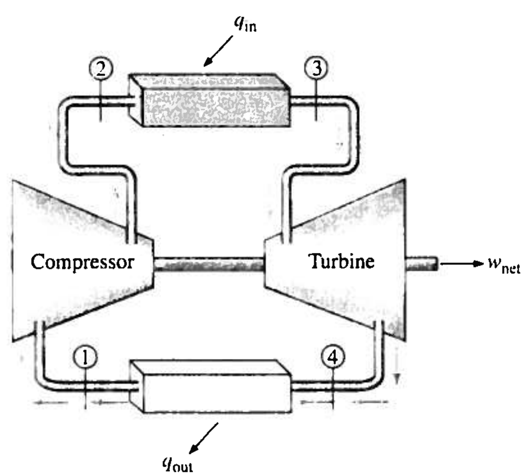

FIGURE P9-173

9–183 Repeat Problem 9–181 using helium as the working fluid.

9–184 Using EES (or other) software, determine the effect of the number of compression and expansion stages on the thermal efficiency of an ideal regenerative Brayton cycle with multistage compression and expansion. Assume that the overall pressure ratio of the cycle is 12, and the air enters each stage of the compressor at 300 K and each stage of the turbine at 1200 K. Using constant specific heats for air at room temperature, determine the thermal efficiency of the cycle by varying the number of stages from 1 to 22 in increments of 3. Plot the thermal efficiency versus the number of stages. Compare your results to the efficiency of an Ericsson cycle operating between the same temperature limits.

9–185 Repeat Problem 9–184 using helium as the working fluid.

Fundamentals of Engineering (FE) Exam Problems

9–186 An Otto cycle with air as the working fluid has a compression ratio of 8.2. Under cold-air-standard conditions, the thermal efficiency of this cycle is

(*a*) 24 percent (*b*) 43 percent (*c*) 52 percent
(*d*) 57 percent (*e*) 75 percent

9–187 For specified limits for the maximum and minimum temperatures, the ideal cycle with the lowest thermal efficiency is

(*a*) Carnot (*b*) Stirling (*c*) Ericsson
(*d*) Otto (*e*) All are the same

9–188 A Carnot cycle operates between the temperature limits of 300 and 2000 K, and produces 600 kW of net power. The rate of entropy change of the working fluid during the heat addition process is

(*a*) 0 (*b*) 0.300 kW/K (*c*) 0.353 kW/K
(*d*) 0.261 kW/K (*e*) 2.0 kW/K

9–189 Air in an ideal Diesel cycle is compressed from 3 to 0.15 L, and then it expands during the constant pressure heat addition process to 0.30 L. Under cold air standard conditions, the thermal efficiency of this cycle is

(*a*) 35 percent (*b*) 44 percent (*c*) 65 percent
(*d*) 70 percent (*e*) 82 percent

9–190 Helium gas in an ideal Otto cycle is compressed from 20°C and 2.5 to 0.25 L, and its temperature increases by an additional 700°C during the heat addition process. The temperature of helium before the expansion process is

(*a*) 1790°C (*b*) 2060°C (*c*) 1240°C
(*d*) 620°C (*e*) 820°C

9–191 In an ideal Otto cycle, air is compressed from 1.20 kg/m^3 and 2.2 to 0.26 L, and the net work output of the cycle is 440 kJ/kg. The mean effective pressure (MEP) for this cycle is

(*a*) 612 kPa (*b*) 599 kPa (*c*) 528 kPa
(*d*) 416 kPa (*e*) 367 kPa

9–192 In an ideal Brayton cycle, air is compressed from 95 kPa and 25°C to 800 kPa. Under cold-air-standard conditions, the thermal efficiency of this cycle is

(*a*) 46 percent (*b*) 54 percent (*c*) 57 percent
(*d*) 39 percent (*e*) 61 percent

9–193 Consider an ideal Brayton cycle executed between the pressure limits of 1200 and 100 kPa and temperature limits of 20 and 1000°C with argon as the working fluid. The net work output of the cycle is

(*a*) 68 kJ/kg (*b*) 93 kJ/kg (*c*) 158 kJ/kg
(*d*) 186 kJ/kg (*e*) 310 kJ/kg

9–194 An ideal Brayton cycle has a net work output of 150 kJ/kg and a back work ratio of 0.4. If both the turbine and the compressor had an isentropic efficiency of 85 percent, the net work output of the cycle would be

(*a*) 74 kJ/kg (*b*) 95 kJ/kg (*c*) 109 kJ/kg
(*d*) 128 kJ/kg (*e*) 177 kJ/kg

9–195 In an ideal Brayton cycle, air is compressed from 100 kPa and 25°C to 1 MPa, and then heated to 1200°C before entering the turbine. Under cold-air-standard conditions, the air temperature at the turbine exit is

(*a*) 490°C (*b*) 515°C (*c*) 622°C
(*d*) 763°C (*e*) 895°C

9–196 In an ideal Brayton cycle with regeneration, argon gas is compressed from 100 kPa and 25°C to 400 kPa, and then heated to 1200°C before entering the turbine. The highest temperature that argon can be heated in the regenerator is

(*a*) 246°C (*b*) 846°C (*c*) 689°C
(*d*) 368°C (*e*) 573°C

9–197 In an ideal Brayton cycle with regeneration, air is compressed from 80 kPa and 10°C to 400 kPa and 175°C, is heated to 450°C in the regenerator, and then further heated to 1000°C before entering the turbine. Under cold-air-standard conditions, the effectiveness of the regenerator is

(*a*) 33 percent (*b*) 44 percent (*c*) 62 percent
(*d*) 77 percent (*e*) 89 percent

9–198 Consider a gas turbine that has a pressure ratio of 6 and operates on the Brayton cycle with regeneration between the temperature limits of 20 and 900°C. If the specific heat ratio of the working fluid is 1.3, the highest thermal efficiency this gas turbine can have is

(*a*) 38 percent (*b*) 46 percent (*c*) 62 percent
(*d*) 58 percent (*e*) 97 percent

9–174 An Otto cycle with a compression ratio of 8 begins its compression at 94 kPa and 10°C. The maximum cycle temperature is 900°C. Utilizing air-standard assumptions, determine the thermal efficiency of this cycle using (*a*) constant specific heats at room temperature and (*b*) variable specific heats. *Answers:* (*a*) 56.5 percent, (*b*) 53.7 percent

9–175 A Diesel cycle has a compression ratio of 22 and begins its compression at 85 kPa and 15°C. The maximum cycle temperature is 1200°C. Utilizing air-standard assumptions, determine the thermal efficiency of this cycle using (*a*) constant specific heats at room temperature and (*b*) variable specific heats.

9–176 Electricity and process heat requirements of a manufacturing facility are to be met by a cogeneration plant consisting of a gas turbine and a heat exchanger for steam production. The plant operates on the simple Brayton cycle between the pressure limits of 100 and 1200 kPa with air as the working fluid. Air enters the compressor at 30°C. Combustion gases leave the turbine and enter the heat exchanger at 500°C, and leave the heat exchanger of 350°C, while the liquid water enters the heat exchanger at 25°C and leaves at 200°C as a saturated vapor. The net power produced by the gas-turbine cycle is 800 kW. Assuming a compressor isentropic efficiency of 82 percent and a turbine isentropic efficiency of 88 percent and using variable specific heats, determine (*a*) the mass flow rate of air, (*b*) the back work ratio and the thermal efficiency, and (*c*) the rate at which steam is produced in the heat exchanger. Also determine (*d*) the utilization efficiency of the cogeneration plant, defined as the ratio of the total energy utilized to the energy supplied to the plant.

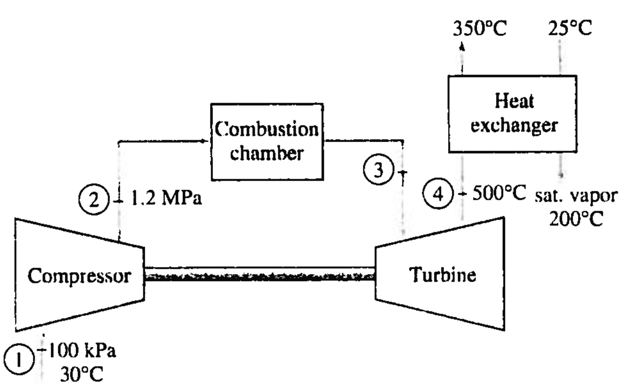

FIGURE P9–176

9–177 A turbojet aircraft flies with a velocity of 900 km/h at an altitude where the air temperature and pressure are −35°C and 40 kPa. Air leaves the diffuser at 50 kPa with a velocity of 15 m/s, and combustion gases enter the turbine at 450 kPa and 950°C. The turbine produces 500 kW of power, all of which is used to drive the compressor. Assuming an isentropic efficiency of 83 percent for the compressor, turbine, and nozzle, and using variable specific heats, determine (*a*) the pressure of combustion gases at the turbine exit, (*b*) the mass flow rate of air through the compressor, (*c*) the velocity of the gases at the nozzle exit, and (*d*) the propulsive power and the propulsive efficiency for this engine. *Answers:* (*a*) 147 kPa, (*b*) 1.76 kg/s, (*c*) 719 m/s, (*d*) 206 kW, 0.156

9–178 Using EES (or other) software, determine the effects of compression ratio on the net work output and the thermal efficiency of the Otto cycle for a maximum cycle temperature of 2000 K. Take the working fluid to be air that is at 100 kPa and 300 K at the beginning of the compression process, and assume variable specific heats. Vary the compression ratio from 6 to 15 with an increment of 1. Tabulate and plot your results against the compression ratio.

9–179 Using EES (or other) software, determine the effects of pressure ratio on the net work output and the thermal efficiency of a simple Brayton cycle for a maximum cycle temperature of 1800 K. Take the working fluid to be air that is at 100 kPa and 300 K at the beginning of the compression process, and assume variable specific heats. Vary the pressure ratio from 5 to 24 with an increment of 1. Tabulate and plot your results against the pressure ratio. At what pressure ratio does the net work output become a maximum? At what pressure ratio does the thermal efficiency become a maximum?

9–180 Repeat Problem 9–179 assuming isentropic efficiencies of 85 percent for both the turbine and the compressor.

9–181 Using EES (or other) software, determine the effects of pressure ratio, maximum cycle temperature, and compressor and turbine efficiencies on the net work output per unit mass and the thermal efficiency of a simple Brayton cycle with air as the working fluid. Air is at 100 kPa and 300 K at the compressor inlet. Also, assume constant specific heats for air at room temperature. Determine the net work output and the thermal efficiency for all combinations of the following parameters, and draw conclusions from the results.

Pressure ratio:	5, 8, 14
Maximum cycle temperature:	800, 1200, 1600 K
Compressor isentropic efficiency:	80, 100 percent
Turbine isentropic efficiency:	80, 100 percent

9–182 Repeat Problem 9–181 by considering the variation of specific heats of air with temperature.

Very low temperatures can be achieved by operating two or more vapor-compression systems in series, called *cascading*. The COP of a refrigeration system also increases as a result of cascading. Another way of improving the performance of a vapor-compression refrigeration system is by using *multistage compression with regenerative cooling*. A refrigerator with a single compressor can provide refrigeration at several temperatures by throttling the refrigerant in stages. The vapor-compression refrigeration cycle can also be used to liquefy gases after some modifications.

The power cycles can be used as refrigeration cycles by simply reversing them. Of these, the *reversed Brayton cycle*, which is also known as the *gas refrigeration cycle*, is used to cool aircraft and to obtain very low (cryogenic) temperatures after it is modified with regeneration. The work output of the turbine can be used to reduce the work input requirements to the compressor. Thus the COP of a gas refrigeration cycle is

$$\text{COP}_{\text{absorption}} = \frac{q_L}{w_{\text{net,in}}} = \frac{q_L}{w_{\text{comp,in}} - w_{\text{turb,out}}}$$

Another form of refrigeration that becomes economically attractive when there is a source of inexpensive thermal energy at a temperature of 100 to 200°C is *absorption refrigeration*, where the refrigerant is absorbed by a transport medium and compressed in liquid form. The most widely used absorption refrigeration system is the ammonia–water system, where ammonia serves as the refrigerant and water as the transport medium. The work input to the pump is usually very small, and the COP of absorption refrigeration systems is defined as

$$\text{COP}_{\text{absorption}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{Q_{\text{gen}} + W_{\text{pump,in}}} \cong \frac{Q_L}{Q_{\text{gen}}}$$

The maximum COP an absorption refrigeration system can have is determined by assuming totally reversible conditions, which yields

$$\text{COP}_{\text{rev,absorption}} = \eta_{\text{th,rev}}\,\text{COP}_{\text{R,rev}} = \left(1 - \frac{T_0}{T_s}\right)\left(\frac{T_L}{T_0 - T_L}\right)$$

where T_0, T_L, and T_s are the thermodynamic temperatures of the environment, the refrigerated space, and the heat source, respectively.

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4. W. F. Stoecker. "Growing Opportunities for Ammonia Refrigeration." *Proceedings of the Meeting of the International Institute of Ammonia Refrigeration*, Austin, Texas, 1989.
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PROBLEMS*

The Reversed Carnot Cycle

11–1C Why is the reversed Carnot cycle executed within the saturation dome not a realistic model for refrigeration cycles?

11–2 A steady-flow Carnot refrigeration cycle uses refrigerant-134a as the working fluid. The refrigerant changes from saturated vapor to saturated liquid at 30°C in the condenser as it rejects heat. The evaporator pressure is 160 kPa. Show the cycle on a *T-s* diagram relative to saturation lines, and determine (*a*) the coefficient of performance, (*b*) the amount of heat absorbed from the refrigerated space, and (*c*) the net work input.

11–3 Refrigerant-134a enters the condenser of a steady-flow Carnot refrigerator as a saturated vapor at 0.6 MPa, and it leaves with a quality of 0.05. The heat absorption from the refrigerated space takes place at a pressure of 0.2 MPa. Show

*Problems designated by a "C" are concept questions, and students are encouraged to answer them all. Problems with the icon are solved using EES, and complete solutions together with parametric studies are included on the enclosed DVD. Problems with the icon are comprehensive in nature, and are intended to be solved with a computer, preferably using the EES software that accompanies this text.

the cycle on a *T-s* diagram relative to saturation lines, and determine (*a*) the coefficient of performance, (*b*) the quality at the beginning of the heat-absorption process, and (*c*) the net work input.

Ideal and Actual Vapor-Compression Refrigeration Cycles

11–4C Does the ideal vapor-compression refrigeration cycle involve any internal irreversibilities?

11–5C Why is the throttling valve not replaced by an isentropic turbine in the ideal vapor-compression refrigeration cycle?

11–6C It is proposed to use water instead of refrigerant-134a as the working fluid in air-conditioning applications where the minimum temperature never falls below the freezing point. Would you support this proposal? Explain.

11–7C In a refrigeration system, would you recommend condensing the refrigerant-134a at a pressure of 0.7 or 1.0 MPa if heat is to be rejected to a cooling medium at 15°C? Why?

11–8C Does the area enclosed by the cycle on a *T-s* diagram represent the net work input for the reversed Carnot cycle? How about for the ideal vapor-compression refrigeration cycle?

11–9C Consider two vapor-compression refrigeration cycles. The refrigerant enters the throttling valve as a saturated liquid at 30°C in one cycle and as subcooled liquid at 30°C in the other one. The evaporator pressure for both cycles is the same. Which cycle do you think will have a higher COP?

11–10C The COP of vapor-compression refrigeration cycles improves when the refrigerant is subcooled before it enters the throttling valve. Can the refrigerant be subcooled indefinitely to maximize this effect, or is there a lower limit? Explain.

11–11 A commercial refrigerator with refrigerant-134a as the working fluid is used to keep the refrigerated space at −30°C by rejecting its waste heat to cooling water that enters the condenser at 18°C at a rate of 0.25 kg/s and leaves at 26°C. The refrigerant enters the condenser at 1.2 MPa and 65°C and leaves at 42°C. The inlet state of the compressor is 60 kPa and −34°C and the compressor is estimated to gain a net heat of 450 W from the surroundings. Determine (*a*) the quality of the refrigerant at the evaporator inlet, (*b*) the refrigeration load, (*c*) the COP of the refrigerator, and (*d*) the theoretical maximum refrigeration load for the same power input to the compressor.

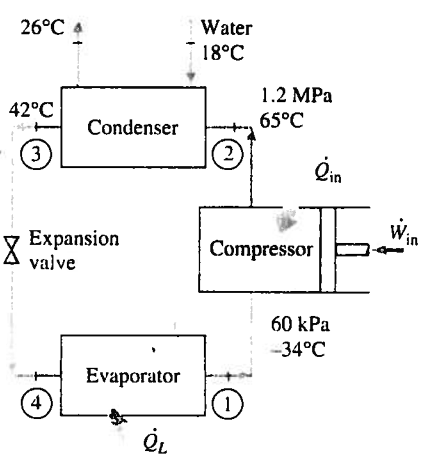

FIGURE P11–11

11–12 An ideal vapor-compression refrigeration cycle that uses refrigerant-134a as its working fluid maintains a condenser at 1000 kPa and the evaporator at 4°C. Determine this system's COP and the amount of power required to service a 400 kW cooling load. *Answers: 6.46, 61.9 kW*

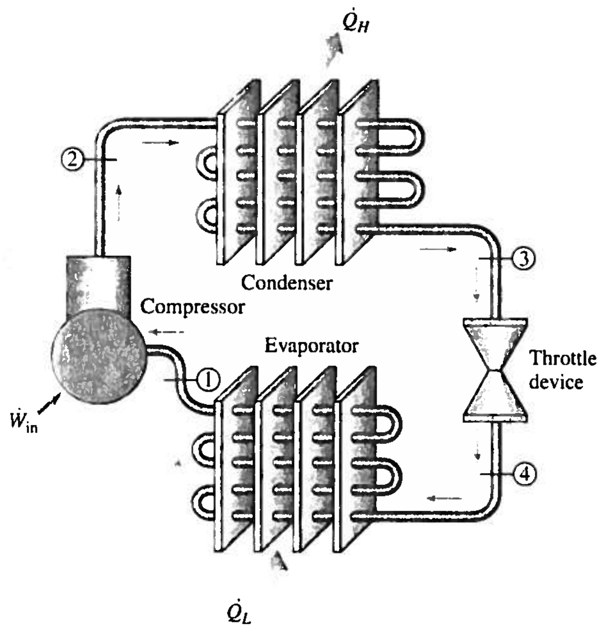

FIGURE P11–12

11–13 A 10-kW cooling load is to be served by operating an ideal vapor-compression refrigeration cycle with its evaporator at 400 kPa and its condenser at 800 kPa. Calculate the refrigerant mass flow rate and the compressor power requirement when refrigerant-134a is used.

11–14 A refrigerator uses refrigerant-134a as the working fluid and operates on an ideal vapor-compression refrigeration cycle between 0.12 and 0.7 MPa. The mass flow rate of the refrigerant is 0.05 kg/s. Show the cycle on a *T-s* diagram with respect to saturation lines. Determine (*a*) the rate of heat removal from the refrigerated space and the power input to the compressor, (*b*) the rate of heat rejection to the environment, and (*c*) the coefficient of performance.

11–15 Repeat Prob. 11–14 for a condenser pressure of 0.9 MPa.

11–16 If the throttling valve in Prob. 11–15 is replaced by an isentropic turbine, determine the percentage increase in the COP and in the rate of heat removal from the refrigerated space. *Answers:* 4.2 percent, 4.2 percent

11–17 Refrigerant-134a enters the compressor of a refrigerator as superheated vapor at 0.14 MPa and −10°C at a rate of 0.12 kg/s, and it leaves at 0.7 MPa and 50°C. The refrigerant is cooled in the condenser to 24°C and 0.65 MPa, and it is throttled to 0.15 MPa. Disregarding any heat transfer and pressure drops in the connecting lines between the components, show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the rate of heat removal from the refrigerated space and the power input to the compressor, (*b*) the isentropic efficiency of the compressor, and (*c*) the COP of the refrigerator. *Answers:* (*a*) 19.4 kW, 5.06 kW, (*b*) 82.5 percent, (*c*) 3.83

11–18 An air conditioner using refrigerant-134a as the working fluid and operating on the ideal vapor-compression refrigeration cycle is to maintain a space at 22°C while operating its condenser at 1000 kPa. Determine the COP of the system when a temperature difference of 2°C is allowed for the transfer of heat in the evaporator.

11–19 A refrigerator operates on the ideal vapor-compression refrigeration cycle and uses refrigerant-134a as the working fluid. The condenser operates at 1.6 MPa and the evaporator at −6°C. If an adiabatic, reversible expansion device were available and used to expand the liquid leaving the condenser, how much would the COP improve by using this device instead of the throttle device? *Answer:* 9.7 percent

11–20 An ideal vapor-compression refrigeration cycle using refrigerant-134a as the working fluid is used to cool a brine solution to −5°C. This solution is pumped to various buildings for the purpose of air conditioning. The refrigerant evaporates at −10°C with a total mass flow rate of 7 kg/s, and condenses at 600 kPa. Determine the COP of the cycle and the total cooling load.

11–21 Refrigerant-134a enters the compressor of a refrigerator at 140 kPa and −10°C at a rate of 0.3 m³/min and leaves at 1 MPa. The isentropic efficiency of the compressor is 78 percent. The refrigerant enters the throttling valve at 0.95 MPa and 30°C and leaves the evaporator as saturated vapor at −18.5°C. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the power input to the compressor, (*b*) the rate of heat removal from the refrigerated space, and (*c*) the pressure drop and rate of heat gain in the line between the evaporator and the compressor. *Answers:* [illegible]

11–22 [EES] Reconsider Prob. 11–21. Using EES (or other) software, investigate the effects of varying the compressor isentropic efficiency over the range 60 to 100 percent and the compressor inlet volume flow rate from 0.1 to 1.0 m³/min on the power input and the rate of refrigeration. Plot the rate of refrigeration and the power input to the compressor as functions of compressor efficiency for compressor inlet volume flow rates of 0.1, 0.5, and 1.0 m³/min, and discuss the results.

11–23 A refrigerator uses refrigerant-134a as the working fluid and operates on the ideal vapor-compression refrigeration cycle. The refrigerant enters the evaporator at 120 kPa with a quality of 30 percent and leaves the compressor at 60°C. If the compressor consumes 450 W of power, determine (*a*) the mass flow rate of the refrigerant, (*b*) the condenser pressure, and (*c*) the COP of the refrigerator. *Answers:* (*a*) 0.00727 kg/s, (*b*) 672 kPa, (*c*) 2.43

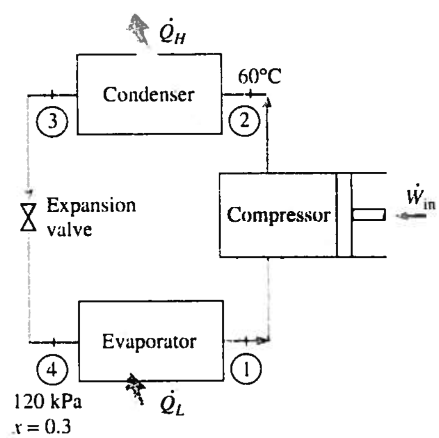

FIGURE P11–23

Selecting the Right Refrigerant

11–24C When selecting a refrigerant for a certain application, what qualities would you look for in the refrigerant?

11–25C Consider a refrigeration system using refrigerant-134a as the working fluid. If this refrigerator is to operate in an environment at 30°C, what is the minimum pressure to which the refrigerant should be compressed? Why?

11–26C A refrigerant-134a refrigerator is to maintain the refrigerated space at −10°C. Would you recommend an evaporator pressure of 0.12 or 0.14 MPa for this system? Why?

11–27 A refrigerator that operates on the ideal vapor-compression cycle with refrigerant-134a is to maintain the refrigerated space at −10°C while rejecting heat to the environment at 25°C. Select reasonable pressures for the evaporator and the condenser, and explain why you chose those values.

11–28 A heat pump that operates on the ideal vapor-compression cycle with refrigerant-134a is used to heat a house and maintain it at 22°C by using underground water at 10°C as the heat source. Select reasonable pressures for the evaporator and the condenser, and explain why you chose those values.

Heat Pump Systems

11–29C Do you think a heat pump system will be more cost-effective in New York or in Miami? Why?

11–30C What is a water-source heat pump? How does the COP of a water-source heat pump system compare to that of an air-source system?

11–31 Refrigerant-134a enters the condenser of a residential heat pump at 800 kPa and 55°C at a rate of 0.018 kg/s and leaves at 750 kPa subcooled by 3°C. The refrigerant enters the compressor at 200 kPa superheated by 4°C. Determine (*a*) the isentropic efficiency of the compressor, (*b*) the rate of heat supplied to the heated room, and (*c*) the COP of the heat pump. Also, determine (*d*) the COP and the rate of heat supplied to the heated room if this heat pump operated on the ideal vapor-compression cycle between the pressure limits of 200 and 800 kPa.

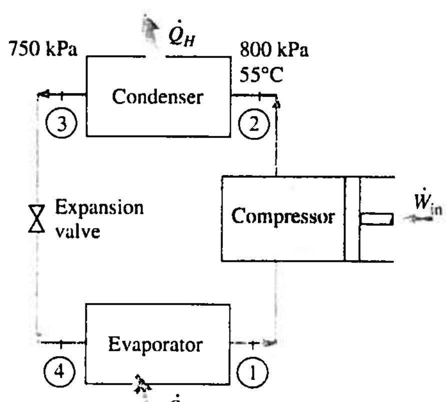

FIGURE P11–31

11–32 A heat pump operates on the ideal vapor-compression refrigeration cycle and uses refrigerant-134a as the working fluid. The condenser operates at 1200 kPa and the evaporator at 280 kPa. Determine this system's COP and the rate of heat supplied to the evaporator when the compressor consumes 20 kW.

11–33 A heat pump using refrigerant-134a as a refrigerant operates its condenser at 800 kPa and its evaporator at −1.25°C. It operates on the ideal vapor-compression refrigeration cycle, except for the compressor, which has an isentropic efficiency of 85 percent. How much do the compressor irreversibilities reduce this heat pump's COP as compared to an ideal vapor-compression refrigeration cycle? *Answer:* 13.1 percent

11–34 What is the effect on the COP of Prob. 11–33 when the vapor entering the compressor is superheated by 2°C and the compressor has no irreversibilities?

11–35 The liquid leaving the condenser of a 30 kW heat pump using refrigerant-134a as the working fluid is subcooled by 5.4°C. The condenser operates at 1 MPa and the evaporator at 0.4 MPa. How does this subcooling change the power required to drive the compressor as compared to an ideal vapor-compression refrigeration cycle? *Answers:* 3.41 kW, 3.25 kW

11–36 What is the effect on the compressor power requirement when the vapor entering the compressor of Prob. 11–35 is superheated by 11.1°C and the condenser operates ideally?

11–37 A heat pump with refrigerant-134a as the working fluid is used to keep a space at 25°C by absorbing heat from geothermal water that enters the evaporator at 50°C at a rate of 0.065 kg/s and leaves at 40°C. The refrigerant enters the evaporator at 20°C with a quality of 23 percent and leaves at the inlet pressure as saturated vapor. The refrigerant loses 300 W of heat to the surroundings as it flows through the compressor and the refrigerant leaves the compressor at 1.4 MPa at the same entropy as the inlet. Determine (*a*) the degrees of subcooling of the refrigerant in the condenser, (*b*) the mass

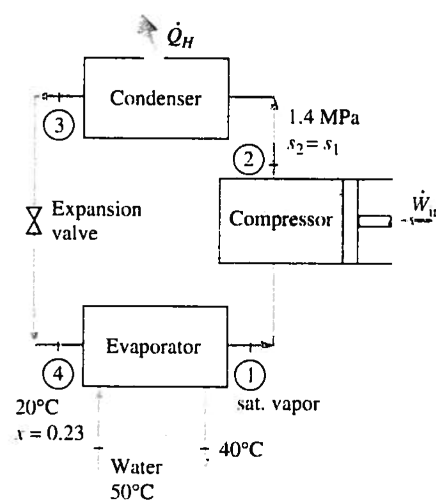

FIGURE P11–37

flow rate of the refrigerant, (*c*) the heating load and the COP of the heat pump, and (*d*) the theoretical minimum power input to the compressor for the same heating load. *Answers:* (*a*) 3.8°C, (*b*) 0.0194 kg/s, (*c*) 3.07 kW, 4.68, (*d*) 0.238 kW

Innovative Refrigeration Systems

11–38C What is cascade refrigeration? What are the advantages and disadvantages of cascade refrigeration?

11–39C How does the COP of a cascade refrigeration system compare to the COP of a simple vapor-compression cycle operating between the same pressure limits?

11–40C A certain application requires maintaining the refrigerated space at −32°C. Would you recommend a simple refrigeration cycle with refrigerant-134a or a two-stage cascade refrigeration cycle with a different refrigerant at the bottoming cycle? Why?

11–41C Consider a two-stage cascade refrigeration cycle and a two-stage compression refrigeration cycle with a flash chamber. Both cycles operate between the same pressure limits and use the same refrigerant. Which system would you favor? Why?

11–42C Can a vapor-compression refrigeration system with a single compressor handle several evaporators operating at different pressures? How?

11–43C In the liquefaction process, why are gases compressed to very high pressures?

11–44 A two-stage compression refrigeration system operates with refrigerant-134a between the pressure limits of 1 and 0.14 MPa. The refrigerant leaves the condenser as a saturated liquid and is throttled to a flash chamber operating at 0.5 MPa. The refrigerant leaving the low-pressure compressor at 0.5 MPa is also routed to the flash chamber. The vapor in the flash chamber is then compressed to the condenser pressure by the high-pressure compressor, and the liquid is throttled to the evaporator pressure. Assuming the refrigerant leaves the evaporator as saturated vapor and both compressors are isentropic, determine (*a*) the fraction of the refrigerant that evaporates as it is throttled to the flash chamber, (*b*) the rate of heat removed from the refrigerated space for a mass flow rate of 0.25 kg/s through the condenser, and (*c*) the coefficient of performance.

11–45 Repeat Prob. 11–44 for a flash chamber pressure of 0.32 MPa.

11–46 Reconsider Prob. 11–44. Using EES (or other) software, investigate the effect of the various refrigerants for compressor efficiencies of 80, 90, and 100 percent. Compare the performance of the refrigeration system with different refrigerants.

11–47 Consider a two-stage cascade refrigeration system operating between the pressure limits of 1.2 MPa and 200 kPa with refrigerant-134a as the working fluid. Heat rejection from the lower cycle to the upper cycle takes place in an adiabatic counterflow heat exchanger where the pressure in the upper and lower cycles are 0.4 and 0.5 MPa, respectively. In both cycles, the refrigerant is a saturated liquid at the condenser exit and a saturated vapor at the compressor inlet, and the isentropic efficiency of the compressor is 80 percent. If the mass flow rate of the refrigerant through the lower cycle is 0.15 kg/s, determine (*a*) the mass flow rate of the refrigerant through the upper cycle, (*b*) the rate of heat removal from the refrigerated space, and (*c*) the COP of this refrigerator. *Answers:* (*a*) 0.212 kg/s, (*b*) 25.7 kW, (*c*) 2.63

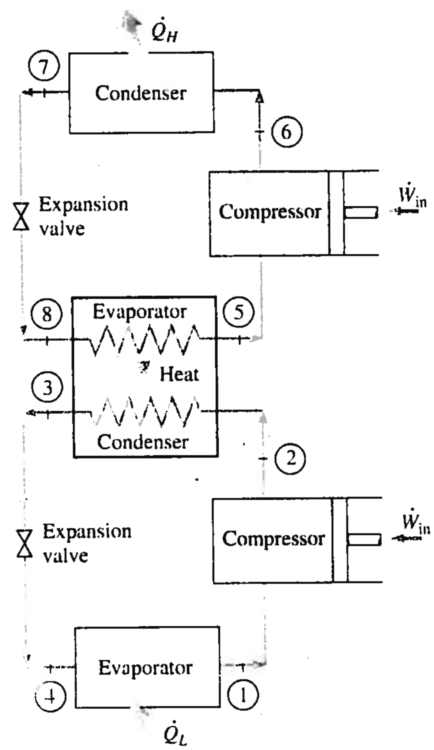

FIGURE P11–47

11–48 A two-evaporator compression refrigeration system as shown in the figure uses refrigerant-134a as the working fluid. The system operates evaporator 1 at 0°C, evaporator 2 at −26.4°C, and the condenser at 800 kPa. The refrigerant is circulated through the compressor at a rate of 0.1 kg/s and the low-temperature evaporator serves a cooling load of 8 kW.

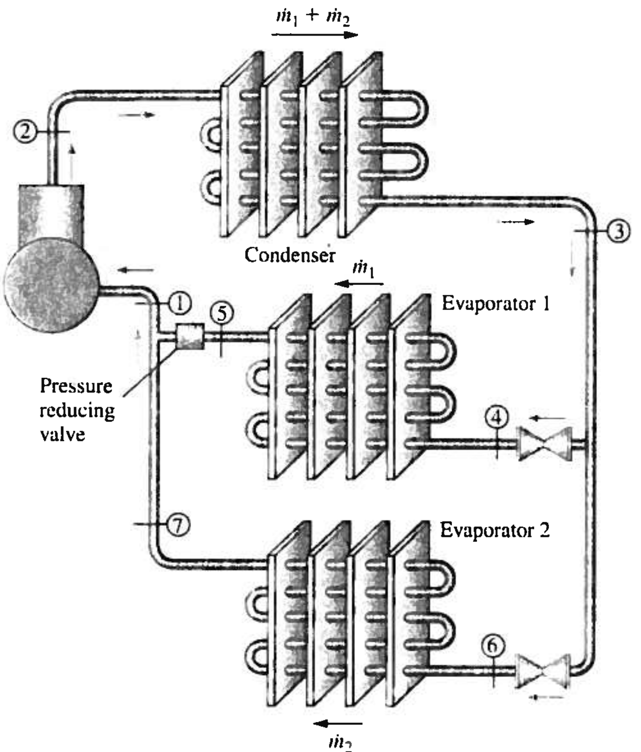

FIGURE P11–48

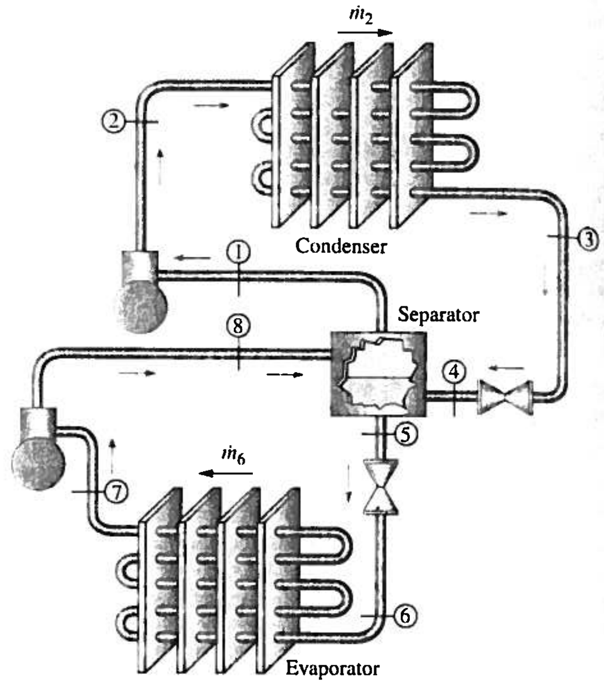

FIGURE P11–49

Determine the cooling rate of the high-temperature evaporator, the power required by the compressor, and the COP of the system. The refrigerant is saturated liquid at the exit of the condenser and saturated vapor at the exit of each evaporator, and the compressor is isentropic. *Answers:* 6.58 kW, 4.50 kW, 3.24

11–49 A two-stage compression refrigeration system with an adiabatic liquid-vapor separation unit as shown in Fig. P11–49 uses refrigerant-134a as the working fluid. The system operates the evaporator at −40°C, the condenser at 800 kPa, and the separator at −10.1°C. This system is to serve a 30-kW cooling load. Determine the mass flow rate through each of the two compressors, the power used by the compressors, and the system's COP. The refrigerant is saturated liquid at the inlet of each expansion valve and saturated vapor at the inlet of each compressor, and the compressors are isentropic. *Answers:* 0.160 kg/s, 0.230 kg/s, 10.9 kW, 2.74

11–50 A two-stage compression refrigeration system with an adiabatic liquid-vapor separation unit like that in Fig. P11–49 uses refrigerant-134a as the working fluid. The system operates the evaporator at 0.4 MPa, the condenser at 1.6 MPa, and the separator at 0.8 MPa. The compressors use 25 kW of power. Determine the rate of cooling provided by the evaporator and the COP of this cycle. The refrigerant is saturated liquid at the inlet of each expansion valve and saturated vapor at the inlet of each compressor, and the compressors are isentropic.

11–51 A two-stage cascade refrigeration system is to provide cooling at −40°C while operating the high-temperature condenser at 1.6 MPa. Each stage operates on the ideal vapor-compression refrigeration cycle. The upper vapor compression refrigeration system (VCRS) uses water as its working fluid and operates its evaporator at 5°C. The lower cycle uses refrigerant-134a as its working fluid and operates its condenser at 400 kPa. This system produces a cooling effect of 20 kJ/s. Determine the mass flow rate of R-134a and water in their respective cycles, and the overall COP of this cascaded system.

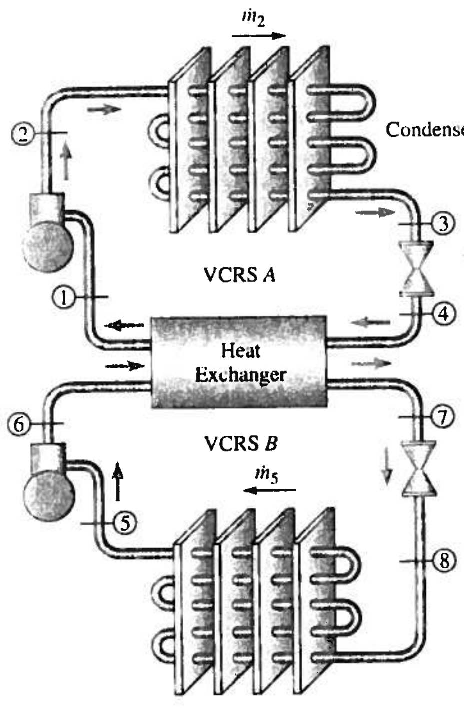

FIGURE P11–51

11–52 Perform a second-law analysis of the cascaded system of Prob. 11–51 when the low-temperature reservoir is at −30°C and the high-temperature reservoir is at 30°C. Where does the largest exergy destruction occur?

Gas Refrigeration Cycle

11–53C How does the ideal-gas refrigeration cycle differ from the Brayton cycle?

11–54C Devise a refrigeration cycle that works on the reversed Stirling cycle. Also, determine the COP for this cycle.

11–55C How does the ideal-gas refrigeration cycle differ from the Carnot refrigeration cycle?

11–56C How is the ideal-gas refrigeration cycle modified for aircraft cooling?

11–57C In gas refrigeration cycles, can we replace the turbine by an expansion valve as we did in vapor-compression refrigeration cycles? Why?

11–58C How do we achieve very low temperatures with gas refrigeration cycles?

11–59 Air enters the compressor of an ideal gas refrigeration cycle at 12°C and 50 kPa and the turbine at 47°C and 250 kPa. The mass flow rate of air through the cycle is 0.08 kg/s. Assuming variable specific heats for air, determine (*a*) the rate of refrigeration, (*b*) the net power input, and (*c*) the coefficient of performance. *Answers:* (*a*) 6.57 kW, (*b*) 3.38 kW, (*c*) 1.72

11–60 Repeat Prob. 11–59 for a compressor isentropic efficiency of 80 percent and a turbine isentropic efficiency of 85 percent.

11–61 Reconsider Prob. 11–60. Using EES (or other) software, study the effects of compressor and turbine isentropic efficiencies as they are varied from 70 to 100 percent on the rate of refrigeration, the net power input, and the COP. Plot the *T-s* diagram of the cycle for the isentropic case.

11–62 A gas refrigeration cycle with a pressure ratio of 3 uses helium as the working fluid. The temperature of the helium is −10°C at the compressor inlet and 50°C at the turbine inlet. Assuming isentropic efficiencies of 80 percent for both the turbine and the compressor, determine (*a*) the minimum temperature in the cycle, (*b*) the coefficient of performance, and (*c*) the mass flow rate of the helium for a refrigeration rate of 18 kW.

11–63 A gas refrigeration system using air as the working fluid has a pressure ratio of 5. Air enters the compressor at 0°C. The high-pressure air is cooled to 35°C by rejecting heat to the surroundings. The refrigerant leaves the turbine at −80°C and then it absorbs heat from the refrigerated space before entering the regenerator. The mass flow rate of air is 0.4 kg/s. Assuming isentropic efficiencies of 80 percent for the compressor and 85 percent for the turbine and using constant specific heats at room temperature, determine (*a*) the effectiveness of the regenerator, (*b*) the rate of heat removal from the refrigerated space, and (*c*) the COP of the cycle. Also, determine (*d*) the refrigeration load and the COP if this system operated on the simple gas refrigeration cycle. Use the same compressor inlet temperature as given, the same turbine inlet temperature as calculated, and the same compressor and turbine efficiencies. *Answers:* (*a*) 0.434, (*b*) 21.4 kW, (*c*) 0.478, (*d*) 24.7 kW, 0.599

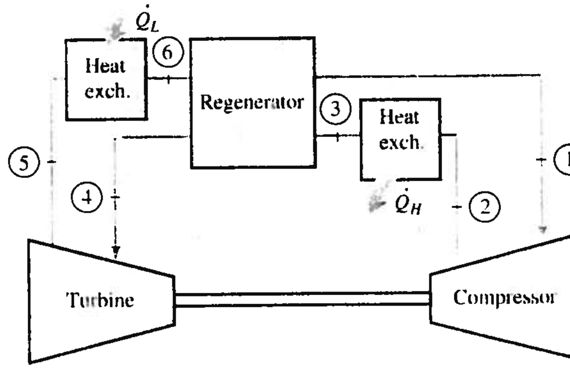

FIGURE P11–63

11–64 An ideal gas refrigeration cycle uses air as the working fluid. The air is at 35 kPa and −23°C as it enters the compressor with a compression ratio of 4. The temperature at the turbine entrance is 37°C. Determine this cycle's COP. Use constant specific heats at room temperature.

11–65 Rework Prob. 11–64 when the compressor isentropic efficiency is 87 percent, the turbine isentropic efficiency is 94 percent, and the pressure drop across each heat exchanger is 7 kPa. *Answer:* 0.377

11–66 An ideal gas refrigeration system operates with air as the working. Air is at 100 kPa and 20°C before compression, and 500 kPa and 30°C before expansion. The system is to provide 15 kW of cooling. Calculate the rate at which air is circulated in this system, as well as the rates of heat addition and rejection. Use constant specific heats at room temperature.

11–67 A 20 kJ/kg cooling load at 0°C is to be serviced by an ideal gas refrigeration cycle using air as the working fluid. Waste heat from this cycle is rejected to the surrounding environment at 20°C. At the inlet of the compressor, the air is at 100 kPa and −5°C. Determine the minimum pressure ratio for this system to operate properly. Use constant specific heats at room temperature.

11–68 An ideal gas refrigeration system with two stages of compression with intercooling as shown in Fig. P11–68 operates with air entering the first compressor at 90 kPa and −18°C. Each compression stage has a pressure ratio of 4 and the two intercoolers can cool the air to 10°C. Calculate the coefficient of performance of this system and the rate at which air must be circulated through this system to service a 75,000 kJ/h cooling load. Use constant specific heats at room temperature. *Answers:* 1.19, 0.163 kg/s

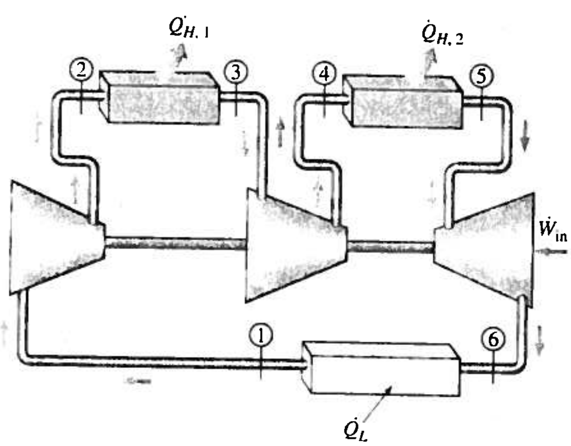

FIGURE P11–68

11–69 How will the answers of Prob. 11–68 change when the isentropic efficiency of each compressor is 85 percent and the isentropic efficiency of the turbine is 95 percent?

Absorption Refrigeration Systems

11–70C What is absorption refrigeration? How does an absorption refrigeration system differ from a vapor-compression refrigeration system?

11–71C What are the advantages and disadvantages of absorption refrigeration?

11–72C Can water be used as a refrigerant in air-conditioning applications? Explain.

11–73C In absorption refrigeration cycles, why is the fluid in the absorber cooled and the fluid in the generator heated?

11–74C How is the coefficient of performance of an absorption refrigeration system defined?

11–75C What are the functions of the rectifier and the regenerator in an absorption refrigeration system?

11–76 An absorption refrigeration system that receives heat from a source at 130°C and maintains the refrigerated space at −5°C is claimed to have a COP of 2. If the environment temperature is 27°C, can this claim be valid? Justify your answer.

11–77 An absorption refrigeration system receives heat from a source at 120°C and maintains the refrigerated space at 0°C. If the temperature of the environment is 25°C, what is the maximum COP this absorption refrigeration system can have?

11–78 Heat is supplied to an absorption refrigeration system from a geothermal well at 130°C at a rate of 5×10^5 kJ/h. The environment is at 25°C, and the refrigerated space is maintained at −30°C. Determine the maximum rate at which this system can remove heat from the refrigerated space. *Answer:* 5.75 × 10⁵ kJ/h

11–79 Heat is supplied to an absorption refrigeration system from a geothermal well at 120°C at a rate of 10^5 kJ/h. The environment is at 25°C, and the refrigerated space is maintained at −18°C. If the COP of the system is 0.55, determine the rate at which this system can remove heat from the refrigerated space.

11–80 A reversible absorption refrigerator consists of a reversible heat engine and a reversible refrigerator. The system removes heat from a cooled space at −10°C at a rate of 22 kW. The refrigerator operates in an environment at 25°C. If the heat is supplied to the cycle by condensing saturated steam at 200°C, determine (*a*) the rate at which the steam condenses and (*b*) the power input to the reversible refrigerator. (*c*) If the COP of an actual absorption chiller at the same temperature limits has a COP of 0.7, determine the second law efficiency of this chiller. *Answers:* (*a*) 0.00408 kg/s, (*b*) 2.33 kW, (*c*) 0.252

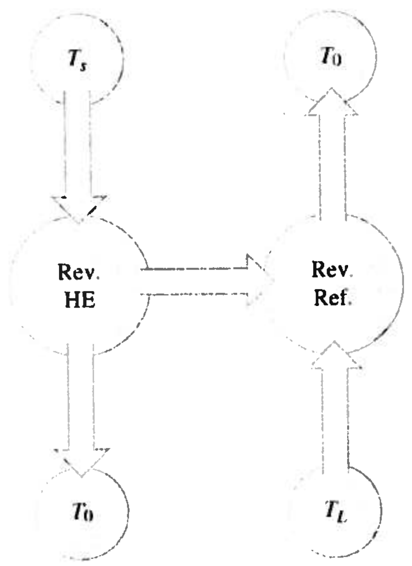

FIGURE P11–80

Special Topic: Thermoelectric Power Generation and Refrigeration Systems

11–81C What is a thermoelectric circuit?

11–82C Describe the Seebeck and the Peltier effects.

11–83C Consider a circular copper wire formed by connecting the two ends of a copper wire. The connection point is now heated by a burning candle. Do you expect any current to flow through the wire?

11–84C An iron and a constantan wire are formed into a closed circuit by connecting the ends. Now both junctions are heated and are maintained at the same temperature. Do you expect any electric current to flow through this circuit?

11–85C A copper and a constantan wire are formed into a closed circuit by connecting the ends. Now one junction is heated by a burning candle while the other is maintained at room temperature. Do you expect any electric current to flow through this circuit?

11–86C How does a thermocouple work as a temperature measurement device?

11–87C Why are semiconductor materials preferable to metals in thermoelectric refrigerators?

11–88C Is the efficiency of a thermoelectric generator limited by the Carnot efficiency? Why?

11–89 A thermoelectric generator receives heat from a source at 71°C and rejects the waste heat to the environment at 32°C. What is the maximum thermal efficiency this thermoelectric generator can have? *Answer:* 31.3 percent

11–90 A thermoelectric refrigerator removes heat from a refrigerated space at −5°C at a rate of 130 W and rejects it to an environment at 20°C. Determine the maximum coefficient of performance this thermoelectric refrigerator can have and the minimum required power input. *Answers:* 10.72, 12.1 W

11–91 A thermoelectric cooler has a COP of 0.15 and removes heat from a refrigerated space at a rate of 180 W. Determine the required power input to the thermoelectric cooler, in W.

11–92 A thermoelectric refrigerator is powered by a 12-V car battery that draws 3 A of current when running. The refrigerator resembles a small ice chest and is claimed to cool nine canned drinks, 0.350-L each, from 25 to 3°C in 12 h. Determine the average COP of this refrigerator.

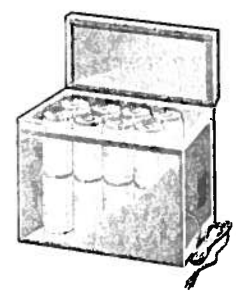

FIGURE P11–92

11–93 Thermoelectric coolers that plug into the cigarette lighter of a car are commonly available. One such cooler is claimed to cool a 350-g drink from 26 to 3°C or to heat a cup of coffee from 24 to 54°C in about 15 min in a well-insulated cup holder. Assuming an average COP of 0.2 in the cooling mode, determine (*a*) the average rate of heat removal from the drink, (*b*) the average rate of heat supply to the coffee, and (*c*) the electric power drawn from the battery of the car, all in W.

11–94 It is proposed to run a thermoelectric generator in conjunction with a solar pond that can supply heat at a rate of 10^6 kJ/h at 80°C. The waste heat is to be rejected to the environment at 30°C. What is the maximum power this thermoelectric generator can produce?

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2. Y. A. Çengel, Y. Cerci, and B. Wood, "Second Law Analysis of Separation Processes of Mixtures," *ASME International Mechanical Engineering Congress and Exposition,* Nashville, Tennessee, 1999.
3. Y. Cerci, Y. A. Çengel, and B. Wood, "The Minimum Separation Work for Desalination Processes," *ASME International Mechanical Engineering Congress and Exposition,* Nashville, Tennessee, 1999.
4. K. Wark, Jr. *Advanced Thermodynamics for Engineers.* New York: McGraw-Hill, 1995.

PROBLEMS*

Composition of Gas Mixtures

13–1C What is the *apparent gas constant* for a gas mixture? Can it be larger than the largest gas constant in the mixture?

13–2C Consider a mixture of two gases. Can the apparent molar mass of this mixture be determined by simply taking the arithmetic average of the molar masses of the individual gases? When will this be the case?

13–3C What is the *apparent molar mass* for a gas mixture? Does the mass of every molecule in the mixture equal the apparent molar mass?

13–4C Consider a mixture of several gases of identical masses. Will all the mass fractions be identical? How about the mole fractions?

13–5C The sum of the mole fractions for an ideal-gas mixture is equal to 1. Is this also true for a real-gas mixture?

13–6C What are mass and mole fractions?

13–7C Using the definitions of mass and mole fractions, derive a relation between them.

13–8C Somebody claims that the mass and mole fractions for a mixture of CO_2 and N_2O gases are identical. Is this true? Why?

13–9C Consider a mixture of two gases A and B. Show that when the mass fractions mf_A and mf_B are known, the mole fractions can be determined from

$$y_A = \frac{M_B}{M_A(1/mf_A - 1) + M_B} \quad \text{and} \quad y_B = 1 - y_A$$

where M_A and M_B are the molar masses of A and B.

*Problems designated by a "C" are concept questions, and students are encouraged to answer them all. Problems with the icon are solved using EES, and complete solutions together with parametric studies are included on the enclosed DVD. Problems with the icon are comprehensive in nature, and are intended to be solved with a computer, preferably using the EES software that accompanies this text.

13–10 The *weight fraction* of a component in a mixture of several substances is defined as *the weight of the component alone divided by the total weight of the mixture.* What is the relationship between the weight fraction and the mass fraction?

13–11 A gaseous mixture consists of 1 kmol of helium, 2 kmol of oxygen, 0.1 kmol of water vapor, and 1.5 kmol of nitrogen. Determine the mole fraction of the various constituents and the apparent molecular weight of this mixture, in kg/kmol.

13–12 A gas mixture consists of 5 kg of O_2, 8 kg of N_2, and 10 kg of CO_2. Determine (*a*) the mass fraction of each component, (*b*) the mole fraction of each component, and (*c*) the average molar mass and gas constant of the mixture.

13–13 Determine the mole fractions of a gas mixture that consists of 75 percent CH_4 and 25 percent CO_2 by mass. Also, determine the gas constant of the mixture.

13–14 A gas mixture consists of 8 kmol of H_2 and 2 kmol of N_2. Determine the mass of each gas and the apparent gas constant of the mixture. *Answers:* 16 kg, 56 kg, 1.155 kJ/kg·K

13–15 A gas mixture consists of 20 percent O_2, 30 percent N_2, and 50 percent CO_2 on mass basis. Determine the volumetric analysis of the mixture and the apparent gas constant.

P-v-T Behavior of Gas Mixtures

13–16C Is a mixture of ideal gases also an ideal gas? Give an example.

13–17C Express Dalton's law of additive pressures. Does this law hold exactly for ideal-gas mixtures? How about nonideal-gas mixtures?

13–18C Express Amagat's law of additive volumes. Does this law hold exactly for ideal-gas mixtures? How about nonideal-gas mixtures?

13–19C How is the *P-v-T* behavior of a component in an ideal-gas mixture expressed? How is the *P-v-T* behavior of a component in a real-gas mixture expressed?

13–20C What is the difference between the *component pressure* and the *partial pressure*? When are these two equivalent?

13–21C What is the difference between the *component volume* and the *partial volume*? When are these two equivalent?

13–22C In a gas mixture, which component will have the higher partial pressure—the one with the higher mole number or the one with the larger molar mass?

13–23C Consider a rigid tank that contains a mixture of two ideal gases. A valve is opened and some gas escapes. As a result, the pressure in the tank drops. Will the partial pressure of each component change? How about the pressure fraction of each component?

13–24C Consider a rigid tank that contains a mixture of two ideal gases. The gas mixture is heated, and the pressure and temperature in the tank rise. Will the partial pressure of each component change? How about the pressure fraction of each component?

13–25C Is this statement correct? *The volume of an ideal-gas mixture is equal to the sum of the volumes of each individual gas in the mixture.* If not, how would you correct it?

13–26C Is this statement correct? *The temperature of an ideal-gas mixture is equal to the sum of the temperatures of each individual gas in the mixture.* If not, how would you correct it?

13–27C Is this statement correct? *The pressure of an ideal-gas mixture is equal to the sum of the partial pressures of each individual gas in the mixture.* If not, how would you correct it?

13–28C Explain how a real-gas mixture can be treated as a pseudopure substance using Kay's rule.

13–29 A rigid tank contains 0.5 kmol of Ar and 2 kmol of N_2 at 250 kPa and 280 K. The mixture is now heated to 400 K. Determine the volume of the tank and the final pressure of the mixture.

13–30 A gas mixture at 300 K and 200 kPa consists of 1 kg of CO_2 and 3 kg of CH_4. Determine the partial pressure of each gas and the apparent molar mass of the gas mixture.

13–31 A 0.3-m³ rigid tank contains 0.6 kg of N_2 and 0.4 kg of O_2 at 300 K. Determine the partial pressure of each gas and the total pressure of the mixture. *Answers:* 178.1 kPa, 103.9 kPa, 282.0 kPa

13–32 A rigid tank that contains 1 kg of N_2 at 25°C and 300 kPa is connected to another rigid tank that contains 3 kg of O_2 at 25°C and 500 kPa. The valve connecting the two tanks is opened, and the two gases are allowed to mix. If the final mixture temperature is 25°C, determine the volume of each tank and the final mixture pressure. *Answers:* [illegible] m³, [illegible] m³, [illegible]22 kPa

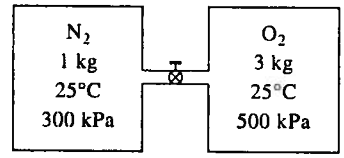


FIGURE P13–32

13–33 One liter of a liquid whose specific volume is 0.0003 m³/kg is mixed with 2 liters of a liquid whose specific volume is 0.00023 m³/kg in a container whose total volume is 3 liters. What is the density of the resulting mixture, in kg/m³?

13–34 One kilogram of a gas whose density is 0.01 kg/m³ is mixed with 2 kg of a gas whose density is 0.02 kg/m³ such that the pressure and temperature of the gases do not change. Determine the resulting mixture's volume, in m³, and specific volume, in m³/kg.

13–35 A mixture of gases consists of 0.1 kg of oxygen, 1 kg of carbon dioxide, and 0.5 kg of helium. This mixture is maintained at 100 kPa and 27°C. Determine the apparent molecular weight of this mixture, the volume it occupies, the partial volume of the oxygen, and the partial pressure of the helium. *Answers:* 10.61 kg/kmol, 3.76 m³, 0.078 m³, 52.3 kPa

13–36 The mass fractions of a mixture of gases are 15 percent nitrogen, 5 percent helium, 60 percent methane, and 20 percent ethane. Determine the mole fractions of each constituent, the mixture's apparent molecular weight, the partial pressure of each constituent when the mixture pressure is 1200 kPa and the apparent specific heats of the mixture when the mixture is at the room temperature.

13–37 The volumetric analysis of a mixture of gases is 30 percent oxygen, 40 percent nitrogen, 10 percent carbon dioxide, and 20 percent methane. Calculate the apparent specific heats and molecular weight of this mixture of gases. *Answers:* 1.105 kJ/kg·K, 0.812 kJ/kg·K, 28.40 kg/kmol

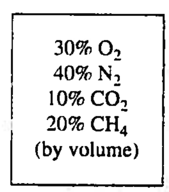


FIGURE P13–37

13–38 A mixture of hydrocarbon gases is composed of 60 percent methane, 25 percent propane, and 15 percent butane by weight. Determine the volume occupied by 100 kg of this mixture when its pressure is 3 MPa and its temperature is 37°C.

13–39 A 0.15 m^3 scuba diver's tank is filled with a mixture of oxygen, nitrogen, and helium. The mass fractions of these constituents are 60 percent N_2, 30 percent O_2, and 10 percent He. Determine the mass of the mixture in the tank when the pressure and temperature are 2100 kPa and 20°C, and the partial volumes of the oxygen, nitrogen, and helium.

13–40 A 30 percent (by mass) ethane and 70 percent methane mixture is to be blended in a 100-m^3 tank at 130 kPa and 25°C. If the tank is initially evacuated, to what pressure should ethane be added before methane is added?

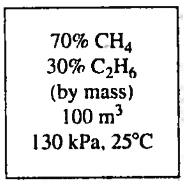


FIGURE P13–40

13–41 The dry stack gas of an electrical-generation station boiler has the following Orsat analysis: 15 percent CO_2, 15 percent O_2, and 1 percent CO. This gas passes through a 1-m^2 cross section metering duct at a velocity of 6 m/s at standard atmospheric pressure and 90°C. Determine the gas mixture's mass flow rate. *Answer: 5.24 kg/s*

13–42 Separation units often use membranes, absorbers, and other devices to reduce the mole fraction of selected constituents in gaseous mixtures. Consider a mixture of hydrocarbons that consists of 60 percent (by volume) methane, 20 percent ethane, and 10 percent propane. After passing through a separator, the mole fraction of the propane is reduced to 1 percent. The mixture pressure before and after the separation is 100 kPa. Determine the change in the partial pressures of all the constituents in the mixture.

13–43 Atmospheric contaminants are often measured in parts per million (by volume). What would the partial pressure of refrigerant-134a be in atmospheric air at 100 kPa and 20°C to form a 100-ppm contaminant?

13–44 A volume of 0.3 m^3 of O_2 at 200 K and 8 MPa is mixed with 0.5 m^3 of N_2 at the same temperature and pressure, forming a mixture at 200 K and 8 MPa. Determine the volume of the mixture, using (*a*) the ideal-gas equation of state, (*b*) Kay's rule, and (*c*) the compressibility chart and Amagat's law.

13–45 A rigid tank contains 1 kmol of Ar gas at 220 K and 5 MPa. A valve is now opened, and 3 kmol of N_2 gas is allowed to enter the tank at 190 K and 8 MPa. The final mixture temperature is 200 K. Determine the pressure of the mixture, using (*a*) the ideal-gas equation of state and (*b*) the compressibility chart and Dalton's law.

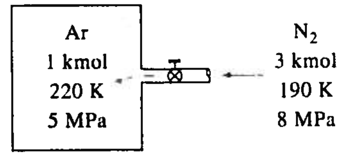


FIGURE P13–45

13–46 Reconsider Prob. 13–45. Using EES (or other) software, study the effect of varying the moles of nitrogen supplied to the tank over the range of 1 to 10 kmol of N_2. Plot the final pressure of the mixture as a function of the amount of nitrogen supplied using the ideal-gas equation of state and the compressibility chart with Dalton's law.

Properties of Gas Mixtures

13–47C Is the total internal energy of an ideal-gas mixture equal to the sum of the internal energies of each individual gas in the mixture? Answer the same question for a real-gas mixture.

13–48C Is the specific internal energy of a gas mixture equal to the sum of the specific internal energies of each individual gas in the mixture?

13–49C Answer Prob. 13–47C and 13–48C for entropy.

13–50C Is the total internal energy change of an ideal-gas mixture equal to the sum of the internal energy changes of each individual gas in the mixture? Answer the same question for a real-gas mixture.

13–51C When evaluating the entropy change of the components of an ideal-gas mixture, do we have to use the partial pressure of each component or the total pressure of the mixture?

13–52C Suppose we want to determine the enthalpy change of a real-gas mixture undergoing a process. The enthalpy change of each individual gas is determined by using the generalized enthalpy chart, and the enthalpy change of the mixture is determined by summing them. Is this an exact approach? Explain.

13–53 A mixture that is 15 percent carbon dioxide, 5 percent carbon monoxide, 10 percent oxygen, and 70 percent nitrogen by volume undergoes an adiabatic compression process having a compression ratio of 8. If the initial state of the mixture is 300 K and 100 kPa, determine the makeup of the mixture on a mass basis and the internal energy change per unit mass of mixture.

13–54 Propane and air are supplied to an internal combustion engine such that the air-fuel ratio is 16 when the pressure is 95 kPa and the temperature is 30°C. The compression ratio of the engine is 9.5. If the compression process is isentropic, determine the required work input for this compression process, in kJ/kg of mixture.

13–55 An insulated rigid tank is divided into two compartments by a partition. One compartment contains 2.5 kmol of CO_2 at 27°C and 200 kPa, and the other compartment contains 7.5 kmol of H_2 gas at 40°C and 400 kPa. Now the partition is removed, and the two gases are allowed to mix. Determine (*a*) the mixture temperature and (*b*) the mixture pressure after equilibrium has been established. Assume constant specific heats at room temperature for both gases.

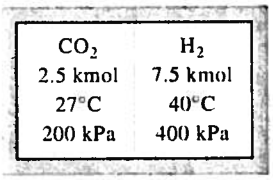


FIGURE P13–55

13–56 Ethane (C_2H_6) at 20°C and 200 kPa and methane (CH_4) at 45°C and 200 kPa enter an adiabatic mixing chamber. The mass flow rate of ethane is 9 kg/s, which is twice the mass flow rate of methane. Determine (*a*) the mixture temperature and (*b*) the rate of entropy generation during this process, in kW/K.

13–57 Reconsider Prob. 13–56. Using EES (or other) software, determine the effect of the mass fraction of methane in the mixture on the mixture temperature and the rate of exergy destruction. The total mass flow rate is maintained constant at 13.5 kg/s, and the mass fraction of methane is varied from 0 to 1. Plot the mixture temperature and the rate of exergy destruction against the mass fraction, and discuss the results. Take T_0 = 25°C.

13–58 A mixture of hydrogen and oxygen has a hydrogen mass fraction of 0.33. Determine the difference in the entropy of the mixture between a state of 750 kPa, 150°C and another state of 150 kPa, 150°C, in kJ/kg · K.

13–59 A mixture of nitrogen and carbon dioxide with a carbon dioxide mass fraction of 50 percent has a constant-volume specific heat of 0.792 kJ/kg · K. This mixture is heated at constant pressure in a closed system from 120 kPa and 30°C to 200°C. Calculate the work produced during this heating, in kJ/kg. *Answer: 37.4 kJ/kg*

13–60 The mass fractions of a mixture of gases are 15 percent nitrogen, 5 percent helium, 60 percent methane, and 20 percent ethane. This mixture is compressed from 140 kPa and 37°C in an isentropic process to 1400 kPa. Determine the final mixture temperature and the work required per unit mass of the mixture.

13–61 A mixture of hydrocarbon gases is composed of 60 percent methane, 25 percent propane, and 15 percent butane by weight. This mixture is compressed from 100 kPa and 20°C to 1000 kPa in a reversible, isothermal, steady-flow compressor. Calculate the work and heat transfer for this compression per unit mass of the mixture.

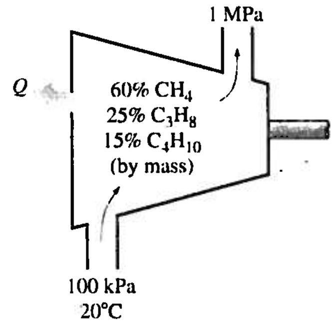


FIGURE P13–61

13–62 A mixture of gases consists of 0.1 kg of oxygen, 1 kg of carbon dioxide, and 0.5 kg of helium. This mixture is heated from 10°C to 260°C while its pressure is maintained constant at 350 kPa. Determine the change in the volume of the mixture and the total heat transferred to the mixture. *Answers: 0.396 m³, 552 kJ/kg*

13–63 During the expansion process of the ideal Otto cycle, the gas is a mixture whose volumetric composition is 25 percent nitrogen, 7 percent oxygen, 28 percent water, and 40 percent carbon dioxide. Calculate the thermal efficiency of this cycle when the air at the beginning of the compression is at 83 kPa and 13°C; the compression ratio is 7; and the maximum cycle temperature is 870°C. Model the heat-addition and heat-rejection processes using constant gas properties that are the average of the air and expansion gas properties.

13–64 How does the thermal efficiency of the cycle in Prob. 13–63 compare to that predicted by air-standard analysis?

13–65 The gas passing through the turbine of a simple ideal Brayton cycle has the volumetric composition 30 percent nitrogen, 10 percent oxygen, 40 percent carbon dioxide, and 20 percent water. Calculate the thermal efficiency of this cycle when the air enters the compressor at 100 kPa and 20°C, the pressure ratio is 8, and the temperature at the turbine inlet is 1000°C. Model the heat-addition and heat-rejection processes using constant gas properties that are the average of the air and expansion gas properties. *Answer: 37.5 percent*

13–66 How does the thermal efficiency of the cycle in Prob. 13–65 compare to that predicted by air-standard analysis?

13–67 In a liquid-oxygen plant, it is proposed that the pressure and temperature of air that is initially at 9000 kPa and 10°C be adiabatically reduced to 50 kPa and −73°C. Using

Kay's rule and the departure charts, determine whether this is possible. If so, then how much work per unit mass will this process produce?

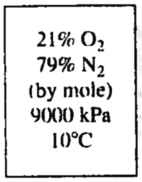


FIGURE P13-67

13–68 A mixture of 80 percent N_2 and 20 percent CO_2 gases (on a mass basis) enters the nozzle of a turbojet engine at 600 kPa and 1000 K with a low velocity, and it expands to a pressure of 85 kPa. If the isentropic efficiency of the nozzle is 92 percent, determine (*a*) the exit temperature and (*b*) the exit velocity of the mixture. Assume constant specific heats at room temperature.

13–69 Reconsider Prob. 13–68. Using EES (or other) software, first solve the stated problem and then, for all other conditions being the same, resolve the problem to determine the composition of the nitrogen and carbon dioxide that is required to have an exit velocity of 800 m/s at the nozzle exit.

13–70 A piston–cylinder device contains a mixture of 0.5 kg of H_2 and 1.6 kg of N_2 at 100 kPa and 300 K. Heat is now transferred to the mixture at constant pressure until the volume is doubled. Assuming constant specific heats at the average temperature, determine (*a*) the heat transfer and (*b*) the entropy change of the mixture.

13–71 A piston–cylinder device contains 6 kg of H_2 and 21 kg of N_2 at 160 K and 5 MPa. Heat is now transferred to the device, and the mixture expands at constant pressure until the temperature rises to 200 K. Determine the heat transfer during this process by treating the mixture (*a*) as an ideal gas and (*b*) as a nonideal gas and using Amagat's law.
Answers: [illegible]

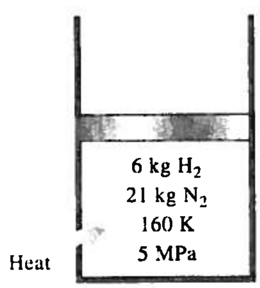


FIGURE P13–71

13–72 Determine the total entropy change and exergy destruction associated with the process described in Prob. 13–71 by treating the mixture (*a*) as an ideal gas and (*b*) as a nonideal gas and using Amagat's law. Assume constant specific heats at room temperature and take T_0 = 30°C.

13–73 Air, which may be considered as a mixture of 79 percent N_2 and 21 percent O_2 by mole numbers, is compressed isothermally at 200 K from 4 to 8 MPa in a steady-flow device. The compression process is internally reversible, and the mass flow rate of air is 2.9 kg/s. Determine the power input to the compressor and the rate of heat rejection by treating the mixture (*a*) as an ideal gas and (*b*) as a nonideal gas and using Amagat's law. *Answers:* (*a*) 115.3 kW, 115.3 kW, (*b*) 143.6 kW, 94.2 kW

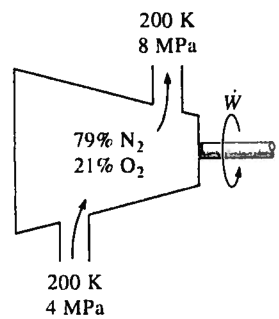


FIGURE P13–73

13–74 Reconsider Prob. 13–73. Using EES (or other) software, compare the results obtained by assuming ideal behavior, real gas behavior with Amagat's law, and real gas behavior with EES data.

13–75 The combustion of a hydrocarbon fuel with air results in a mixture of products of combustion having the composition on a volume basis as follows: 4.89 percent carbon dioxide, 6.50 percent water vapor, 12.20 percent oxygen, and 76.41 percent nitrogen. Determine the average molar mass of the mixture, the average specific heat at constant pressure of the mixture at 600 K, in kJ/kmol · K, and the partial pressure of the water vapor in the mixture for a mixture pressure of 200 kPa.

Special Topic: Chemical Potential and the Separation Work of Mixtures

13–76C It is common experience that two gases brought into contact mix by themselves. In the future, could it be possible to invent a process that will enable a mixture to separate into its components by itself without any work (or exergy) input?

9.85

9-98 A simple Brayton cycle with air as the working fluid has a pressure ratio of 8. The air temperature at the turbine exit, the net work output, and the thermal efficiency are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The air-standard assumptions are applicable. 3 Kinetic and potential energy changes are negligible. 4 Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg·K and k = 1.4 (Table A-2).

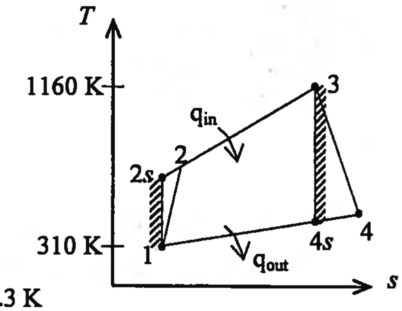
Analysis (*a*) Using the compressor and turbine efficiency relations,

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (310\ \text{K})(8)^{0.4/1.4} = 561.5\ \text{K}$$

$$T_{4s} = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1160\ \text{K})\left(\frac{1}{8}\right)^{0.4/1.4} = 640.4\ \text{K}$$

$$\eta_C = \frac{h_{2s}-h_1}{h_2-h_1} = \frac{c_p(T_{2s}-T_1)}{c_p(T_2-T_1)} \longrightarrow T_2 = T_1 + \frac{T_{2s}-T_1}{\eta_C}$$

$$= 310 + \frac{561.5-310}{0.75} = 645.3\ \text{K}$$



$$\eta_T = \frac{h_3-h_4}{h_3-h_{4s}} = \frac{c_p(T_3-T_4)}{c_p(T_3-T_{4s})} \longrightarrow T_4 = T_3 - \eta_T(T_3 - T_{4s})$$

$$= 1160 - (0.82)(1160-640.4)$$

$$= \mathbf{733.9\ K}$$

(*b*)

$$q_{in} = h_3 - h_2 = c_p(T_3-T_2) = (1.005\ \text{kJ/kg}\cdot\text{K})(1160-645.3)\text{K} = 517.3\ \text{kJ/kg}$$

$$q_{out} = h_4 - h_1 = c_p(T_4-T_1) = (1.005\ \text{kJ/kg}\cdot\text{K})(733.9-310)\text{K} = 426.0\ \text{kJ/kg}$$

$$w_{net,out} = q_{in} - q_{out} = 517.3 - 426.0 = \mathbf{91.3\ kJ/kg}$$

(*c*)

$$\eta_{th} = \frac{w_{net,out}}{q_{in}} = \frac{91.3\ \text{kJ/kg}}{517.3\ \text{kJ/kg}} = \mathbf{17.6\%}$$

9.89

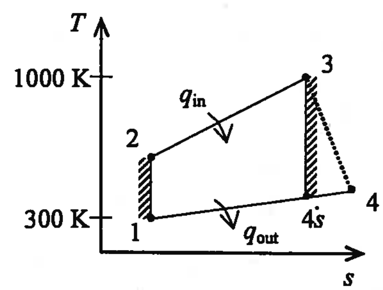
~~9-95~~ A simple Brayton cycle with air as the working fluid operates between the specified temperature and pressure limits. The net work and the thermal efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The air-standard assumptions are applicable. **3** Kinetic and potential energy changes are negligible. **4** Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are $c_p = 1.005$ kJ/kg·K and $k = 1.4$ (Table A-2a).

Analysis Using the isentropic relations for an ideal gas,

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (300\text{ K})\left(\frac{2000\text{ kPa}}{100\text{ kPa}}\right)^{0.4/1.4} = 706.1\text{ K}$$



For the expansion process,

$$T_{4s} = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1000\text{ K})\left(\frac{100\text{ kPa}}{2000\text{ kPa}}\right)^{0.4/1.4} = 424.9\text{ K}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} = \frac{c_p(T_3 - T_4)}{c_p(T_3 - T_{4s})} \longrightarrow T_4 = T_3 - \eta_T(T_3 - T_{4s})$$
$$= 1000 - (0.90)(1000 - 424.9)$$
$$= 482.4\text{ K}$$

Applying the first law to the constant-pressure heat addition process 2-3 produces

$$Q_{in} = m(h_3 - h_2) = mc_p(T_3 - T_2) = (1\text{ kg})(1.005\text{ kJ/kg}\cdot\text{K})(1000 - 706.1)\text{K} = 295.4\text{ kJ}$$

Similarly,

$$Q_{out} = m(h_4 - h_1) = mc_p(T_4 - T_1) = (1\text{ kg})(1.005\text{ kJ/kg}\cdot\text{K})(482.4 - 300)\text{K} = 183.3\text{ kJ}$$

The net work production is then

$$W_{net} = Q_{in} - Q_{out} = 295.4 - 183.3 = \mathbf{112.1\text{ kJ}}$$

and the thermal efficiency of this cycle is

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{112.1\text{ kJ}}{295.4\text{ kJ}} = \mathbf{0.379}$$

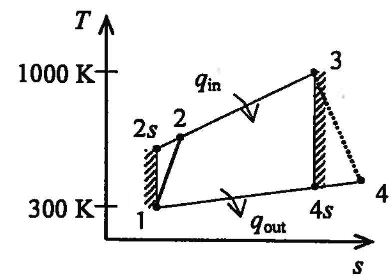
9.90

9-96 A simple Brayton cycle with air as the working fluid operates between the specified temperature and pressure limits. The net work and the thermal efficiency are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The air-standard assumptions are applicable. 3 Kinetic and potential energy changes are negligible. 4 Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are $c_p = 1.005$ kJ/kg·K and $k = 1.4$ (Table A-2a).

Analysis For the compression process,



$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (300\text{ K})\left(\frac{2000\text{ kPa}}{100\text{ kPa}}\right)^{0.4/1.4} = 706.1\text{ K}$$

$$\eta_C = \frac{h_{2s}-h_1}{h_2-h_1} = \frac{c_p(T_{2s}-T_1)}{c_p(T_2-T_1)} \longrightarrow T_2 = T_1 + \frac{T_{2s}-T_1}{\eta_C}$$

$$= 300 + \frac{706.1-300}{0.80} = 807.6\text{ K}$$

For the expansion process,

$$T_{4s} = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1000\text{ K})\left(\frac{100\text{ kPa}}{2000\text{ kPa}}\right)^{0.4/1.4} = 424.9\text{ K}$$

$$\eta_T = \frac{h_3-h_4}{h_3-h_{4s}} = \frac{c_p(T_3-T_4)}{c_p(T_3-T_{4s})} \longrightarrow T_4 = T_3 - \eta_T(T_3-T_{4s})$$

$$= 1000-(0.90)(1000-424.9)$$

$$= 482.4\text{ K}$$

Applying the first law to the constant-pressure heat addition process 2-3 produces

$$Q_{in} = m(h_3-h_2) = mc_p(T_3-T_2) = (1\text{ kg})(1.005\text{ kJ/kg}\cdot\text{K})(1000-807.6)\text{K} = 193.4\text{ kJ}$$

Similarly,

$$Q_{out} = m(h_4-h_1) = mc_p(T_4-T_1) = (1\text{ kg})(1.005\text{ kJ/kg}\cdot\text{K})(482.4-300)\text{K} = 183.3\text{ kJ}$$

The net work production is then

$$W_{net} = Q_{in} - Q_{out} = 193.4 - 183.3 = \mathbf{10.1\text{ kJ}}$$

and the thermal efficiency of this cycle is

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{10.1\text{ kJ}}{193.4\text{ kJ}} = \mathbf{0.0522}$$

9.96

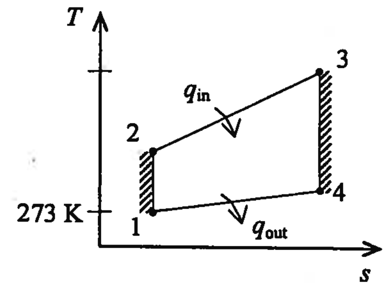
9-103 An aircraft engine operates as a simple ideal Brayton cycle with air as the working fluid. The pressure ratio and the rate of heat input are given. The net power and the thermal efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The air-standard assumptions are applicable. **3** Kinetic and potential energy changes are negligible. **4** Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg·K and k = 1.4 (Table A-2a).

Analysis For the isentropic compression process,

$$T_2 = T_1 r_p^{(k-1)/k} = (273\,\text{K})(10)^{0.4/1.4} = 527.1\,\text{K}$$



The heat addition is

$$q_{\text{in}} = \frac{\dot{Q}_{\text{in}}}{\dot{m}} = \frac{500\,\text{kW}}{1\,\text{kg/s}} = 500\,\text{kJ/kg}$$

Applying the first law to the heat addition process,

$$q_{\text{in}} = c_p(T_3 - T_2)$$

$$T_3 = T_2 + \frac{q_{\text{in}}}{c_p} = 527.1\,\text{K} + \frac{500\,\text{kJ/kg}}{1.005\,\text{kJ/kg}\cdot\text{K}} = 1025\,\text{K}$$

The temperature at the exit of the turbine is

$$T_4 = T_3\left(\frac{1}{r_p}\right)^{(k-1)/k} = (1025\,\text{K})\left(\frac{1}{10}\right)^{0.4/1.4} = 530.9\,\text{K}$$

Applying the first law to the adiabatic turbine and the compressor produce

$$w_{\text{T}} = c_p(T_3 - T_4) = (1.005\,\text{kJ/kg}\cdot\text{K})(1025 - 530.9)\text{K} = 496.6\,\text{kJ/kg}$$

$$w_{\text{C}} = c_p(T_2 - T_1) = (1.005\,\text{kJ/kg}\cdot\text{K})(527.1 - 273)\text{K} = 255.4\,\text{kJ/kg}$$

The net power produced by the engine is then

$$\dot{W}_{\text{net}} = \dot{m}(w_{\text{T}} - w_{\text{C}}) = (1\,\text{kg/s})(496.6 - 255.4)\text{kJ/kg} = \mathbf{241.2\,kW}$$

Finally the thermal efficiency is

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{241.2\,\text{kW}}{500\,\text{kW}} = \mathbf{0.482}$$

9.97

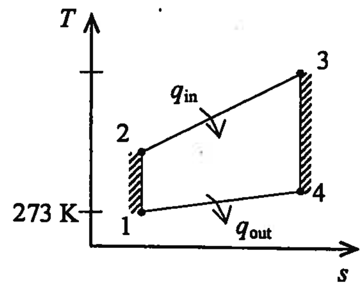
9-104 An aircraft engine operates as a simple ideal Brayton cycle with air as the working fluid. The pressure ratio and the rate of heat input are given. The net power and the thermal efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The air-standard assumptions are applicable. **3** Kinetic and potential energy changes are negligible. **4** Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg·K and k = 1.4 (Table A-2a).

Analysis For the isentropic compression process,

$$T_2 = T_1 r_p^{(k-1)/k} = (273\text{ K})(15)^{0.4/1.4} = 591.8\text{ K}$$



The heat addition is

$$q_{in} = \frac{\dot{Q}_{in}}{\dot{m}} = \frac{500\text{ kW}}{1\text{ kg/s}} = 500\text{ kJ/kg}$$

Applying the first law to the heat addition process,

$$q_{in} = c_p(T_3 - T_2)$$

$$T_3 = T_2 + \frac{q_{in}}{c_p} = 591.8\text{ K} + \frac{500\text{ kJ/kg}}{1.005\text{ kJ/kg}\cdot\text{K}} = 1089\text{ K}$$

The temperature at the exit of the turbine is

$$T_4 = T_3\left(\frac{1}{r_p}\right)^{(k-1)/k} = (1089\text{ K})\left(\frac{1}{15}\right)^{0.4/1.4} = 502.3\text{ K}$$

Applying the first law to the adiabatic turbine and the compressor produce

$$w_T = c_p(T_3 - T_4) = (1.005\text{ kJ/kg}\cdot\text{K})(1089 - 502.3)\text{K} = 589.6\text{ kJ/kg}$$

$$w_C = c_p(T_2 - T_1) = (1.005\text{ kJ/kg}\cdot\text{K})(591.8 - 273)\text{K} = 320.4\text{ kJ/kg}$$

The net power produced by the engine is then

$$\dot{W}_{net} = \dot{m}(w_T - w_C) = (1\text{ kg/s})(589.6 - 320.4)\text{kJ/kg} = \mathbf{269.2\text{ kW}}$$

Finally the thermal efficiency is

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{269.2\text{ kW}}{500\text{ kW}} = \mathbf{0.538}$$

Brayton Cycle with Regeneration

9-106C Regeneration increases the thermal efficiency of a Brayton cycle by capturing some of the waste heat from the exhaust gases and preheating the air before it enters the combustion chamber.

9-107C Yes. At very high compression ratios, the gas temperature at the turbine exit may be lower than the temperature at the compressor exit. Therefore, if these two streams are brought into thermal contact in a regenerator, heat will flow to the exhaust gases instead of from the exhaust gases. As a result, the thermal efficiency will decrease.

9-108C The extent to which a regenerator approaches an ideal regenerator is called the effectiveness ε, and is defined as $\varepsilon = q_{\text{regen, act}} / q_{\text{regen, max}}$.

9-109C (b) turbine exit.

9.103C

9-110C The steam injected increases the mass flow rate through the turbine and thus the power output. This, in turn, increases the thermal efficiency since $\eta = W / Q_{\text{in}}$ and W increases while Q_{in} remains constant. Steam can be obtained by utilizing the hot exhaust gases.

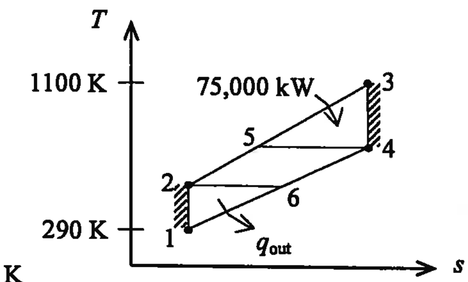
9.113

~~9-120~~ A stationary gas-turbine power plant operating on an ideal regenerative Brayton cycle with air as the working fluid is considered. The power delivered by this plant is to be determined for two cases.

Assumptions **1** The air standard assumptions are applicable. **2** Air is an ideal gas. **3** Kinetic and potential energy changes are negligible.

Properties When assuming constant specific heats, the properties of air at room temperature are c_p = 1.005 kJ/kg.K and k = 1.4 (Table A-2a). When assuming variable specific heats, the properties of air are obtained from Table A-17.

Analysis (*a*) Assuming constant specific heats,



$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (290\text{ K})(8)^{0.4/1.4} = 525.3\text{ K}$$

$$T_4 = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1100\text{ K})\left(\frac{1}{8}\right)^{0.4/1.4} = 607.2\text{ K}$$

$$\varepsilon = 100\% \longrightarrow T_5 = T_4 = 607.2\text{ K and } T_6 = T_2 = 525.3\text{ K}$$

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{c_p(T_6 - T_1)}{c_p(T_3 - T_5)} = 1 - \frac{T_6 - T_1}{T_3 - T_5} = 1 - \frac{525.3 - 290}{1100 - 607.2} = 0.5225$$

$$\dot{W}_{\text{net}} = \eta_T \dot{Q}_{\text{in}} = (0.5225)(75{,}000\text{ kW}) = \mathbf{39{,}188\ kW}$$

(*b*) Assuming variable specific heats,

$$T_1 = 290\text{K} \longrightarrow \begin{array}{l} h_1 = 290.16\text{ kJ/kg} \\ P_{r_1} = 1.2311 \end{array}$$

$$P_{r_2} = \frac{P_2}{P_1} P_{r_1} = (8)(1.2311) = 9.8488 \longrightarrow h_2 = 526.12\text{ kJ/kg}$$

$$T_3 = 1100\text{K} \longrightarrow \begin{array}{l} h_3 = 1161.07\text{ kJ/kg} \\ P_{r_3} = 167.1 \end{array}$$

$$P_{r_4} = \frac{P_4}{P_3} P_{r_3} = \left(\frac{1}{8}\right)(167.1) = 20.89 \longrightarrow h_4 = 651.37\text{ kJ/kg}$$

$$\varepsilon = 100\% \longrightarrow h_5 = h_4 = 651.37\text{ kJ/kg and } h_6 = h_2 = 526.12\text{ kJ/kg}$$

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{h_6 - h_1}{h_3 - h_5} = 1 - \frac{526.12 - 290.16}{1161.07 - 651.37} = 0.5371$$

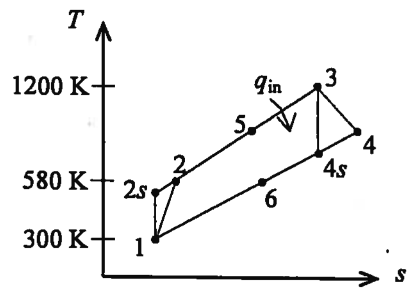
$$\dot{W}_{\text{net}} = \eta_T \dot{Q}_{\text{in}} = (0.5371)(75{,}000\text{ kW}) = \mathbf{40{,}283\ kW}$$

9.114

~~9-122~~ A regenerative gas-turbine engine using air as the working fluid is considered. The amount of heat transfer in the regenerator and the thermal efficiency are to be determined.

Assumptions **1** The air standard assumptions are applicable. **2** Air is an ideal gas with constant specific heats. **3** Kinetic and potential energy changes are negligible.

Properties The properties of air at room temperature are $c_p = 1.005$ kJ/kg.K and $k = 1.4$ (Table A-2a).



Analysis (a) Using the isentropic relations and turbine efficiency,

$$r_p = P_2 / P_1 = 800/100 = 8$$

$$T_{4s} = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1200\text{ K})\left(\frac{1}{8}\right)^{0.4/1.4} = 662.5\text{ K}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} = \frac{c_p(T_3 - T_4)}{c_p(T_3 - T_{4s})} \longrightarrow T_4 = T_3 - \eta_T(T_3 - T_{4s})$$
$$= 1200 - (0.86)(1200 - 662.5)$$
$$= 737.8\text{ K}$$

$$q_{regen} = \varepsilon(h_4 - h_2) = \varepsilon c_p(T_4 - T_2) = (0.72)(1.005\text{ kJ/kg}\cdot\text{K})(737.8 - 580)\text{K} = \mathbf{114.2\ kJ/kg}$$

(b)

$$w_{net} = w_{T,out} - w_{C,in} = c_p(T_3 - T_4) - c_p(T_2 - T_1)$$
$$= (1.005\text{ kJ/kg}\cdot\text{K})[(1200 - 737.8) - (580 - 300)]\text{K} = 183.1\text{ kJ/kg}$$
$$q_{in} = (h_3 - h_2) - q_{regen} = c_p(T_3 - T_2) - q_{regen}$$
$$= (1.005\text{ kJ/kg}\cdot\text{K})(1200 - 580)\text{K} - 114.2 = 508.9\text{ kJ/kg}$$
$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{183.1\text{ kJ/kg}}{508.9\text{ kJ/kg}} = \mathbf{36.0\%}$$

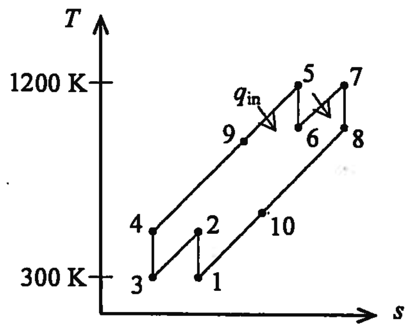
9.124

9-131 An ideal gas-turbine cycle with two stages of compression and two stages of expansion is considered. The back work ratio and the thermal efficiency of the cycle are to be determined for the cases of with and without a regenerator.

Assumptions **1** The air standard assumptions are applicable. **2** Air is an ideal gas with variable specific heats. **3** Kinetic and potential energy changes are negligible.

Properties The properties of air are given in Table A-17.

Analysis (*a*) The work inputs to each stage of compressor are identical, so are the work outputs of each stage of the turbine since this is an ideal cycle. Then,



$$T_1 = 300 \text{ K} \longrightarrow \begin{array}{l} h_1 = 300.19 \text{ kJ/kg} \\ P_{r_1} = 1.386 \end{array}$$

$$P_{r_2} = \frac{P_2}{P_1} P_{r_1} = (3)(1.386) = 4.158 \longrightarrow h_2 = h_4 = 411.26 \text{ kJ/kg}$$

$$T_5 = 1200 \text{ K} \longrightarrow \begin{array}{l} h_5 = h_7 = 1277.79 \text{ kJ/kg} \\ P_{r_5} = 238 \end{array}$$

$$P_{r_6} = \frac{P_6}{P_5} P_{r_5} = \left(\frac{1}{3}\right)(238) = 79.33 \longrightarrow h_6 = h_8 = 946.36 \text{ kJ/kg}$$

$$w_{C,in} = 2(h_2 - h_1) = 2(411.26 - 300.19) = 222.14 \text{ kJ/kg}$$

$$w_{T,out} = 2(h_5 - h_6) = 2(1277.79 - 946.36) = 662.86 \text{ kJ/kg}$$

Thus,

$$r_{bw} = \frac{w_{C,in}}{w_{T,out}} = \frac{222.14 \text{ kJ/kg}}{662.86 \text{ kJ/kg}} = 33.5\%$$

$$q_{in} = (h_5 - h_4) + (h_7 - h_6) = (1277.79 - 411.26) + (1277.79 - 946.36) = 1197.96 \text{ kJ/kg}$$

$$w_{net} = w_{T,out} - w_{C,in} = 662.86 - 222.14 = 440.72 \text{ kJ/kg}$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{440.72 \text{ kJ/kg}}{1197.96 \text{ kJ/kg}} = 36.8\%$$

(*b*) When a regenerator is used, r_{bw} remains the same. The thermal efficiency in this case becomes

$$q_{regen} = \varepsilon(h_8 - h_4) = (0.75)(946.36 - 411.26) = 401.33 \text{ kJ/kg}$$

$$q_{in} = q_{in,old} - q_{regen} = 1197.96 - 401.33 = 796.63 \text{ kJ/kg}$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{440.72 \text{ kJ/kg}}{796.63 \text{ kJ/kg}} = 55.3\%$$

9.126

~~9-135~~ A regenerative gas-turbine cycle with two stages of compression and two stages of expansion is considered. The thermal efficiency of the cycle is to be determined.

Assumptions **1** The air standard assumptions are applicable. **2** Air is an ideal gas with constant specific heats at room temperature. **3** Kinetic and potential energy changes are negligible.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg·K and k = 1.4 (Table A-2a).

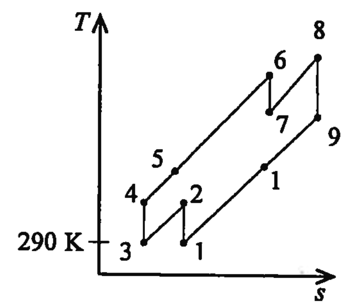
Analysis The temperatures at various states are obtained as follows

$$T_2 = T_4 = T_1 r_p^{(k-1)/k} = (290\text{ K})(4)^{0.4/1.4} = 430.9\text{ K}$$

$$T_5 = T_4 + 20 = 430.9 + 20 = 450.9\text{ K}$$

$$q_{\text{in}} = c_p(T_6 - T_5)$$

$$T_6 = T_5 + \frac{q_{\text{in}}}{c_p} = 450.9\text{ K} + \frac{300\text{ kJ/kg}}{1.005\text{ kJ/kg}\cdot\text{K}} = 749.4\text{ K}$$



$$T_7 = T_6\left(\frac{1}{r_p}\right)^{(k-1)/k} = (749.4\text{ K})\left(\frac{1}{4}\right)^{0.4/1.4} = 504.3\text{ K}$$

$$T_8 = T_7 + \frac{q_{\text{in}}}{c_p} = 504.3\text{ K} + \frac{300\text{ kJ/kg}}{1.005\text{ kJ/kg}\cdot\text{K}} = 802.8\text{ K}$$

$$T_9 = T_8\left(\frac{1}{r_p}\right)^{(k-1)/k} = (802.8\text{ K})\left(\frac{1}{4}\right)^{0.4/1.4} = 540.2\text{ K}$$

$$T_{10} = T_9 - 20 = 540.2 - 20 = 520.2\text{ K}$$

The heat input is

$$q_{\text{in}} = 300 + 300 = 600\text{ kJ/kg}$$

The heat rejected is

$$\begin{aligned} q_{\text{out}} &= c_p(T_{10} - T_1) + c_p(T_2 - T_3) \\ &= (1.005\text{ kJ/kg}\cdot\text{K})(520.2 - 290 + 430.9 - 290)\text{ R} \\ &= 373.0\text{ kJ/kg} \end{aligned}$$

The thermal efficiency of the cycle is then

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{373.0}{600} = \mathbf{0.378}$$

9.134

9-143 A turbofan engine operating on an ideal cycle produces 50,000 N of thrust. The air temperature at the fan outlet needed to produce this thrust is to be determined.

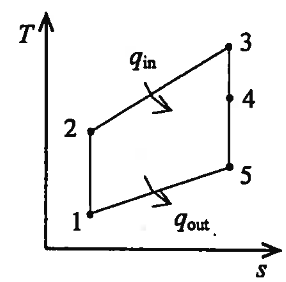
Assumptions **1** Steady operating conditions exist. **2** The air standard assumptions are applicable. **3** Air is an ideal gas with constant specific heats at room temperature. **4** The turbine work output is equal to the compressor work input.

Properties The properties of air at room temperature are $R = 0.287$ kPa·m³/kg·K, $c_p = 1.005$ kJ/kg·K and $k = 1.4$ (Table A-2a).

Analysis The total mass flow rate is

$$v_1 = \frac{RT}{P} = \frac{(0.287\ \text{kPa}\cdot\text{m}^3)(253\ \text{K})}{50\ \text{kPa}} = 1.452\ \text{m}^3/\text{kg}$$

$$\dot{m} = \frac{AV_1}{v_1} = \frac{\pi D^2}{4}\frac{V_1}{v_1} = \frac{\pi(2.5\ \text{m})^2}{4}\frac{200\ \text{m/s}}{1.452\ \text{m}^3/\text{kg}} = 676.1\ \text{kg/s}$$



Now,

$$\dot{m}_e = \frac{\dot{m}}{8} = \frac{676.1\ \text{kg/s}}{8} = 84.51\ \text{kg/s}$$

The mass flow rate through the fan is

$$\dot{m}_f = \dot{m} - \dot{m}_e = 676.1 - 84.51 = 591.6\ \text{kg/s}$$

In order to produce the specified thrust force, the velocity at the fan exit will be

$$F = \dot{m}_f (V_{\text{exit}} - V_{\text{inlet}})$$

$$V_{\text{exit}} = V_{\text{inlet}} + \frac{F}{\dot{m}_f} = (200\ \text{m/s}) + \frac{50{,}000\ \text{N}}{591.6\ \text{kg/s}}\left(\frac{1\ \text{kg}\cdot\text{m/s}^2}{1\ \text{N}}\right) = 284.5\ \text{m/s}$$

An energy balance on the stream passing through the fan gives

$$c_p(T_4 - T_5) = \frac{V_{\text{exit}}^2 - V_{\text{inlet}}^2}{2}$$

$$T_5 = T_4 - \frac{V_{\text{exit}}^2 - V_{\text{inlet}}^2}{2c_p}$$

$$= 253\ \text{K} - \frac{(284.5\ \text{m/s})^2 - (200\ \text{m/s})^2}{2(1.005\ \text{kJ/kg}\cdot\text{K})}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)$$

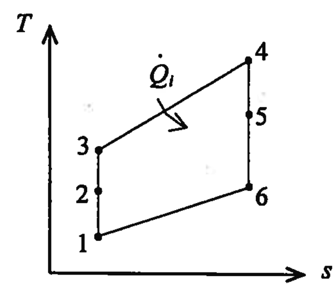
$$= \mathbf{232.6\ K}$$

9.136

9-145 A turbojet aircraft flying at an altitude of 9150 m is operating on the ideal jet propulsion cycle. The velocity of exhaust gases, the propulsive power developed, and the rate of fuel consumption are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The air standard assumptions are applicable. 3 Air is an ideal gas with constant specific heats at room temperature. 4 Kinetic and potential energies are negligible, except at the diffuser inlet and the nozzle exit. 5 The turbine work output is equal to the compressor work input.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg.K and k = 1.4 (Table A-2a).



Analysis (*a*) We assume the aircraft is stationary and the air is moving towards the aircraft at a velocity of V_1 = 320 m/s. Ideally, the air will leave the diffuser with a negligible velocity ($V_2 \cong 0$).

Diffuser:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\;\not{0}\text{ (steady)}} \longrightarrow \dot{E}_{in} = \dot{E}_{out}$$

$$h_1 + V_1^2/2 = h_2 + V_2^2/2 \longrightarrow 0 = h_2 - h_1 + \frac{V_2^{2\;\not{0}} - V_1^2}{2}$$

$$0 = c_p(T_2 - T_1) - V_1^2/2$$

$$T_2 = T_1 + \frac{V_1^2}{2c_p} = 241\text{ K} + \frac{(320\text{ m/s})^2}{(2)(1.005\text{ kJ/kg}\cdot\text{K})}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 291.9\text{ K}$$

$$P_2 = P_1\left(\frac{T_2}{T_1}\right)^{k/(k-1)} = (32\text{ kPa})\left(\frac{291.9\text{ K}}{241\text{ K}}\right)^{1.4/0.4} = 62.6\text{ kPa}$$

Compressor:

$$P_3 = P_4 = (r_p)(P_2) = (12)(62.6\text{ kPa}) = 751.2\text{ kPa}$$

$$T_3 = T_2\left(\frac{P_3}{P_2}\right)^{(k-1)/k} = (291.9\text{ K})(12)^{0.4/1.4} = 593.7\text{ K}$$

Turbine:

$$w_{comp,in} = w_{turb,out} \longrightarrow h_3 - h_2 = h_4 - h_5 \longrightarrow c_p(T_3 - T_2) = c_p(T_4 - T_5)$$

or

$$T_5 = T_4 - T_3 + T_2 = 1400 - 593.7 + 291.9 = 1098.2\text{K}$$

Nozzle:

$$T_6 = T_4\left(\frac{P_6}{P_4}\right)^{(k-1)/k} = (1400\text{ K})\left(\frac{32\text{ kPa}}{751.2\text{ kPa}}\right)^{0.4/1.4} = 568.2\text{ K}$$

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\;\not{0}\text{ (steady)}} \longrightarrow \dot{E}_{in} = \dot{E}_{out}$$

$$h_5 + V_5^2/2 = h_6 + V_6^2/2$$

$$0 = h_6 - h_5 + \frac{V_6^2 - V_5^{2\;\not{0}}}{2} \longrightarrow 0 = c_p(T_6 - T_5) + V_6^2/2$$

or,

$$V_6 = \sqrt{(2)(1.005\ \text{kJ/kg}\cdot\text{K})(1098.2 - 568.2)\text{K}\left(\frac{1000\ \text{m}^2/\text{s}^2}{1\ \text{kJ/kg}}\right)} = \mathbf{1032\ m/s}$$

(*b*) $$\dot{W}_p = \dot{m}(V_{\text{exit}} - V_{\text{inlet}})V_{\text{aircraft}} = (60\ \text{kg/s})(1032 - 320)\text{m/s}(320\ \text{m/s})\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = \mathbf{13{,}670\ kW}$$

(*c*) $$\dot{Q}_{\text{in}} = \dot{m}(h_4 - h_3) = \dot{m}c_p(T_4 - T_3) = (60\ \text{kg/s})(1.005\ \text{kJ/kg}\cdot\text{K})(1400 - 593.7)\text{K} = 48{,}620\ \text{kJ/s}$$

$$\dot{m}_{\text{fuel}} = \frac{\dot{Q}_{\text{in}}}{\text{HV}} = \frac{48{,}620\ \text{kJ/s}}{42{,}700\ \text{kJ/kg}} = \mathbf{1.14\ kg/s}$$

11.11

11-11 A commercial refrigerator with refrigerant-134a as the working fluid is considered. The quality of the refrigerant at the evaporator inlet, the refrigeration load, the COP of the refrigerator, and the theoretical maximum refrigeration load for the same power input to the compressor are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis (*a*) From refrigerant-134a tables (Tables A-11 through A-13)

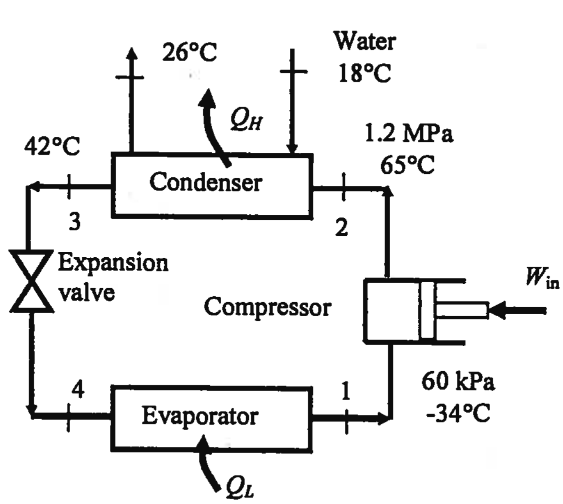
$$\left.\begin{array}{l} P_1 = 60 \text{ kPa} \\ T_1 = -34°\text{C} \end{array}\right\} h_1 = 230.03 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 1200 \text{ kPa} \\ T_2 = 65°\text{C} \end{array}\right\} h_2 = 295.16 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 1200 \text{ kPa} \\ T_3 = 42°\text{C} \end{array}\right\} h_3 = 111.23 \text{ kJ/kg}$$

$$h_4 = h_3 = 111.23 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 60 \text{ kPa} \\ h_4 = 111.23 \text{ kJ/kg} \end{array}\right\} x_4 = \mathbf{0.4795}$$



Using saturated liquid enthalpy at the given temperature, for water we have (Table A-4)

$$h_{w1} = h_{f@18°C} = 75.47 \text{ kJ/kg}$$

$$h_{w2} = h_{f@26°C} = 108.94 \text{ kJ/kg}$$

(*b*) The mass flow rate of the refrigerant may be determined from an energy balance on the compressor

$$\dot{m}_R(h_2 - h_3) = \dot{m}_w(h_{w2} - h_{w1})$$

$$\dot{m}_R(295.16 - 111.23)\text{kJ/kg} = (0.25 \text{ kg/s})(108.94 - 75.47)\text{kJ/kg}$$

$$\longrightarrow \dot{m}_R = 0.0455 \text{ kg/s}$$

The waste heat transferred from the refrigerant, the compressor power input, and the refrigeration load are

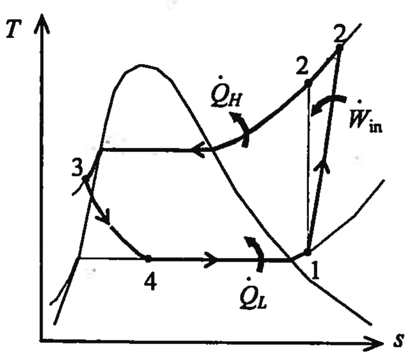
$$\dot{Q}_H = \dot{m}_R(h_2 - h_3) = (0.0455 \text{ kg/s})(295.16 - 111.23)\text{kJ/kg} = 8.367 \text{ kW}$$

$$\dot{W}_{in} = \dot{m}_R(h_2 - h_1) - \dot{Q}_{in} = (0.0455 \text{ kg/s})(295.16 - 230.03)\text{kJ/kg} - 0.45 \text{ kW} = 2.513 \text{ kW}$$

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{in} = 8.367 - 2.513 = \mathbf{5.85 \text{ kW}}$$

(*c*) The COP of the refrigerator is determined from its definition

$$\text{COP} = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{5.85}{2.513} = \mathbf{2.33}$$



(*d*) The reversible COP of the refrigerator for the same temperature limits is

$$\text{COP}_{max} = \frac{1}{T_H / T_L - 1} = \frac{1}{(18+273)/(-30+273) - 1} = 5.063$$

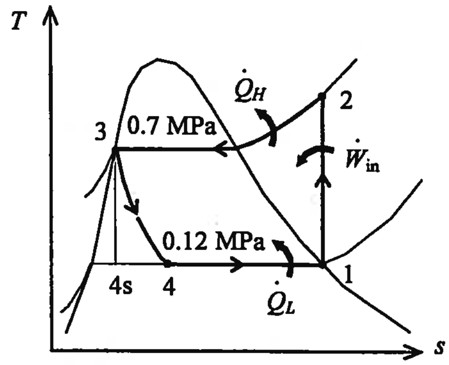
Then, the maximum refrigeration load becomes

$$\dot{Q}_{L,max} = COP_{max}\dot{W}_{in} = (5.063)(2.513 \text{ kW}) = \mathbf{12.72 \text{ kW}}$$

11.16

~~11-18~~ An ideal vapor-compression refrigeration cycle with refrigerant-134a as the working fluid is considered. The throttling valve in the cycle is replaced by an isentropic turbine. The percentage increase in the COP and in the rate of heat removal from the refrigerated space due to this replacement are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.



Analysis If the throttling valve in the previous problem is replaced by an isentropic turbine, we would have $s_{4s} = s_3 = s_{f @ 0.7 \text{ MPa}} = 0.33230$ kJ/kg·K, and the enthalpy at the turbine exit would be

$$x_{4s} = \left(\frac{s_3 - s_f}{s_{fg}}\right)_{@ 120 \text{ kPa}} = \frac{0.33230 - 0.09275}{0.85503} = 0.2802$$

$$h_{4s} = \left(h_f + x_{4s} h_{fg}\right)_{@ 120 \text{ kPa}} = 22.49 + (0.2802)(214.48) = 82.58 \text{ kJ/kg}$$

Then,

$$\dot{Q}_L = \dot{m}(h_1 - h_{4s}) = (0.05 \text{ kg/s})(236.97 - 82.58) \text{ kJ/kg} = 7.72 \text{ kW}$$

and

$$\text{COP}_\text{R} = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{7.72 \text{ kW}}{1.83 \text{ kW}} = 4.23$$

Then the percentage increase in $\dot{Q}$ and COP becomes

$$\text{Increase in } \dot{Q}_L = \frac{\Delta \dot{Q}_L}{\dot{Q}_L} = \frac{7.72 - 7.41}{7.41} = \mathbf{4.2\%}$$

$$\text{Increase in COP}_\text{R} = \frac{\Delta \text{COP}_\text{R}}{\text{COP}_\text{R}} = \frac{4.23 - 4.06}{4.06} = \mathbf{4.2\%}$$

11.17

~~11-19~~ A refrigerator with refrigerant-134a as the working fluid is considered. The rate of heat removal from the refrigerated space, the power input to the compressor, the isentropic efficiency of the compressor, and the COP of the refrigerator are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis (*a*) From the refrigerant tables (Tables A-12 and A-13),

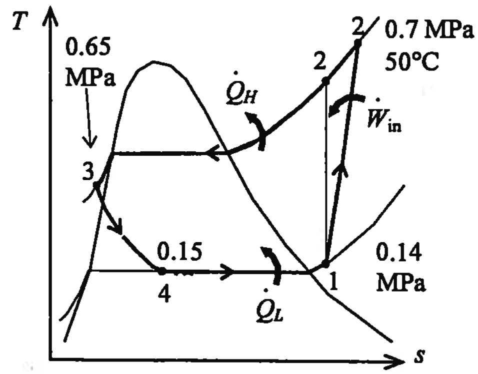
$$\left.\begin{array}{l} P_1 = 0.14 \text{ MPa} \\ T_1 = -10°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 246.36 \text{ kJ/kg} \\ s_1 = 0.97236 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 0.7 \text{ MPa} \\ T_2 = 50°\text{C} \end{array}\right\} h_2 = 288.53 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_{2s} = 0.7 \text{ MPa} \\ s_{2s} = s_1 \end{array}\right\} h_{2s} = 281.16 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 0.65 \text{ MPa} \\ T_3 = 24°\text{C} \end{array}\right\} h_3 = h_{f\,@\,24°\text{C}} = 84.98 \text{ kJ/kg}$$

$$h_4 \cong h_3 = 84.98 \text{ kJ/kg (throttling)}$$



Then the rate of heat removal from the refrigerated space and the power input to the compressor are determined from

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.12 \text{ kg/s})(246.36 - 84.98) \text{ kJ/kg} = \mathbf{19.4 \text{ kW}}$$

and

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = (0.12 \text{ kg/s})(288.53 - 246.36) \text{ kJ/kg} = \mathbf{5.06 \text{ kW}}$$

(*b*) The adiabatic efficiency of the compressor is determined from

$$\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{281.16 - 246.36}{288.53 - 246.36} = \mathbf{82.5\%}$$

(*c*) The COP of the refrigerator is determined from its definition,

$$\text{COP}_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{19.4 \text{ kW}}{5.06 \text{ kW}} = \mathbf{3.83}$$

11.18

~~11-20~~ An air conditioner operating on the ideal vapor-compression refrigeration cycle with refrigerant-134a as the working fluid is considered. The COP of the system is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

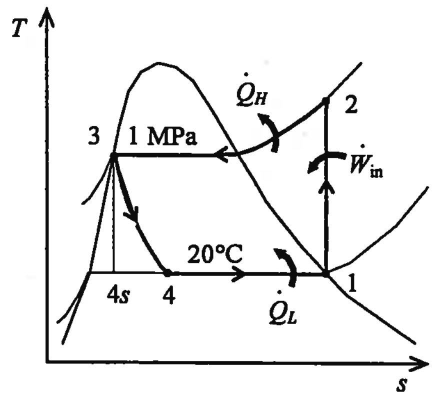
Analysis In an ideal vapor-compression refrigeration cycle, the compression process is isentropic, the refrigerant enters the compressor as a saturated vapor at the evaporator pressure, and leaves the condenser as saturated liquid at the condenser pressure. The evaporating temperature will be 22-2=20°C. From the refrigerant tables (Tables A-11, A-12, and A-13),

$$\left.\begin{array}{l} T_1 = 20°\text{C} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} h_1 = h_{g\,@\,20°\text{C}} = 261.59 \text{ kJ/kg} \\ s_1 = s_{g\,@\,20°\text{C}} = 0.92234 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 1\text{ MPa} \\ s_2 = s_1 \end{array}\right\} h_2 = 273.11 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 1\text{ MPa} \\ \text{sat. liquid} \end{array}\right\} h_3 = h_{f\,@\,1\text{MPa}} = 107.32 \text{ kJ/kg}$$

$$h_4 \cong h_3 = 107.32 \text{ kJ/kg} \quad \text{(throttling)}$$



The COP of the air conditioner is determined from its definition,

$$\text{COP}_{\text{AC}} = \frac{q_L}{w_{\text{in}}} = \frac{h_1 - h_4}{h_2 - h_1} = \frac{261.59 - 107.32}{273.11 - 261.59} = \mathbf{13.39}$$

11.32

~~11-34~~ A heat pump operating on the ideal vapor-compression refrigeration cycle with refrigerant-134a as the working fluid is considered. The COP and the rate of heat supplied to the evaporator are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

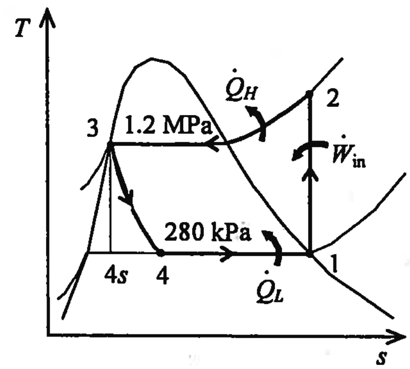
Analysis In an ideal vapor-compression refrigeration cycle, the compression process is isentropic, the refrigerant enters the compressor as a saturated vapor at the evaporator pressure, and leaves the condenser as saturated liquid at the condenser pressure. From the refrigerant tables (Tables A-11, A-12, and A-13),

$$\left.\begin{array}{l} P_1 = 280 \text{ kPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} h_1 = h_{g\,@\,280\text{ kPa}} = 249.72 \text{ kJ/kg} \\ s_1 = s_{g\,@\,280\text{ kPa}} = 0.93210 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 1200 \text{ kPa} \\ s_2 = s_1 \end{array}\right\} h_2 = 280.00 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 1200 \text{ kPa} \\ \text{sat. liquid} \end{array}\right\} h_3 = h_{f\,@\,1200\text{ kPa}} = 117.77 \text{ kJ/kg}$$

$$h_4 \cong h_3 = 117.77 \text{ kJ/kg} \quad \text{(throttling)}$$



The mass flow rate of the refrigerant is determined from

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) \longrightarrow \dot{m} = \frac{\dot{W}_{in}}{h_2 - h_1} = \frac{20 \text{ kJ/s}}{(280.00 - 249.72) \text{ kJ/kg}} = 0.6605 \text{ kg/s}$$

Then the rate of heat supplied to the evaporator is

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.6605 \text{ kg/s})(249.72 - 117.77) \text{ kJ/kg} = \mathbf{87.15 \text{ kW}}$$

The COP of the heat pump is determined from its definition,

$$\text{COP}_{\text{HP}} = \frac{q_H}{w_{in}} = \frac{h_2 - h_3}{h_2 - h_1} = \frac{280.00 - 117.77}{280.00 - 249.72} = \mathbf{5.36}$$

11.33

~~11-35~~ A heat pump operating on a vapor-compression refrigeration cycle with refrigerant-134a as the working fluid is considered. The effect of compressor irreversibilities on the COP of the cycle is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

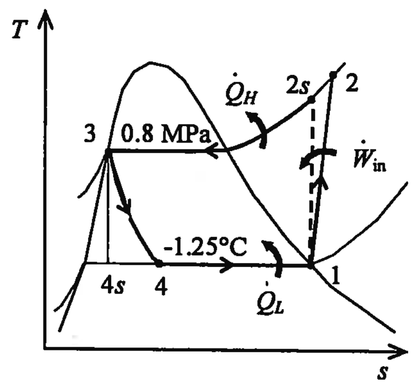
Analysis In this cycle, the refrigerant enters the compressor as a saturated vapor at the evaporator pressure, and leaves the condenser as saturated liquid at the condenser pressure. The compression process is not isentropic. The saturation pressure of refrigerant at −1.25°C is 280 kPa. From the refrigerant tables (Tables A-11, A-12, and A-13),

$$\left.\begin{array}{l} P_1 = 280 \text{ kPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} h_1 = h_{g\,@\,280\text{ kPa}} = 249.72 \text{ kJ/kg} \\ s_1 = s_{g\,@\,280\text{ kPa}} = 0.93210 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 800 \text{ kPa} \\ s_2 = s_1 \end{array}\right\} h_{2s} = 271.50 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 800 \text{ kPa} \\ \text{sat. liquid} \end{array}\right\} h_3 = h_{f\,@\,800\text{ kPa}} = 95.47 \text{ kJ/kg}$$

$$h_4 \cong h_3 = 95.47 \text{ kJ/kg} \quad \text{(throttling)}$$



The actual enthalpy at the compressor exit is determined by using the compressor efficiency:

$$\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1} \longrightarrow h_2 = h_1 + \frac{h_{2s} - h_1}{\eta_C} = 249.72 + \frac{271.50 - 249.72}{0.85} = 275.34 \text{ kJ/kg}$$

The COPs of the heat pump for isentropic and irreversible compression cases are

$$\text{COP}_{\text{HP, ideal}} = \frac{q_H}{w_{in}} = \frac{h_{2s} - h_3}{h_{2s} - h_1} = \frac{271.50 - 95.47}{271.50 - 249.72} = \mathbf{8.082}$$

$$\text{COP}_{\text{HP, actual}} = \frac{q_H}{w_{in}} = \frac{h_2 - h_3}{h_2 - h_1} = \frac{275.34 - 95.47}{275.34 - 249.72} = \mathbf{7.021}$$

The irreversible compressor decreases the COP by **13.1%**.

11.37

11-39 A geothermal heat pump is considered. The degrees of subcooling done on the refrigerant in the condenser, the mass flow rate of the refrigerant, the heating load, the COP of the heat pump, the minimum power input are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.

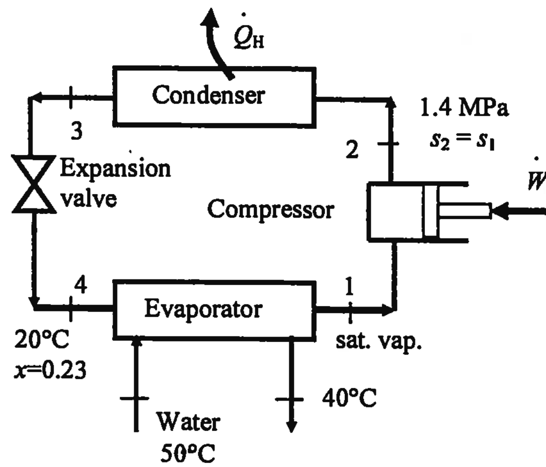
Analysis (*a*) From the refrigerant-134a tables (Tables A-11 through A-13)

$$\left.\begin{array}{l} T_4 = 20°\text{C} \\ x_4 = 0.23 \end{array}\right\} \begin{array}{l} P_4 = 572.1 \text{ kPa} \\ h_4 = 121.24 \text{ kJ/kg} \end{array}$$

$$h_3 = h_4$$

$$\left.\begin{array}{l} P_1 = 572.1 \text{ kPa} \\ x_1 = 1 \text{ (sat. vap.)} \end{array}\right\} \begin{array}{l} h_1 = 261.59 \text{ kJ/kg} \\ s_1 = 0.9223 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 1400 \text{ kPa} \\ s_2 = s_1 \end{array}\right\} h_2 = 280.00 \text{ kJ/kg}$$



From the steam tables (Table A-4)

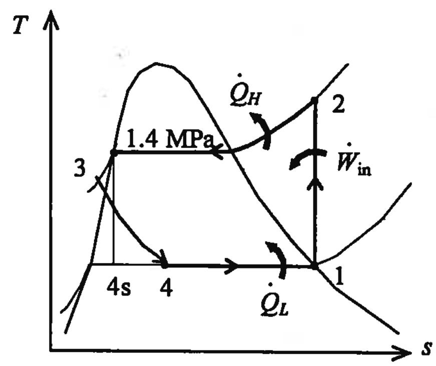
$$h_{w1} = h_{f@50°C} = 209.34 \text{ kJ/kg}$$

$$h_{w2} = h_{f@40°C} = 167.53 \text{ kJ/kg}$$

The saturation temperature at the condenser pressure of 1400 kPa and the actual temperature at the condenser outlet are

$$T_{\text{sat}@1400\text{ kPa}} = 52.40°\text{C}$$

$$\left.\begin{array}{l} P_3 = 1400 \text{ kPa} \\ h_3 = 121.24 \text{ kJ} \end{array}\right\} T_3 = 48.59°\text{C (from EES)}$$



Then, the degrees of subcooling is

$$\Delta T_{\text{subcool}} = T_{\text{sat}} - T_3 = 52.40 - 48.59 = \mathbf{3.81°C}$$

(*b*) The rate of heat absorbed from the geothermal water in the evaporator is

$$\dot{Q}_L = \dot{m}_w (h_{w1} - h_{w2}) = (0.065 \text{ kg/s})(209.34 - 167.53)\text{kJ/kg} = 2.718 \text{ kW}$$

This heat is absorbed by the refrigerant in the evaporator

$$\dot{m}_R = \frac{\dot{Q}_L}{h_1 - h_4} = \frac{2.718 \text{ kW}}{(261.59 - 121.24)\text{kJ/kg}} = \mathbf{0.01936 \text{ kg/s}}$$

(*c*) The power input to the compressor, the heating load and the COP are

$$\dot{W}_{\text{in}} = \dot{m}_R (h_2 - h_1) + \dot{Q}_{\text{out}} = (0.01936 \text{ kg/s})(280.00 - 261.59)\text{kJ/kg} = 0.6564 \text{ kW}$$

$$\dot{Q}_H = \dot{m}_R (h_2 - h_3) = (0.01936 \text{ kg/s})(280.00 - 121.24)\text{kJ/kg} = \mathbf{3.074 \text{ kW}}$$

$$\text{COP} = \frac{\dot{Q}_H}{\dot{W}_{in}} = \frac{3.074 \text{ kW}}{0.6564 \text{ kW}} = \mathbf{4.68}$$

(*d*) The reversible COP of the cycle is

$$\text{COP}_{\text{rev}} = \frac{1}{1 - T_L / T_H} = \frac{1}{1 - (25 + 273)/(50 + 273)} = 12.92$$

The corresponding minimum power input is

$$\dot{W}_{\text{in,min}} = \frac{\dot{Q}_H}{\text{COP}_{\text{rev}}} = \frac{3.074 \text{ kW}}{12.92} = \mathbf{0.238 \text{ kW}}$$

11.47

11-49 A two-stage cascade refrigeration cycle is considered. The mass flow rate of the refrigerant through the upper cycle, the rate of heat removal from the refrigerated space, and the COP of the refrigerator are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis (*a*) The properties are to be obtained from the refrigerant tables (Tables A-11 through A-13):

$$h_1 = h_{g@\,200\text{ kPa}} = 244.46\text{ kJ/kg}$$
$$s_1 = s_{g@\,200\text{ kPa}} = 0.9377\text{ kJ/kg.K}$$

$$\left.\begin{array}{l} P_2 = 500\text{ kPa} \\ s_2 = s_1 \end{array}\right\} h_{2s} = 263.30\text{ kJ/kg}$$

$$\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1}$$

$$0.80 = \frac{263.30 - 244.46}{h_2 - 244.46} \longrightarrow h_2 = 268.01\text{ kJ/kg}$$

$$h_3 = h_{f@\,500\text{ kPa}} = 73.33\text{ kJ/kg}$$
$$h_4 = h_3 = 73.33\text{ kJ/kg}$$

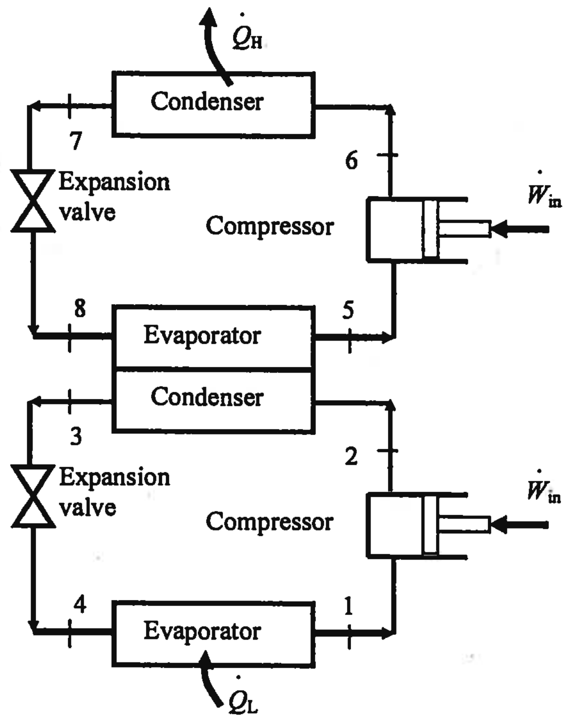
$$h_5 = h_{g@\,400\text{ kPa}} = 255.55\text{ kJ/kg}$$
$$s_5 = s_{g@\,400\text{ kPa}} = 0.9269\text{ kJ/kg.K}$$

$$\left.\begin{array}{l} P_6 = 1200\text{ kPa} \\ s_6 = s_5 \end{array}\right\} h_{6s} = 278.33\text{ kJ/kg}$$

$$\eta_C = \frac{h_{6s} - h_5}{h_6 - h_5}$$

$$0.80 = \frac{278.33 - 255.55}{h_6 - 255.55} \longrightarrow h_6 = 284.02\text{ kJ/kg}$$

$$h_7 = h_{f@\,1200\text{ kPa}} = 117.77\text{ kJ/kg}$$
$$h_8 = h_7 = 117.77\text{ kJ/kg}$$



The mass flow rate of the refrigerant through the upper cycle is determined from an energy balance on the heat exchanger

$$\dot{m}_A(h_5 - h_8) = \dot{m}_B(h_2 - h_3)$$

$$\dot{m}_A(255.55 - 117.77)\text{kJ/kg} = (0.15\text{ kg/s})(268.01 - 73.33)\text{kJ/kg} \longrightarrow \dot{m}_A = \mathbf{0.212\ kg/s}$$

(*b*) The rate of heat removal from the refrigerated space is

$$\dot{Q}_L = \dot{m}_B(h_1 - h_4) = (0.15\text{ kg/s})(244.46 - 73.33)\text{kJ/kg} = \mathbf{25.67\ kW}$$

(*c*) The power input and the COP are

$$\dot{W}_{in} = \dot{m}_A(h_6 - h_5) + \dot{m}_B(h_2 - h_1)$$
$$= (0.15\text{ kg/s})(284.02 - 255.55)\text{kJ/kg} + (0.212\text{ kg/s})(268.01 - 244.46)\text{kJ/kg} = 9.566\text{ kW}$$

$$\text{COP} = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{25.67}{9.566} = \mathbf{2.68}$$

✓ **13-12** The masses of the constituents of a gas mixture are given. The mass fractions, the mole fractions, the average molar mass, and gas constant are to be determined.

Properties The molar masses of O_2, N_2, and CO_2 are 32.0, 28.0 and 44.0 kg/kmol, respectively (Table A-1)

Analysis (*a*) The total mass of the mixture is

$$m_m = m_{O_2} + m_{N_2} + m_{CO_2} = 5\text{ kg} + 8\text{ kg} + 10\text{ kg} = 23\text{ kg}$$

5 kg O_2 8 kg N_2 10 kg CO_2

Then the mass fraction of each component becomes

$$\text{mf}_{O_2} = \frac{m_{O_2}}{m_m} = \frac{5\text{ kg}}{23\text{ kg}} = \mathbf{0.217}$$

$$\text{mf}_{N_2} = \frac{m_{N_2}}{m_m} = \frac{8\text{ kg}}{23\text{ kg}} = \mathbf{0.348}$$

$$\text{mf}_{CO_2} = \frac{m_{CO_2}}{m_m} = \frac{10\text{ kg}}{23\text{ kg}} = \mathbf{0.435}$$

(*b*) To find the mole fractions, we need to determine the mole numbers of each component first,

$$N_{O_2} = \frac{m_{O_2}}{M_{O_2}} = \frac{5\text{ kg}}{32\text{ kg/kmol}} = 0.156\text{ kmol}$$

$$N_{N_2} = \frac{m_{N_2}}{M_{N_2}} = \frac{8\text{ kg}}{28\text{ kg/kmol}} = 0.286\text{ kmol}$$

$$N_{CO_2} = \frac{m_{CO_2}}{M_{CO_2}} = \frac{10\text{ kg}}{44\text{ kg/kmol}} = 0.227\text{ kmol}$$

Thus,

$$N_m = N_{O_2} + N_{N_2} + N_{CO_2} = 0.156\text{ kmol} + 0.286\text{ kmol} + 0.227\text{ kmol} = 0.669\text{ kmol}$$

and

$$y_{O_2} = \frac{N_{O_2}}{N_m} = \frac{0.156\text{ kmol}}{0.699\text{ kmol}} = \mathbf{0.233}$$

$$y_{N_2} = \frac{N_{N_2}}{N_m} = \frac{0.286\text{ kmol}}{0.669\text{ kmol}} = \mathbf{0.428}$$

$$y_{CO_2} = \frac{N_{CO_2}}{N_m} = \frac{0.227\text{ kmol}}{0.669\text{ kmol}} = \mathbf{0.339}$$

(*c*) The average molar mass and gas constant of the mixture are determined from their definitions:

$$M_m = \frac{m_m}{N_m} = \frac{23\text{ kg}}{0.669\text{ kmol}} = \mathbf{34.4\text{ kg/kmol}}$$

and

$$R_m = \frac{R_u}{M_m} = \frac{8.314\text{ kJ/kmol}\cdot\text{K}}{34.4\text{ kg/kmol}} = \mathbf{0.242\text{ kJ/kg}\cdot\text{K}}$$

✓ **13-14** The mole numbers of the constituents of a gas mixture are given. The mass of each gas and the apparent gas constant are to be determined.

Properties The molar masses of H_2, and N_2 are 2.0 and 28.0 kg/kmol, respectively (Table A-1)

Analysis The mass of each component is determined from

$$N_{H_2} = 8\text{ kmol} \longrightarrow m_{H_2} = N_{H_2}M_{H_2} = (8\text{ kmol})(2.0\text{ kg/kmol}) = \mathbf{16\ kg}$$

$$N_{N_2} = 2\text{ kmol} \longrightarrow m_{N_2} = N_{N_2}M_{N_2} = (2\text{ kmol})(28\text{ kg/kmol}) = \mathbf{56\ kg}$$

8 kmol H_2 2 kmol N_2

The total mass and the total number of moles are

$$m_m = m_{H_2} + m_{N_2} = 16\text{ kg} + 56\text{ kg} = 72\text{ kg}$$

$$N_m = N_{H_2} + N_{N_2} = 8\text{ kmol} + 2\text{ kmol} = 10\text{ kmol}$$

The molar mass and the gas constant of the mixture are determined from their definitions,

$$M_m = \frac{m_m}{N_m} = \frac{72\text{ kg}}{10\text{ kmol}} = 7.2\text{ kg/kmol}$$

and

$$R_m = \frac{R_u}{M_m} = \frac{8.314\text{ kJ/kmol}\cdot\text{K}}{7.2\text{ kg/kmol}} = \mathbf{1.155\ kJ/kg\cdot K}$$

13-15E The mole numbers of the constituents of a gas mixture are given. The mass of each gas and the apparent gas constant are to be determined.

Properties The molar masses of H_2, and N_2 are 2.0 and 28.0 lbm/lbmol, respectively (Table A-1E).

Analysis The mass of each component is determined from

$$N_{H_2} = 5\text{ lbmol} \longrightarrow m_{H_2} = N_{H_2}M_{H_2} = (5\text{ lbmol})(2.0\text{ lbm/lbmol}) = \mathbf{10\ lbm}$$

$$N_{N_2} = 4\text{ lbmol} \longrightarrow m_{N_2} = N_{N_2}M_{N_2} = (4\text{ lbmol})(28\text{ lbm/lbmol}) = \mathbf{112\ lbm}$$

5 lbmol H_2 4 lbmol N_2

The total mass and the total number of moles are

$$m_m = m_{H_2} + m_{N_2} = 10\text{ lbm} + 112\text{ lbm} = 122\text{ lbm}$$

$$N_m = N_{H_2} + N_{N_2} = 5\text{ lbmol} + 4\text{ lbmol} = 9\text{ lbmol}$$

The molar mass and the gas constant of the mixture are determined from their definitions,

$$M_m = \frac{m_m}{N_m} = \frac{122\text{ lbm}}{9\text{ lbmol}} = 13.56\text{ lbm/lbmol}$$

and

$$R_m = \frac{R_u}{M_m} = \frac{1.986\text{ Btu/lbmol}\cdot\text{R}}{13.56\text{ lbm/lbmol}} = \mathbf{0.1465\ Btu/lbm\cdot R}$$

13-30

~~13-31~~ The masses of the constituents of a gas mixture at a specified pressure and temperature are given. The partial pressure of each gas and the apparent molar mass of the gas mixture are to be determined.

Assumptions Under specified conditions both CO_2 and CH_4 can be treated as ideal gases, and the mixture as an ideal gas mixture.

Properties The molar masses of CO_2 and CH_4 are 44.0 and 16.0 kg/kmol, respectively (Table A-1)

Analysis The mole numbers of the constituents are

$$m_{CO_2} = 1 \text{ kg} \longrightarrow N_{CO_2} = \frac{m_{CO_2}}{M_{CO_2}} = \frac{1 \text{ kg}}{44 \text{ kg/kmol}} = 0.0227 \text{ kmol}$$

$$m_{CH_4} = 3 \text{ kg} \longrightarrow N_{CH_4} = \frac{m_{CH_4}}{M_{CH_4}} = \frac{3 \text{ kg}}{16 \text{ kg/kmol}} = 0.1875 \text{ kmol}$$

$$N_m = N_{CO_2} + N_{CH_4} = 0.0227 \text{ kmol} + 0.1875 \text{ kmol} = 0.2102 \text{ kmol}$$

1 kg CO_2 3 kg CH_4 300 K 200 kPa

$$y_{CO_2} = \frac{N_{CO_2}}{N_m} = \frac{0.0227 \text{ kmol}}{0.2102 \text{ kmol}} = 0.108$$

$$y_{CH_4} = \frac{N_{CH_4}}{N_m} = \frac{0.1875 \text{ kmol}}{0.2102 \text{ kmol}} = 0.892$$

Then the partial pressures become

$$P_{CO_2} = y_{CO_2} P_m = (0.108)(200 \text{ kPa}) = \mathbf{21.6 \text{ kPa}}$$

$$P_{CH_4} = y_{CH_4} P_m = (0.892)(200 \text{ kPa}) = \mathbf{178.4 \text{ kPa}}$$

The apparent molar mass of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{4 \text{ kg}}{0.2102 \text{ kmol}} = \mathbf{19.03 \text{ kg/kmol}}$$

13-32 The masses of the constituents of a gas mixture at a specified temperature are given. The partial pressure of each gas and the total pressure of the mixture are to be determined.

Assumptions Under specified conditions both N_2 and O_2 can be treated as ideal gases, and the mixture as an ideal gas mixture.

Analysis The partial pressures of constituent gases are

$$P_{N_2} = \left(\frac{mRT}{V}\right)_{N_2} = \frac{(0.6 \text{ kg})(0.2968 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300 \text{ K})}{0.3 \text{ m}^3} = \mathbf{178.1 \text{ kPa}}$$

$$P_{O_2} = \left(\frac{mRT}{V}\right)_{O_2} = \frac{(0.4 \text{ kg})(0.2598 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300 \text{ K})}{0.3 \text{ m}^3} = \mathbf{103.9 \text{ kPa}}$$

0.3 m³ 0.6 kg N_2 0.4 kg O_2 300 K

and

$$P_m = P_{N_2} + P_{O_2} = 178.1 \text{ kPa} + 103.9 \text{ kPa} = \mathbf{282.0 \text{ kPa}}$$

13-60 A mixture of hydrogen and oxygen is considered. The entropy change of this mixture between the two specified states is to be determined.

Assumptions Hydrogen and oxygen are ideal gases.

Properties The gas constants of hydrogen and oxygen are 4.124 and 0.2598 kJ/kg·K, respectively (Table A-1).

Analysis The effective gas constant of this mixture is

$$R = \mathrm{mf}_{H2} R_{H2} + \mathrm{mf}_{O2} R_{O2} = (0.33)(4.1240) + (0.67)(0.2598) = 1.5350 \text{ kJ/kg}\cdot\text{K}$$ Since the temperature of the two states is the same, the entropy change is determined from

$$s_2 - s_1 = -R \ln\frac{P_2}{P_1} = -(1.5350 \text{ kJ/kg}\cdot\text{K}) \ln\frac{150 \text{ kPa}}{750 \text{ kPa}} = \mathbf{2.470 \text{ kJ/kg}\cdot\text{K}}$$

13-59

~~13-61~~ A mixture of nitrogen and carbon dioxide is heated at constant pressure in a closed system. The work produced is to be determined.

Assumptions **1** Nitrogen and carbon dioxide are ideal gases. **2** The process is reversible.

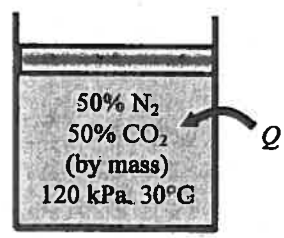
Properties The mole numbers of nitrogen and carbon dioxide are 28.0 and 44.0 kg/kmol, respectively (Table A-1).

Analysis One kg of this mixture consists of 0.5 kg of nitrogen and 0.5 kg of carbon dioxide or 0.5 kg×28.0 kg/kmol=14.0 kmol of nitrogen and 0.5 kg×44.0 kg/kmol=22.0 kmol of carbon dioxide. The constituent mole fraction are then

Please note that there is an error in the calculation of the number of moles. The relation should be: N=m/M

$$y_{N2} = \frac{N_{N2}}{N_{total}} = \frac{14 \text{ kmol}}{36 \text{ kmol}} = 0.3889$$

$$y_{CO2} = \frac{N_{CO2}}{N_{total}} = \frac{22 \text{ kmol}}{36 \text{ kmol}} = 0.6111$$



The effective molecular weight of this mixture is

$$M = y_{N2}M_{N2} + y_{CO2}M_{CO2} = (0.3889)(28) + (0.6111)(44) = 37.78 \text{ kg/kmol}$$

The work done is determined from

$$w = \int_1^2 P dV = P_2 v_2 - P_1 v_1 = R(T_2 - T_1)$$

$$= \frac{R_u}{M}(T_2 - T_1) = \frac{8.314 \text{ kJ/kmol}\cdot\text{K}}{37.78 \text{ kg/kmol}}(200 - 30)\text{K}$$

$$= \mathbf{37.4 \text{ kJ/kg}}$$

13-62

~~13-64~~ The masses of components of a gas mixture are given. This mixture is heated at constant pressure. The change in the volume of the mixture and the total heat transferred to the mixture are to be determined.

Assumptions All gases will be modeled as ideal gases with constant specific heats.

Properties The molar masses of O_2, CO_2, and He are 32.0, 44.0, and 4.0 kg/kmol, respectively (Table A-1). The constant-pressure specific heats of these gases at room temperature are 0.918, 0.846, and 5.1926 kJ/kg·K, respectively (Table A-2a).

Analysis The total mass of the mixture is

$$m_m = m_{\text{O2}} + m_{\text{CO2}} + m_{\text{He}} = 0.1 + 1 + 0.5 = 1.6\ \text{kg}$$

The mole numbers of each component are

0.1 kg O_2 1 kg CO_2 0.5 kg He 350 kPa, 10°C

$$N_{\text{O2}} = \frac{m_{\text{O2}}}{M_{\text{O2}}} = \frac{0.1\ \text{kg}}{32\ \text{kg/kmol}} = 0.003125\ \text{kmol}$$

$$N_{\text{CO2}} = \frac{m_{\text{CO2}}}{M_{\text{CO2}}} = \frac{1\ \text{kg}}{44\ \text{kg/kmol}} = 0.02273\ \text{kmol}$$

$$N_{\text{He}} = \frac{m_{\text{He}}}{M_{\text{He}}} = \frac{0.5\ \text{kg}}{4\ \text{kg/kmol}} = 0.125\ \text{kmol}$$

The mole number of the mixture is

$$N_m = N_{\text{O2}} + N_{\text{CO2}} + N_{\text{He}} = 0.003125 + 0.02273 + 0.125 = 0.15086\ \text{kmol}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{1.6\ \text{kg}}{0.15086\ \text{kmol}} = 10.61\ \text{kg/kmol}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{8.314\ \text{kJ/kmol}\cdot\text{K}}{10.61\ \text{kg/kmol}} = 0.7836\ \text{kJ/kg}\cdot\text{K}$$

The mass fractions are

$$\text{mf}_{\text{O2}} = \frac{m_{\text{O2}}}{m_m} = \frac{0.1\ \text{kg}}{1.6\ \text{kg}} = 0.0625$$

$$\text{mf}_{\text{CO2}} = \frac{m_{\text{CO2}}}{m_m} = \frac{1\ \text{kg}}{1.6\ \text{kg}} = 0.625$$

$$\text{mf}_{\text{He}} = \frac{m_{\text{He}}}{m_m} = \frac{0.5\ \text{kg}}{1.6\ \text{kg}} = 0.3125$$

The constant-pressure specific heat of the mixture is determined from

$$\begin{aligned} c_p &= \text{mf}_{\text{O2}} c_{p,\text{O2}} + \text{mf}_{\text{CO2}} c_{p,\text{CO2}} + \text{mf}_{\text{He}} c_{p,\text{He}} \\ &= 0.0625 \times 0.918 + 0.625 \times 0.846 + 0.3125 \times 5.1926 \\ &= 2.209\ \text{kJ/kg}\cdot\text{K} \end{aligned}$$

The change in the volume of this ideal gas mixture is

$$\Delta V_m = \frac{m_m R \Delta T}{P} = \frac{(1.6\ \text{kg})(0.7836\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(260-10)\ \text{K}}{350\ \text{kPa}} = \mathbf{0.8955\ m^3}$$

The heat transfer is determined to be

$$q_{\text{in}} = c_p(T_2 - T_1) = (2.209\ \text{kJ/kg}\cdot\text{K})(260-10)\ \text{K} = \mathbf{552\ kJ/kg}$$

13-65

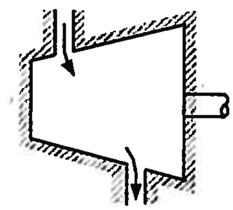
~~13-67~~ The volume fractions of components of a gas mixture passing through the turbine of a simple ideal Brayton cycle are given. The thermal efficiency of this cycle is to be determined.

Assumptions All gases will be modeled as ideal gases with constant specific heats.

Properties The molar masses of N_2, O_2, H_2O, and CO_2 are 28.0, 32.0, 18.0, and 44.0 kg/kmol, respectively (Table A-1). The constant-pressure specific heats of these gases at room temperature are 1.039, 0.918, 1.8723, and 0.846 kJ/kg·K, respectively. The air properties at room temperature are c_p = 1.005 kJ/kg·K, c_v = 0.718 kJ/kg·K, k = 1.4 (Table A-2a).

Analysis We consider 100 kmol of this mixture. Noting that volume fractions are equal to the mole fractions, mass of each component are

$$m_{N2} = N_{N2}M_{N2} = (30\text{ kmol})(28\text{ kg/kmol}) = 840\text{ kg}$$
$$m_{O2} = N_{O2}M_{O2} = (10\text{ kmol})(32\text{ kg/kmol}) = 320\text{ kg}$$
$$m_{H2O} = N_{H2O}M_{H2O} = (20\text{ kmol})(18\text{ kg/kmol}) = 360\text{ kg}$$
$$m_{CO2} = N_{CO2}M_{CO2} = (40\text{ kmol})(44\text{ kg/kmol}) = 1760\text{ kg}$$

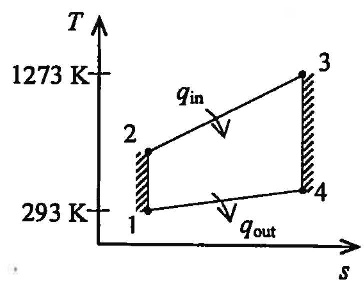


The total mass is

$$\begin{aligned} m_m &= m_{N2} + m_{O2} + m_{H2O} + m_{CO2} \\ &= 840 + 320 + 360 + 1760 \\ &= 3280\text{ kg} \end{aligned}$$

Then the mass fractions are

$$\text{mf}_{N2} = \frac{m_{N2}}{m_m} = \frac{840\text{ kg}}{3280\text{ kg}} = 0.2561$$
$$\text{mf}_{O2} = \frac{m_{O2}}{m_m} = \frac{320\text{ kg}}{3280\text{ kg}} = 0.09756$$
$$\text{mf}_{H2O} = \frac{m_{H2O}}{m_m} = \frac{360\text{ kg}}{3280\text{ kg}} = 0.1098$$
$$\text{mf}_{CO2} = \frac{m_{CO2}}{m_m} = \frac{1760\text{ kg}}{3280\text{ kg}} = 0.5366$$



The constant-pressure specific heat of the mixture is determined from

$$\begin{aligned} c_p &= \text{mf}_{N2}c_{p,N2} + \text{mf}_{O2}c_{p,O2} + \text{mf}_{H2O}c_{p,H2O} + \text{mf}_{CO2}c_{p,CO2} \\ &= 0.2561\times 1.039 + 0.09756\times 0.918 + 0.1098\times 1.8723 + 0.5366\times 0.846 \\ &= 1.015\text{ kJ/kg}\cdot\text{K} \end{aligned}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{3280\text{ kg}}{100\text{ kmol}} = 32.80\text{ kg/kmol}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{8.314\text{ kJ/kmol}\cdot\text{K}}{32.80\text{ kg/kmol}} = 0.2535\text{ kJ/kg}\cdot\text{K}$$

Then the constant-volume specific heat is

$$c_v = c_p - R = 1.015 - 0.2535 = 0.762\text{ kJ/kg}\cdot\text{K}$$

The specific heat ratio is

$$k = \frac{c_p}{c_v} = \frac{1.015}{0.762} = 1.332$$

The average of the air properties at room temperature and combustion gas properties are

$$c_{p,\text{avg}} = 0.5(1.015 + 1.005) = 1.010 \text{ kJ/kg}\cdot\text{K}$$
$$c_{v,\text{avg}} = 0.5(0.762 + 0.718) = 0.740 \text{ kJ/kg}\cdot\text{K}$$
$$k_{\text{avg}} = 0.5(1.332 + 1.4) = 1.366$$

These average properties will be used for heat addition and rejection processes. For compression, the air properties at room temperature and during expansion, the mixture properties will be used. During the compression process,

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (293\text{ K})(8)^{0.4/1.4} = 531\text{ K}$$

During the heat addition process,

$$q_{\text{in}} = c_{p,\text{avg}}(T_3 - T_2) = (1.010 \text{ kJ/kg}\cdot\text{K})(1273 - 531)\text{ K} = 749.4 \text{ kJ/kg}$$

During the expansion process,

$$T_4 = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1273\text{ K})\left(\frac{1}{8}\right)^{0.332/1.332} = 758\text{ K}$$

During the heat rejection process,

$$q_{\text{out}} = c_{p,\text{avg}}(T_4 - T_1) = (1.010 \text{ kJ/kg}\cdot\text{K})(758 - 293)\text{ K} = 469.7 \text{ kJ/kg}$$

The thermal efficiency of the cycle is then

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{469.7 \text{ kJ/kg}}{749.4 \text{ kJ/kg}} = \mathbf{0.373}$$

14–16 A tank contains 21 kg of dry air and 0.3 kg of water vapor at 30°C and 100 kPa total pressure. Determine (*a*) the specific humidity, (*b*) the relative humidity, and (*c*) the volume of the tank.

14–17 Repeat Prob. 14–16 for a temperature of 24°C.

14–18 A room contains air at 20°C and 98 kPa at a relative humidity of 85 percent. Determine (*a*) the partial pressure of dry air, (*b*) the specific humidity of the air, and (*c*) the enthalpy per unit mass of dry air.

14–19 Repeat Prob. 14–18 for a pressure of 85 kPa.

14–20 Determine the masses of dry air and the water vapor contained in a 240-m^3 room at 98 kPa, 23°C, and 50 percent relative humidity. *Answers:* 273 kg, 2.5 kg

Dew-Point, Adiabatic Saturation, and Wet-Bulb Temperatures

14–21C What is the dew-point temperature?

14–22C Andy and Wendy both wear glasses. On a cold winter day, Andy comes from the cold outside and enters the warm house while Wendy leaves the house and goes outside. Whose glasses are more likely to be fogged? Explain.

14–23C In summer, the outer surface of a glass filled with iced water frequently "sweats." How can you explain this sweating?

14–24C In some climates, cleaning the ice off the windshield of a car is a common chore on winter mornings. Explain how ice forms on the windshield during some nights even when there is no rain or snow.

14–25C When are the dry-bulb and dew-point temperatures identical?

14–26C When are the adiabatic saturation and wet-bulb temperatures equivalent for atmospheric air?

14–27 A house contains air at 25°C and 65 percent relative humidity. Will any moisture condense on the inner surfaces of the windows when the temperature of the window drops to 10°C?

14–28 After a long walk in the 8°C outdoors, a person wearing glasses enters a room at 25°C and 40 percent relative humidity. Determine whether the glasses will become fogged.

14–29 Repeat Prob. 14–28 for a relative humidity of 30 percent.

14–30 A thirsty woman opens the refrigerator and picks up a cool canned drink at 5°C. Do you think the can will "sweat" as she enjoys the drink in a room at 25°C and 50 percent relative humidity?

14–31 The dry- and wet-bulb temperatures of atmospheric air at 95 kPa are 25 and 17°C, respectively. Determine (*a*) the specific humidity, (*b*) the relative humidity, and (*c*) the enthalpy of the air, in kJ/kg dry air.

14–32 The air in a room has a dry-bulb temperature of 22°C and a wet-bulb temperature of 16°C. Assuming a pressure of 100 kPa, determine (*a*) the specific humidity, (*b*) the relative humidity, and (*c*) the dew-point temperature. *Answers:* (*a*) 0.0090 kg H_2O/kg dry air, (*b*) 54.1 percent, (*c*) 12.3°C

14–33 Reconsider Prob. 14–32. Determine the required properties using EES (or other) software. What would the property values be at a pressure of 300 kPa?

14–34 Atmospheric air at 35°C flows steadily into an adiabatic saturation device and leaves as a saturated mixture at 25°C. Makeup water is supplied to the device at 25°C. Atmospheric pressure is 98 kPa. Determine the relative humidity and specific humidity of the air.

Psychrometric Chart

14–35C How do constant-enthalpy and constant-wet-bulb-temperature lines compare on the psychrometric chart?

14–36C At what states on the psychrometric chart are the dry-bulb, wet-bulb, and dew-point temperatures identical?

14–37C How is the dew-point temperature at a specified state determined on the psychrometric chart?

14–38C Can the enthalpy values determined from a psychrometric chart at sea level be used at higher elevations?

14–39 The air in a room is at 1 atm, 32°C, and 60 percent relative humidity. Determine (*a*) the specific humidity, (*b*) the enthalpy, in kJ/kg dry air, (*c*) the wet-bulb temperature, (*d*) the dew-point temperature, and (*e*) the specific volume of the air, in m^3/kg dry air. Use the psychrometric chart or available software.

14–40 A room contains air at 1 atm, 26°C, and 70 percent relative humidity. Using the psychrometric chart, determine (*a*) the specific humidity, (*b*) the enthalpy, in kJ/kg dry air, (*c*) the wet-bulb temperature, (*d*) the dew-point temperature, and (*e*) the specific volume of the air, in m^3/kg dry air.

14–41 Reconsider Prob. 14–40. Determine the required properties using EES (or other) software instead of the psychrometric chart. What would the property values be at a location at 2000 m altitude?

14–42 The air in a room has a pressure of 1 atm, a dry-bulb temperature of 24°C, and a wet-bulb temperature of 17°C. Using the psychrometric chart, determine (*a*) the specific humidity, (*b*) the enthalpy, in kJ/kg dry air, (*c*) the relative humidity, (*d*) the dew-point temperature, and (*e*) the specific volume of the air, in m^3/kg dry air.

14–43 Reconsider Prob. 14–42. Determine the required properties using EES (or other) software instead of the psychrometric chart. What would the property values be at a location at 3000 m altitude?

14–44 Atmospheric air at a pressure of 1 atm and dry-bulb temperature of 30°C has a relative humidity of 80 percent.

Using the psychrometric chart, determine (*a*) the wet-bulb temperature, (*b*) the humidity ratio, (*c*) the enthalpy, (*d*) the dew-point temperature, and (*e*) the water vapor pressure.

14–45 Atmospheric air at a pressure of 1 atm and dry-bulb temperature of 32°C has a wet-bulb temperature of 29°C. Using the psychrometric chart, determine (*a*) the relative humidity, (*b*) the humidity ratio, (*c*) the enthalpy, (*d*) the dew-point temperature, and (*e*) the water vapor pressure.

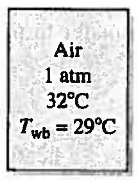


FIGURE P14–45

14–46 Determine the adiabatic saturation temperature of the humid air in Prob. 14–45. *Answer:* 29°C

14–47 Atmospheric air at a pressure of 1 atm and dry-bulb temperature of 28°C has a dew-point temperature of 20°C. Using the psychrometric chart, determine (*a*) the relative humidity, (*b*) the humidity ratio, (*c*) the enthalpy, (*d*) the wet-bulb temperature, and (*e*) the water vapor pressure.

14–48 Determine the adiabatic saturation temperature of the humid air in Prob. 14–47.

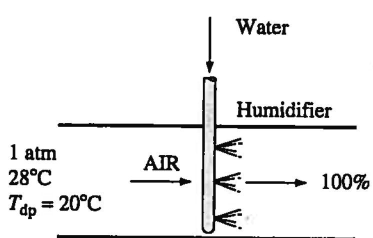


FIGURE P14–48

Human Comfort and Air-Conditioning

14–49C What does a modern air-conditioning system do besides heating or cooling the air?

14–50C How does the human body respond to (*a*) hot weather, (*b*) cold weather, and (*c*) hot and humid weather?

14–51C What is the radiation effect? How does it affect human comfort?

14–52C How does the air motion in the vicinity of the human body affect human comfort?

14–53C Consider a tennis match in cold weather where both players and spectators wear the same clothes. Which group of people will feel colder? Why?

14–54C Why do you think little babies are more susceptible to cold?

14–55C How does humidity affect human comfort?

14–56C What are humidification and dehumidification?

14–57C What is metabolism? What is the range of metabolic rate for an average man? Why are we interested in the metabolic rate of the occupants of a building when we deal with heating and air-conditioning?

14–58C Why is the metabolic rate of women, in general, lower than that of men? What is the effect of clothing on the environmental temperature that feels comfortable?

14–59C What is sensible heat? How is the sensible heat loss from a human body affected by the (*a*) skin temperature, (*b*) environment temperature, and (*c*) air motion?

14–60C What is latent heat? How is the latent heat loss from the human body affected by the (*a*) skin wettedness and (*b*) relative humidity of the environment? How is the rate of evaporation from the body related to the rate of latent heat loss?

14–61 An average person produces 0.25 kg of moisture while taking a shower and 0.05 kg while bathing in a tub. Consider a family of four who each showers once a day in a bathroom that is not ventilated. Taking the heat of vaporization of water to be 2450 kJ/kg, determine the contribution of showers to the latent heat load of the air conditioner per day in summer.

14–62 An average (1.82 kg) chicken has a basal metabolic rate of 5.47 W and an average metabolic rate of 10.2 W (3.78 W sensible and 6.42 W latent) during normal activity. If there are 100 chickens in a breeding room, determine the rate of total heat generation and the rate of moisture production in the room. Take the heat of vaporization of water to be 2430 kJ/kg.

14–63 A department store expects to have 120 customers and 15 employees at peak times in summer. Determine the contribution of people to the total cooling load of the store.

14–64 In a movie theater in winter, 500 people, each generating sensible heat at a rate of 70 W, are watching a movie. The heat losses through the walls, windows, and the roof are estimated to be 140,000 kJ/h. Determine if the theater needs to be heated or cooled.

14–65 For an infiltration rate of 1.2 air changes per hour (ACH), determine sensible, latent, and total infiltration heat load of a building at sea level, in kW, that is 20 m long, 13 m wide, and 3 m high when the outdoor air is at 32°C and 50 percent relative humidity. The building is maintained at 24°C and 50 percent relative humidity at all times.

14–66 Repeat Prob. 14–65 for an infiltration rate of 1.8 ACH.

Simple Heating and Cooling

14–67C How do relative and specific humidities change during a simple heating process? Answer the same question for a simple cooling process.

14–68C Why does a simple heating or cooling process appear as a horizontal line on the psychrometric chart?

14–69 Air enters a 40-cm-diameter cooling section at 1 atm, 32°C, and 30 percent relative humidity at 18 m/s. Heat is removed from the air at a rate of 1200 kJ/min. Determine (*a*) the exit temperature, (*b*) the exit relative humidity of the air, and (*c*) the exit velocity. *Answers:* (*a*) 24.4°C, (*b*) 46.6 percent, (*c*) 17.6 m/s

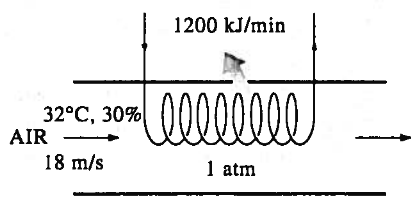


FIGURE P14–69

14–70 Repeat Prob. 14–69 for a heat removal rate of 800 kJ/min.

14–71 Humid air at 150 kPa, 40°C, and 70 percent relative humidity is cooled at constant pressure in a pipe to its dew-point temperature. Calculate the heat transfer, in kJ/kg dry air, required for this process. *Answer:* 6.8 kJ/kg dry air

14–72 Saturated humid air at 200 kPa and 15°C is heated to 30°C as it flows through a 4-cm-diameter pipe with a velocity of 20 m/s. Disregarding pressure losses, calculate the relative humidity at the pipe outlet and the rate of heat transfer, in kW, to the air.

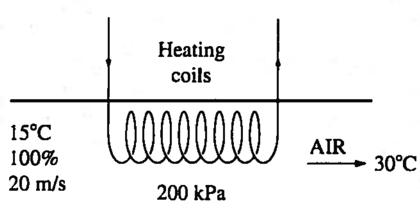


FIGURE P14–72

14–73 Calculate the rate at which the exergy of the humid air of Prob. 14–72 is increased. Take T_0 = 15°C.

Heating with Humidification

14–74C Why is heated air sometimes humidified?

14–75 Air at 1 atm, 15°C, and 60 percent relative humidity is first heated to 20°C in a heating section and then humidified by introducing water vapor. The air leaves the humidifying section at 25°C and 65 percent relative humidity. Determine (*a*) the amount of steam added to the air, and (*b*) the amount of heat transfer to the air in the heating section. *Answers:* (*a*) 0.0065 kg H_2O/kg dry air, (*b*) 5.1 kJ/kg dry air

14–76 An air-conditioning system operates at a total pressure of 1 atm and consists of a heating section and a humidifier that supplies wet steam (saturated water vapor) at 100°C. Air enters the heating section at 10°C and 70 percent relative humidity at a rate of 35 m³/min, and it leaves the humidifying section at 20°C and 60 percent relative humidity. Determine (*a*) the temperature and relative humidity of air when it leaves the heating section, (*b*) the rate of heat transfer in the heating section, and (*c*) the rate at which water is added to the air in the humidifying section.

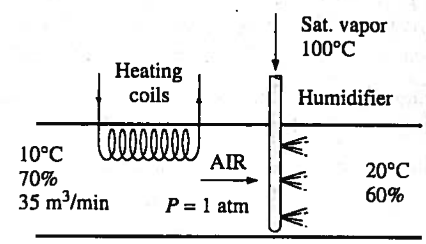


FIGURE P14–76

14–77 Repeat Prob. 14–76 for a total pressure of 95 kPa for the airstream. *Answers:* (*a*) 19.5°C, 37.7 percent, (*b*) 391 kJ/min, (*c*) 0.147 kg/min

Cooling with Dehumidification

14–78C Why is cooled air sometimes reheated in summer before it is discharged to a room?

14–79 An air-conditioning system is to take in air at 1 atm, 34°C, and 70 percent relative humidity and deliver it at 22°C and 50 percent relative humidity. The air flows first over the cooling coils, where it is cooled and dehumidified, and then over the resistance heating wires, where it is heated to the desired temperature. Assuming that the condensate is removed from the cooling section at 10°C, determine (*a*) the tempera-

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ture of air before it enters the heating section, (*b*) the amount of heat removed in the cooling section, and (*c*) the amount of heat transferred in the heating section, both in kJ/kg dry air.

14–80 Air enters a 30-cm-diameter cooling section at 1 atm, 35°C, and 60 percent relative humidity at 120 m/min. The air is cooled by passing it over a cooling coil through which cold water flows. The water experiences a temperature rise of 8°C. The air leaves the cooling section saturated at 20°C. Determine (*a*) the rate of heat transfer, (*b*) the mass flow rate of the water, and (*c*) the exit velocity of the airstream.

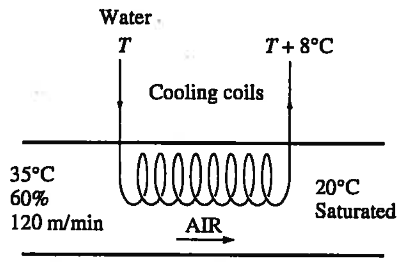

FIGURE P14–80

14–81 Reconsider Prob. 14–80. Using EES (or other) software, develop a general solution of the problem in which the input variables may be supplied and parametric studies performed. For each set of input variables for which the pressure is atmospheric, show the process on the psychrometric chart.

14–82 Repeat Prob. 14–80 for a total pressure of 95 kPa for air. *Answers:* (*a*) 293.2 kJ/min, (*b*) 8.77 kg/min, (*c*) 113 m/min

14–83 Atmospheric air at 1 atm, 30°C, and 80 percent relative humidity is cooled to 20°C while the mixture pressure remains constant. Calculate the amount of water, in kg/kg dry air, removed from the air and the cooling requirement, in kJ/kg dry air, when the liquid water leaves the system at 22°C. *Answers:* 0.0069 kg H_2O/kg dry air, 27.3 kJ/kg dry air

14–84 Three hundred cubic meter per hour of atmospheric air at 1 atm and 30°C with a dew-point temperature of 20°C are to be cooled to 15°C. Determine the rate at which condensate leaves this system and the cooling rate when the condensate leaves the system at 18°C.

14–85 On a summer day in New Orleans, Louisiana, the pressure is 1 atm; the temperature is 32°C; and the relative humidity is 95 percent. This air is to be conditioned to 24°C and 60 percent relative humidity. Determine the amount of cooling, in kJ, required and water removed, in kg, per 1000 m^3 of dry air processed at the entrance to the system.

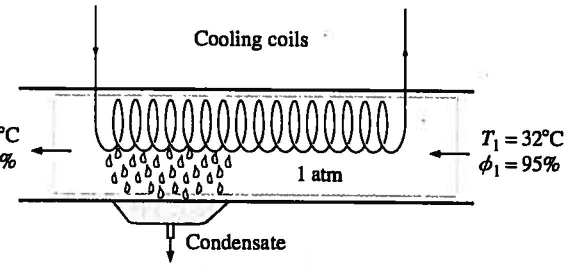

FIGURE P14–85

14–86 How far will the temperature of the humid air of Prob. 14–85 have to be reduced to produce the desired dehumidification? *Answer:* 15.8°C

14–87 A simple ideal vapor-compression refrigeration system using refrigerant-134a as the working fluid is used to provide the cooling required in Prob. 14–85. It operates its evaporator at 4°C and its condenser at a saturation temperature of 39.4°C. The condenser rejects its heat to the New Orleans summer air. Calculate the exergy destruction, in kJ, in the total system per 1000 m^3 of dry air processed.

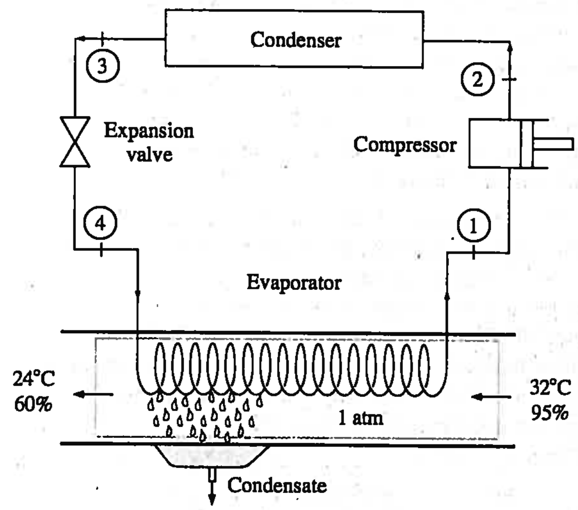

FIGURE P14–87

14–88 Atmospheric air from the inside of an automobile enters the evaporator section of the air conditioner at 1 atm, 27°C and 50 percent relative humidity. The air returns to the automobile at 10°C and 90 percent relative humidity. The passenger compartment has a volume of 2 m^3 and 5 air changes per minute are required to maintain the inside of the automobile at the desired comfort level. Sketch the psychrometric diagram for the atmospheric air flowing through the air conditioning process. Determine the dew point and wet bulb temperatures at the inlet to the evaporator section, in °C. Determine the required heat transfer rate from the atmospheric air to the evaporator fluid, in kW. Determine the rate of condensation of water vapor in the evaporator section, in kg/min.

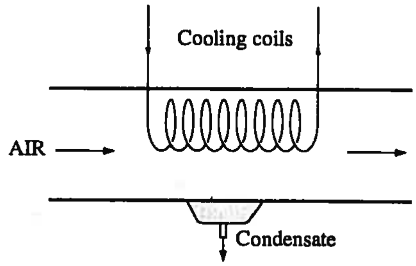

FIGURE P14–88

14–89 Two thousand cubic meters per hour of atmospheric air at 28°C with a dew-point temperature of 25°C flows into an air conditioner that uses chilled water as the cooling fluid. The atmospheric air is to be cooled to 18°C. Sketch the system hardware and the psychrometric diagram for the process. Determine the mass flow rate of the condensate water, if any, leaving the air conditioner, in kg/h. If the cooling water has a 10°C temperature rise while flowing through the air conditioner, determine the volume flow rate of chilled water supplied to the air conditioner heat exchanger, in m³/min. The air conditioning process takes place at 100 kPa.

14–90 An automobile air conditioner uses refrigerant-134a as the cooling fluid. The evaporator operates at 275 kPa gage and the condenser operates at 1.7 MPa gage. The compressor requires a power input of 6 kW and has an isentropic efficiency of 85 percent. Atmospheric air at 22°C and 50 percent relative humidity enters the evaporator and leaves at 8°C and 90 percent relative humidity. Determine the volume flow rate of the atmospheric air entering the evaporator of the air conditioner, in m³/min.

14–91 Air from a workspace enters an air conditioner unit at 30°C dry bulb and 25°C wet bulb. The air leaves the air conditioner and returns to the space at 25°C dry-bulb and 6.5°C dew-point temperature. If there is any, the condensate leaves the air conditioner at the temperature of the air leaving the cooling coils. The volume flow rate of the air returned to the workspace is 1000 m³/min. Atmospheric pressure is 98 kPa. Determine the heat transfer rate from the air, in kW, and the mass flow rate of condensate water, if any, in kg/h.

Evaporative Cooling

14–92C Does an evaporation process have to involve heat transfer? Describe a process that involves both heat and mass transfer.

14–93C During evaporation from a water body to air, under what conditions will the latent heat of vaporization be equal to the heat transfer from the air?

14–94C What is evaporative cooling? Will it work in humid climates?

14–95 Air enters an evaporative cooler at 1 atm, 36°C, and 20 percent relative humidity at a rate of 4 m³/min, and it leaves with a relative humidity of 90 percent. Determine (*a*) the exit temperature of the air and (*b*) the required rate of water supply to the evaporative cooler.

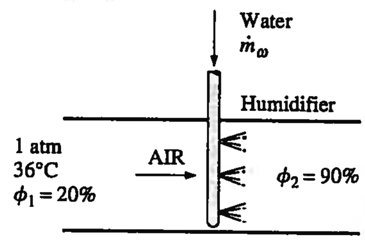

FIGURE P14–95

14–96 Air enters an evaporative cooler at 1 atm, 32°C, and 30 percent relative humidity at a rate of 5 m³/min and leaves at 22°C. Determine (*a*) the final relative humidity and (*b*) the amount of water added to air.

14–97 What is the lowest temperature that air can attain in an evaporative cooler if it enters at 1 atm, 29°C, and 40 percent relative humidity? *Answer:* 19.3°C

14–98 Air at 1 atm, 15°C, and 60 percent relative humidity is first heated to 30°C in a heating section and then passed through an evaporative cooler where its temperature drops to 25°C. Determine (*a*) the exit relative humidity and (*b*) the amount of water added to air, in kg H_2O/kg dry air.

14–99 Desert dwellers often wrap their heads with a water-soaked porous cloth. On a desert where the pressure is 1 atm, temperature is 50°C, and relative humidity is 10 percent, what is the temperature of this cloth?

Adiabatic Mixing of Airstreams

14–100C Two unsaturated airstreams are mixed adiabatically. It is observed that some moisture condenses during the mixing process. Under what conditions will this be the case?

14–101C Consider the adiabatic mixing of two airstreams. Does the state of the mixture on the psychrometric chart have to be on the straight line connecting the two states?

14–102 Two airstreams are mixed steadily and adiabatically. The first stream enters at 32°C and 40 percent relative humidity at a rate of 20 m³/min, while the second stream enters at 12°C and 90 percent relative humidity at a rate of

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25 m^3/min. Assuming that the mixing process occurs at a pressure of 1 atm, determine the specific humidity, the relative humidity, the dry-bulb temperature, and the volume flow rate of the mixture. *Answers:* 0.0096 kg H_2O/kg dry air, 63.4 percent, 20.6°C, 45.0 m^3/min

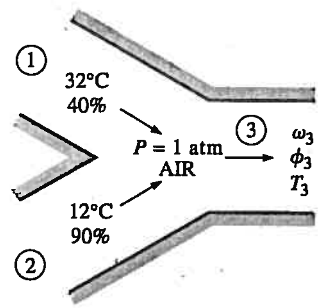


FIGURE P14–102

14–103 Repeat Prob. 14–102 for a total mixing-chamber pressure of 90 kPa.

14–104 Saturated humid air at 1 atm and 10°C is to be mixed with atmospheric air at 1 atm, 32°C, and 80 percent relative humidity, to form air of 70 percent relative humidity. Determine the proportions at which these two streams are to be mixed and the temperature of the resulting air.

14–105 A stream of warm air with a dry-bulb temperature of 40°C and a wet-bulb temperature of 32°C is mixed adiabatically with a stream of saturated cool air at 18°C. The dry air mass flow rates of the warm and cool airstreams are 8 and 6 kg/s, respectively. Assuming a total pressure of 1 atm, determine (*a*) the temperature, (*b*) the specific humidity, and (*c*) the relative humidity of the mixture.

14–106 Reconsider Prob. 14–105. Using EES (or other) software, determine the effect of the mass flow rate of saturated cool air stream on the mixture temperature, specific humidity, and relative humidity. Vary the mass flow rate of saturated cool air from 0 to 16 kg/s while maintaining the mass flow rate of warm air constant at 8 kg/s. Plot the mixture temperature, specific humidity, and relative humidity as functions of the mass flow rate of cool air, and discuss the results.

Wet Cooling Towers

14–107C How does a natural-draft wet cooling tower work?

14–108C What is a spray pond? How does its performance compare to the performance of a wet cooling tower?

14–109 A wet cooling tower is to cool 60 kg/s of water from 40 to 26°C. Atmospheric air enters the tower at 1 atm with dry- and wet-bulb temperatures of 22 and 16°C, respectively, and leaves at 34°C with a relative humidity of 90 percent. Using the psychrometric chart, determine (*a*) the volume flow rate of air into the cooling tower and (*b*) the mass flow rate of the required makeup water. *Answers:* (*a*) 44.9 m^3/s, (*b*) 1.16 kg/s

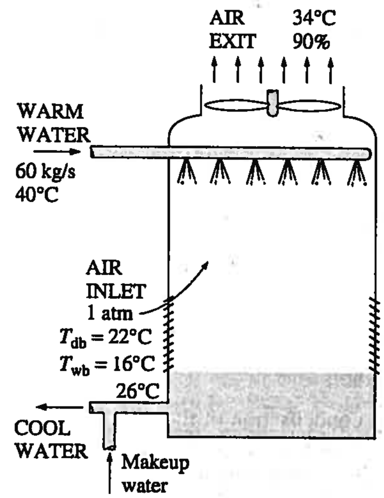


FIGURE P14–109

14–110 Water at 30°C is to be cooled to 22°C in a cooling tower which it enters at a rate of 5 kg/s. Humid air enters this tower at 1 atm and 15°C with a relative humidity of 25 percent and leaves at 18°C with a relative humidity of 95 percent. Determine the mass flow rate of dry air through this tower. *Answer:* 6.29 kg/s

14–111 How much work potential, in kJ/kg dry air, is lost in the cooling tower of Prob. 14–110? Take T_0 = 15°C.

14–112 Water at 38°C is to be cooled in a cooling tower which it enters at a rate of 4500 kg/h. Humid air enters this tower at 1 atm, 15°C, and 20 percent relative humidity with a dry air flow rate of 3000 kg/h and leaves at 24°C and 0.018 kg H_2O/kg dry air. Determine the relative humidity at which the air leaves the tower and the water's exit temperature.

14–113 A wet cooling tower is to cool 25 kg/s of cooling water from 40 to 30°C at a location where the atmospheric pressure is 96 kPa. Atmospheric air enters the tower at 20°C and 70 percent relative humidity and leaves saturated at 35°C. Neglecting the power input to the fan, determine (*a*) the volume flow rate of air into the cooling tower and (*b*) the mass flow rate of the required makeup water. *Answers:* (*a*) 11.2 m^3/s, (*b*) 0.35 kg/s

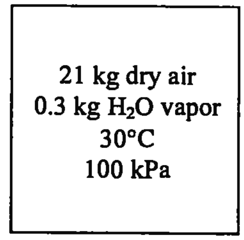
14–114 A natural-draft cooling tower is to remove waste heat from the cooling water flowing through the condenser of a steam power plant. The turbine in the steam power plant receives 42 kg/s of steam from the steam generator. Eighteen percent of the steam entering the turbine is extracted for vari-

14-16 A tank contains dry air and water vapor at specified conditions. The specific humidity, the relative humidity, and the volume of the tank are to be determined.

Assumptions The air and the water vapor are ideal gases.

Analysis (*a*) The specific humidity can be determined form its definition,

$$\omega = \frac{m_v}{m_a} = \frac{0.3\text{ kg}}{21\text{ kg}} = \mathbf{0.0143\ kg\ H_2O/kg\ dry\ air}$$



(*b*) The saturation pressure of water at 30°C is

$$P_g = P_{\text{sat @ 30°C}} = 4.2469\text{ kPa}$$

Then the relative humidity can be determined from

$$\phi = \frac{\omega P}{(0.622+\omega)P_g} = \frac{(0.0143)(100\text{ kPa})}{(0.622+0.0143)(4.2469\text{ kPa})} = \mathbf{52.9\%}$$

(*c*) The volume of the tank can be determined from the ideal gas relation for the dry air,

$$P_v = \phi P_g = (0.529)(4.2469\text{ kPa}) = 2.245\text{ kPa}$$

$$P_a = P - P_v = 100 - 2.245 = 97.755\text{ kPa}$$

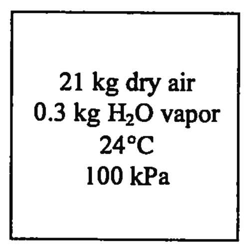
$$V = \frac{m_a R_a T}{P_a} = \frac{(21\text{ kg})(0.287\text{ kJ/kg}\cdot\text{K})(303\text{ K})}{97.755\text{ kPa}} = \mathbf{18.7\ m^3}$$

14-17 A tank contains dry air and water vapor at specified conditions. The specific humidity, the relative humidity, and the volume of the tank are to be determined.

Assumptions The air and the water vapor are ideal gases.

Analysis (*a*) The specific humidity can be determined form its definition,

$$\omega = \frac{m_v}{m_a} = \frac{0.3\text{ kg}}{21\text{ kg}} = \mathbf{0.0143\ kg\ H_2O/kg\ dry\ air}$$



(*b*) The saturation pressure of water at 24°C is

$$P_g = P_{\text{sat @24°C}} = 2.986\text{ kPa}$$

Then the relative humidity can be determined from

$$\phi = \frac{\omega P}{(0.622+\omega)P_g} = \frac{(0.0143)(100\text{ kPa})}{(0.622+0.0143)2.986\text{ kPa}} = \mathbf{75.2\%}$$

(*c*) The volume of the tank can be determined from the ideal gas relation for the dry air,

$$P_v = \phi P_g = (0.752)(2.986\text{ kPa}) = 2.245\text{ kPa}$$

$$P_a = P - P_v = 100 - 2.245 = 97.755\text{ kPa}$$

$$V = \frac{m_a R_a T}{P_a} = \frac{(21\text{ kg})(0.287\text{ kJ/kg}\cdot\text{K})(297\text{ K})}{97.755\text{ kPa}} = \mathbf{18.3\ m^3}$$

Dew-point, Adiabatic Saturation, and Wet-bulb Temperatures

14-22C Dew-point temperature is the temperature at which condensation begins when air is cooled at constant pressure.

14-23C Andy's. The temperature of his glasses may be below the dew-point temperature of the room, causing condensation on the surface of the glasses.

14-24C The outer surface temperature of the glass may drop below the dew-point temperature of the surrounding air, causing the moisture in the vicinity of the glass to condense. After a while, the conde sate may start dripping down because of gravity.

14-25C When the temperature falls below the dew-point temperature, dew forms on the outer surfaces of the car. If the temperature is below 0°C, the dew will freeze. At very low temperatures, the moisture in the air will freeze directly on the car windows.

14-26C When the air is saturated (100% relative humidity).

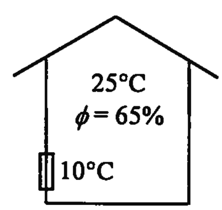
14-27C These two are approximately equal at atmospheric temperatures and pressure.

14.27

~~**14-28**~~ A house contains air at a specified temperature and relative humidity. It is to be determined whether any moisture will condense on the inner surfaces of the windows when the temperature of the window drops to a specified value.

Assumptions The air and the water vapor are ideal gases.

Analysis The vapor pressure P_v is uniform throughout the house, and its value can be determined from



$$P_v = \phi P_{g\,@25°C} = (0.65)(3.1698\text{ kPa}) = 2.06\text{ kPa}$$

The dew-point temperature of the air in the house is

$$T_{dp} = T_{sat\,@P_v} = T_{sat\,@2.06\text{ kPa}} = \mathbf{18.0°C}$$

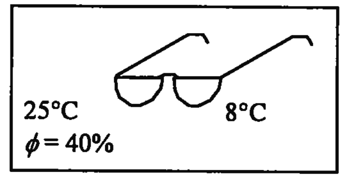
That is, the moisture in the house air will start condensing when the temperature drops below 18.0°C. Since the windows are at a lower temperature than the dew-point temperature, some moisture **will condense** on the window surfaces.

14-28

~~14-29~~ A person wearing glasses enters a warm room at a specified temperature and relative humidity from the cold outdoors. It is to be determined whether the glasses will get fogged.

Assumptions The air and the water vapor are ideal gases.

Analysis The vapor pressure P_v of the air in the house is uniform throughout, and its value can be determined from



$$P_v = \phi P_{g\,@\,25°C} = (0.40)(3.1698\text{ kPa}) = 1.268\text{ kPa}$$

The dew-point temperature of the air in the house is

$$T_{dp} = T_{sat\,@\,P_v} = T_{sat\,@\,1.268\text{ kPa}} = \mathbf{10.5°C} \quad \text{(from EES)}$$

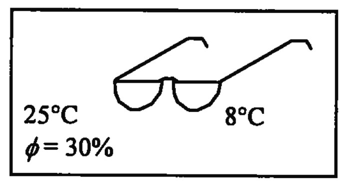
That is, the moisture in the house air will start condensing when the air temperature drops below 10.5°C. Since the glasses are at a lower temperature than the dew-point temperature, some moisture will condense on the glasses, and thus they **will get fogged.**

14-29

~~14-30~~ A person wearing glasses enters a warm room at a specified temperature and relative humidity from the cold outdoors. It is to be determined whether the glasses will get fogged.

Assumptions The air and the water vapor are ideal gases.

Analysis The vapor pressure P_v of the air in the house is uniform throughout, and its value can be determined from



$$P_v = \phi P_{g\,@\,25°C} = (0.30)(3.1698\text{ kPa}) = 0.95\text{ kPa}$$

The dew-point temperature of the air in the house is

$$T_{dp} = T_{sat\,@\,P_v} = T_{sat\,@\,0.95\text{ kPa}} = \mathbf{6.2°C} \quad \text{(from EES)}$$

That is, the moisture in the house air will start condensing when the air temperature drops below 6.2°C. Since the glasses are at a higher temperature than the dew-point temperature, moisture will not condense on the glasses, and thus they **will not get fogged.**

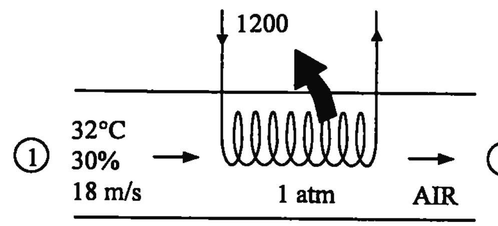
14-69

~~14-71~~ Air enters a cooling section at a specified pressure, temperature, velocity, and relative humidity. The exit temperature, the exit relative humidity of the air, and the exit velocity are to be determined.

Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process ($\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a$). **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Analysis (*a*) The amount of moisture in the air remains constant ($\omega_1 = \omega_2$) as it flows through the cooling section since the process involves no humidification or dehumidification. The inlet state of the air is completely specified, and the total pressure is 1 atm. The properties of the air at the inlet state are determined from the psychrometric chart (Figure A-31) to be

$$h_1 = 55.0 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0089 \text{ kg H}_2\text{O/kg dry air} (= \omega_2)$$
$$v_1 = 0.877 \text{ m}^3\text{/kg dry air}$$



The mass flow rate of dry air through the cooling section is

$$\dot{m}_a = \frac{1}{v_1} V_1 A_1$$
$$= \frac{1}{(0.877 \text{ m}^3\text{/kg})}(18 \text{ m/s})(\pi \times 0.4^2/4 \text{ m}^2)$$
$$= 2.58 \text{ kg/s}$$

From the energy balance on air in the cooling section,

$$-\dot{Q}_{\text{out}} = \dot{m}_a(h_2 - h_1)$$
$$-1200/60 \text{ kJ/s} = (2.58 \text{ kg/s})(h_2 - 55.0) \text{ kJ/kg}$$
$$h_2 = 47.2 \text{ kJ/kg dry air}$$

The exit state of the air is fixed now since we know both h_2 and ω_2. From the psychrometric chart at this state we read

$$T_2 = \mathbf{24.4°C}$$
(*b*) $$\phi_2 = \mathbf{46.6\%}$$
$$v_2 = 0.856 \text{ m}^3\text{/kg dry air}$$

(*c*) The exit velocity is determined from the conservation of mass of dry air,

$$\dot{m}_{a1} = \dot{m}_{a2} \longrightarrow \frac{\dot{V}_1}{v_1} = \frac{\dot{V}_2}{v_2} \longrightarrow \frac{V_1 A}{v_1} = \frac{V_2 A}{v_2}$$
$$V_2 = \frac{v_2}{v_1} V_1 = \frac{0.856}{0.877}(18 \text{ m/s}) = \mathbf{17.6 \text{ m/s}}$$

14-71

~~14-74~~ Humid air at a specified state is cooled at constant pressure to the dew-point temperature. The cooling required for this process is to be determined.

Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process ($\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a$). **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

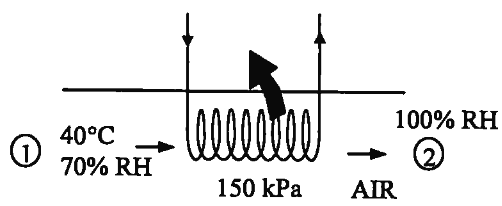
Analysis The amount of moisture in the air remains constant ($\omega_1 = \omega_2$) as it flows through the cooling section since the process involves no humidification or dehumidification. The inlet state of the air is completely specified, and the total pressure is 150 kPa. The properties of the air at the inlet and exit states are determined to be

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 40°C}} = (0.70)(7.3851 \text{ kPa}) = 5.1696 \text{ kPa}$$

$$h_{g1} = h_{g\text{ @ 40°C}} = 2573.5 \text{ kJ/kg}$$

$$\omega_1 = \frac{0.622 P_{v1}}{P_1 - P_{v1}} = \frac{0.622(5.1696 \text{ kPa})}{(150 - 5.1696) \text{ kPa}} = 0.02220 \text{ kg H}_2\text{O/kg dry air}$$

$$h_1 = c_p T_1 + \omega_1 h_{g1}$$
$$= (1.005 \text{ kJ/kg}\cdot°\text{C})(40°\text{C}) + (0.02220)(2573.5 \text{ kJ/kg})$$
$$= 97.33 \text{ kJ/kg dry air}$$



$$P_{v2} = P_{v1} = 5.1696 \text{ kPa}$$

$$P_{g2} = \frac{P_{v2}}{\phi_2} = \frac{5.1696 \text{ kPa}}{1} = 5.1696 \text{ kPa}$$

$$T_2 = T_{\text{sat @ 5.1695 kPa}} = 33.5°\text{C}$$

$$h_{g2} = h_{g\text{ @ 33.5°C}} = 2561.9 \text{ kJ/kg}$$

$$\omega_2 = \omega_1$$

$$h_2 = c_p T_2 + \omega_2 h_{g2}$$
$$= (1.005 \text{ kJ/kg}\cdot°\text{C})(33.5°\text{C}) + (0.02220)(2561.9 \text{ kJ/kg})$$
$$= 90.55 \text{ kJ/kg dry air}$$

From the energy balance on air in the cooling section,

$$q_{\text{out}} = h_1 - h_2 = 97.33 - 90.55 = \mathbf{6.78 \text{ kJ/kg dry air}}$$

Heating with Humidification

14-77C To achieve a higher level of comfort. Very dry air can cause dry skin, respiratory difficulties, and increased static electricity.

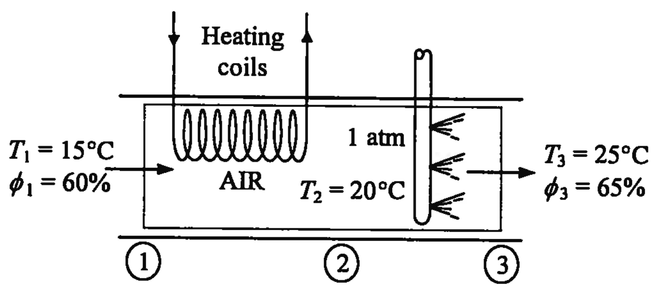
14-75

~~14-78~~ Air is first heated and then humidified by water vapor. The amount of steam added to the air and the amount of heat transfer to the air are to be determined.

Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Properties The inlet and the exit states of the air are completely specified, and the total pressure is 1 atm. The properties of the air at various states are determined from the psychrometric chart (Figure A-31) to be

$$h_1 = 31.1 \text{ kJ / kg dry air}$$
$$\omega_1 = 0.0064 \text{ kg H}_2\text{O / kg dry air } (= \omega_2)$$
$$h_2 = 36.2 \text{ kJ / kg dry air}$$
$$h_3 = 58.1 \text{ kJ / kg dry air}$$
$$\omega_3 = 0.0129 \text{ kg H}_2\text{O / kg dry air}$$



Analysis (*a*) The amount of moisture in the air remains constant it flows through the heating section ($\omega_1 = \omega_2$), but increases in the humidifying section ($\omega_3 > \omega_2$). The amount of steam added to the air in the heating section is

$$\Delta\omega = \omega_3 - \omega_2 = 0.0129 - 0.0064 = \mathbf{0.0065 \text{ kg H}_2\text{O / kg dry air}}$$

(*b*) The heat transfer to the air in the heating section per unit mass of air is

$$q_{\text{in}} = h_2 - h_1 = 36.2 - 31.1 = \mathbf{5.1 \text{ kJ / kg dry air}}$$

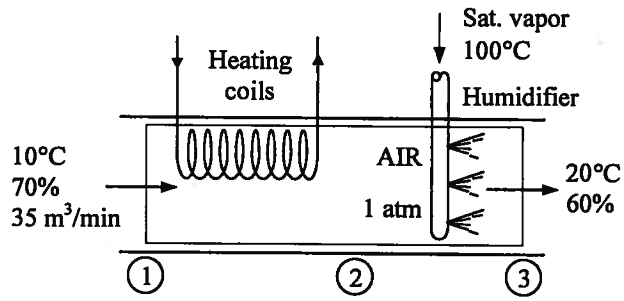
14-76

~~14-80~~ Air is first heated and then humidified by wet steam. The temperature and relative humidity of air at the exit of heating section, the rate of heat transfer, and the rate at which water is added to the air are to be determined.

Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Properties The inlet and the exit states of the air are completely specified, and the total pressure is 1 atm. The properties of the air at various states are determined from the psychrometric chart (Figure A-31) to be

$$h_1 = 23.5 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0053 \text{ kg H}_2\text{O/kg dry air} (= \omega_2)$$
$$v_1 = 0.809 \text{ m}^3\text{/kg dry air}$$
$$h_3 = 42.3 \text{ kJ/kg dry air}$$
$$\omega_3 = 0.0087 \text{ kg H}_2\text{O/kg dry air}$$



Analysis (*a*) The amount of moisture in the air remains constant it flows through the heating section ($\omega_1 = \omega_2$), but increases in the humidifying section ($\omega_3 > \omega_2$). The mass flow rate of dry air is

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{35 \text{ m}^3/\text{min}}{0.809 \text{ m}^3/\text{kg}} = 43.3 \text{ kg/min}$$

Noting that $Q = W = 0$, the energy balance on the humidifying section can be expressed as

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\nearrow 0 \text{ (steady)}} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_w h_w + \dot{m}_{a2} h_2 = \dot{m}_a h_3$$
$$(\omega_3 - \omega_2) h_w + h_2 = h_3$$

Solving for h_2,

$$h_2 = h_3 - (\omega_3 - \omega_2) h_{g@100°C} = 42.3 - (0.0087 - 0.0053)(2675.6) = 33.2 \text{ kJ/kg dry air}$$

Thus at the exit of the heating section we have $\omega_2 = 0.0053$ kg H_2O dry air and $h_2 = 33.2$ kJ/kg dry air, which completely fixes the state. Then from the psychrometric chart we read

$$T_2 = \mathbf{19.5°C}$$
$$\phi_2 = \mathbf{37.8\%}$$

(*b*) The rate of heat transfer to the air in the heating section is

$$\dot{Q}_{in} = \dot{m}_a (h_2 - h_1) = (43.3 \text{ kg/min})(33.2 - 23.5) \text{ kJ/kg} = \mathbf{420 \text{ kJ/min}}$$

(*c*) The amount of water added to the air in the humidifying section is determined from the conservation of mass equation of water in the humidifying section,

$$\dot{m}_w = \dot{m}_a (\omega_3 - \omega_2) = (43.3 \text{ kg/min})(0.0087 - 0.0053) = \mathbf{0.15 \text{ kg/min}}$$

Cooling with Dehumidification

14-82C To drop its relative humidity to more desirable levels.

14-79

14-83 Air is first cooled, then dehumidified, and finally heated. The temperature of air before it enters the heating section, the amount of heat removed in the cooling section, and the amount of heat supplied in the heating section are to be determined.

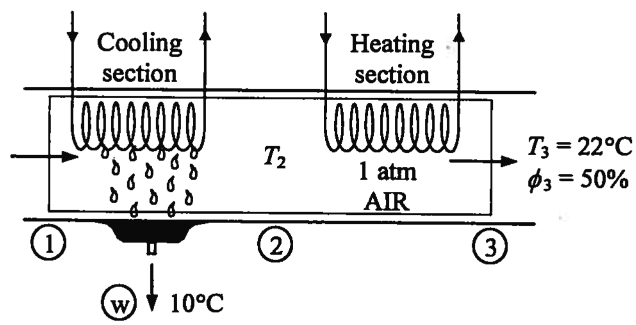
Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Analysis (a) The amount of moisture in the air decreases due to dehumidification ($\omega_3 < \omega_1$), and remains constant during heating ($\omega_3 = \omega_2$). The inlet and the exit states of the air are completely specified, and the total pressure is 1 atm. The intermediate state (state 2) is also known since $\phi_2 = 100\%$ and $\omega_2 = \omega_3$. Therefore, we can determine the properties of the air at all three states from the psychrometric chart (Fig. A-31) to be

$$h_1 = 95.2 \text{ kJ / kg dry air}$$
$$\omega_1 = 0.0238 \text{ kg } H_2O \text{ / kg dry air}$$

and

$$h_3 = 43.1 \text{ kJ / kg dry air}$$
$$\omega_3 = 0.0082 \text{ kg } H_2O \text{ / kg dry air } (= \omega_2)$$



Also,

$$h_w \cong h_{f@10°C} = 42.02 \text{ kJ/kg (Table A-4)}$$
$$h_2 = 31.8 \text{ kJ/kg dry air}$$
$$T_2 = \mathbf{11.1°C}$$

(b) The amount of heat removed in the cooling section is determined from the energy balance equation applied to the cooling section,

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\nearrow 0 \text{ (steady)}} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\Sigma \dot{m}_i h_i = \Sigma \dot{m}_e h_e + \dot{Q}_{out,cooling}$$
$$\dot{Q}_{out,cooling} = \dot{m}_{a1}h_1 - (\dot{m}_{a2}h_2 + \dot{m}_w h_w) = \dot{m}_a(h_1 - h_2) - \dot{m}_w h_w$$

or, per unit mass of dry air,

$$\begin{aligned} q_{out,cooling} &= (h_1 - h_2) - (\omega_1 - \omega_2)h_w \\ &= (95.2 - 31.8) - (0.0238 - 0.0082)42.02 \\ &= \mathbf{62.7 \text{ kJ/kg dry air}} \end{aligned}$$

(c) The amount of heat supplied in the heating section per unit mass of dry air is

$$q_{in,heating} = h_3 - h_2 = 43.1 - 31.8 = \mathbf{11.3 \text{ kJ / kg dry air}}$$

14-83

~~14-87~~ Air is cooled and dehumidified at constant pressure. The amount of water removed from the air and the cooling requirement are to be determined.

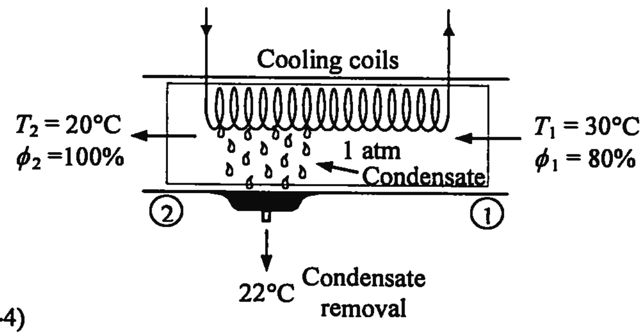
Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process ($\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a$). **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Properties The inlet and the exit states of the air are completely specified, and the total pressure is 1 atm. The properties of the air at various states are determined from the psychrometric chart (Figure A-31) to be

$$h_1 = 85.5 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0217 \text{ kg H}_2\text{O/kg dry air}$$

and

$$\phi_2 = 1.0$$
$$h_2 = 57.6 \text{ kJ/kg dry air}$$
$$\omega_2 = 0.0148 \text{ kg H}_2\text{O/kg dry air}$$



Also,

$$h_w \cong h_{f@22°C} = 92.28 \text{ kJ/kg} \quad \text{(Table A-4)}$$

Analysis The amount of moisture in the air decreases due to dehumidification ($\omega_2 < \omega_1$). Applying the water mass balance and energy balance equations to the combined cooling and dehumidification section,

Water Mass Balance:

$$\sum \dot{m}_{w,i} = \sum \dot{m}_{w,e} \longrightarrow \dot{m}_{a1}\omega_1 = \dot{m}_{a2}\omega_2 + \dot{m}_w$$

$$\Delta\omega = \omega_1 - \omega_2 = 0.0217 - 0.0148 = \mathbf{0.0069 \text{ kg H}_2\text{O/kg dry air}}$$

Energy Balance:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}^{\not 0 \text{ (steady)}} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\sum \dot{m}_i h_i = \dot{Q}_{out} + \sum \dot{m}_e h_e$$
$$\dot{Q}_{out} = \dot{m}_{a1}h_1 - (\dot{m}_{a2}h_2 + \dot{m}_w h_w) = \dot{m}_a(h_1 - h_2) - \dot{m}_w h_w$$
$$q_{out} = h_1 - h_2 - (\omega_1 - \omega_2)h_w$$
$$= (85.5 - 57.6)\text{kJ/kg} - (0.0069)(92.28)$$
$$= \mathbf{27.3 \text{ kJ/kg dry air}}$$

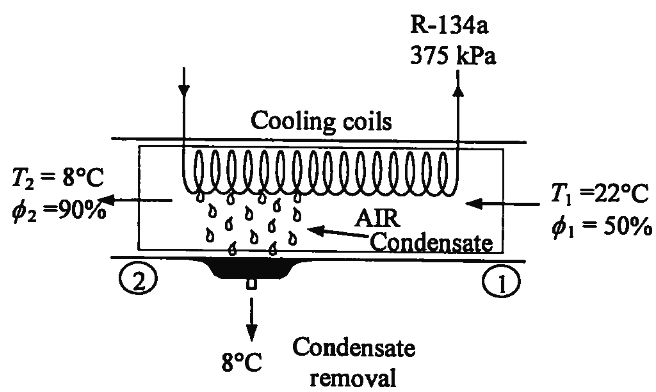
14-90

~~14-94~~ An automobile air conditioner using refrigerant 134a as the cooling fluid is considered. The inlet and exit states of moist air in the evaporator are specified. The volume flow rate of the air entering the evaporator of the air conditioner is to be determined.

Assumptions **1** All processes are steady flow and the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Analysis We assume that the total pressure of moist air is 100 kPa. Then, the inlet and exit states of the moist air for the evaporator are completely specified. The properties may be determined from the psychrometric chart (Fig. A-31) or using EES psychrometric functions to be (we used EES)

$$h_1 = 43.33 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.008337 \text{ kg H}_2\text{O/kg dry air}$$
$$v_1 = 0.8585 \text{ m}^3\text{/kg dry air}$$
$$h_2 = 23.31 \text{ kJ/kg dry air}$$
$$\omega_2 = 0.006065 \text{ kg H}_2\text{O/kg dry air}$$



The mass flow rate of dry air is given by

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{\dot{V}_1}{0.8585 \text{ m}^3\text{/kg}}$$

The mass flow rate of condensate water is expressed as

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = \frac{\dot{V}_1}{0.8585}(0.008337 - 0.006065) = 0.002646\dot{V}_1$$

The enthalpy of condensate water is

$$h_{w2} = h_{f@8°C} = 33.63 \text{ kJ/kg} \quad \text{(Table A-4)}$$

An energy balance on the control volume gives

$$\dot{m}_a h_1 = \dot{Q}_{out} + \dot{m}_a h_2 + \dot{m}_w h_{w2}$$

$$\frac{\dot{V}_1}{0.8585}(43.05) = \dot{Q}_{out} + \frac{\dot{V}_1}{0.8585}(23.11) + 0.002646\dot{V}_1(33.63) \quad (1)$$

The properties of the R-134a at the inlet of the compressor and the enthalpy at the exit for the isentropic process are (R-134a tables)

$$\left.\begin{array}{l} P_{R1} = 375 \text{ kPa} \\ x_{R1} = 1 \end{array}\right\} \begin{array}{l} h_{R1} = 254.48 \text{ kJ/kg} \\ s_{R1} = 0.9278 \text{ kJ/kg.K} \end{array}$$

$$\left.\begin{array}{l} P_{R2} = 1800 \text{ kPa} \\ s_{R2} = s_{R1} \end{array}\right\} h_{R2,s} = 286.90 \text{ kJ/kg}$$

The enthalpies of R-134a at the condenser exit and the throttle exit are

$$h_{R3} = h_{f@1800 \text{ kPa}} = 144.07 \text{ kJ/kg}$$
$$h_{R4} = h_{R3} = 144.07 \text{ kJ/kg}$$

The mass flow rate of the refrigerant can be determined from the expression for the compressor power:

$$\dot{W}_C = \dot{m}_R \frac{h_{R2,s} - h_{R1}}{\eta_C}$$

$$6\text{ kW} = \dot{m}_R \frac{(286.90 - 254.48)\text{ kJ/kg}}{0.85}$$

$$\dot{m}_R = 0.1573\text{ kg/s} = 9.439\text{ kg/min}$$

The rate of heat absorbed by the R-134a in the evaporator is

$$\dot{Q}_{R,\text{in}} = \dot{m}_R(h_{R1} - h_{R4}) = (9.439\text{ kg/min})(254.48 - 144.07)\text{ kJ/kg} = 1042.1\text{ kJ/min}$$

The rate of heat lost from the air in the evaporator is absorbed by the refrigerant-134a. That is, $\dot{Q}_{R,\text{in}} = \dot{Q}_{\text{out}}$. Then, the volume flow rate of the air at the inlet of the evaporator can be determined from Eq. (1) to be

$$\frac{\dot{V}_1}{0.8474}(43.05) = 1042.1 + \frac{\dot{V}_1}{0.8474}(23.11) + 0.002646\dot{V}_1(33.63) \longrightarrow \dot{V}_1 = \mathbf{44.87\ m^3/min}$$

Evaporative Cooling

14-96C In steady operation, the mass transfer process does not have to involve heat transfer. However, a mass transfer process that involves phase change (evaporation, sublimation, condensation, melting etc.) must involve heat transfer. For example, the evaporation of water from a lake into air (mass transfer) requires the transfer of latent heat of water at a specified temperature to the liquid water at the surface (heat transfer).

14-97C During evaporation from a water body to air, the latent heat of vaporization will be equal to *convection* heat transfer from the air when *conduction* from the lower parts of the water body to the surface is negligible, and temperature of the surrounding surfaces is at about the temperature of the water surface so that the *radiation* heat transfer is negligible.

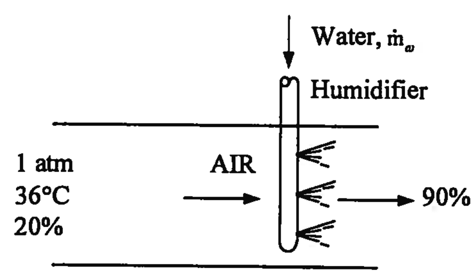
14-98C Evaporative cooling is the cooling achieved when water evaporates in dry air. It will not work on humid climates.

14-95

~~14-99~~ Air is cooled by an evaporative cooler. The exit temperature of the air and the required rate of water supply are to be determined.

Analysis (*a*) From the psychrometric chart (Fig. A-31) at 36°C and 20% relative humidity we read

$$T_{wb1} = 19.5°C$$
$$\omega_1 = 0.0074 \text{ kg } H_2O/\text{kg dry air}$$
$$v_1 = 0.887 \text{ m}^3/\text{kg dry air}$$



Assuming the liquid water is supplied at a temperature not much different than the exit temperature of the air stream, the evaporative cooling process follows a line of constant wet-bulb temperature. That is,

$$T_{wb2} \cong T_{wb1} = 19.5°C$$

At this wet-bulb temperature and 90% relative humidity we read

$$T_2 = \mathbf{20.5°C}$$
$$\omega_2 = 0.0137 \text{ kg } H_2O / \text{kg dry air}$$

Thus air will be cooled to 20.5°C in this evaporative cooler.

(*b*) The mass flow rate of dry air is

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{4 \text{ m}^3/\text{min}}{0.887 \text{ m}^3/\text{kg dry air}} = 4.51 \text{ kg/min}$$

Then the required rate of water supply to the evaporative cooler is determined from

$$\dot{m}_{supply} = \dot{m}_{w2} - \dot{m}_{w1} = \dot{m}_a(\omega_2 - \omega_1)$$
$$= (4.51 \text{ kg/min})(0.0137 - 0.0074) = \mathbf{0.028 \text{ kg/min}}$$

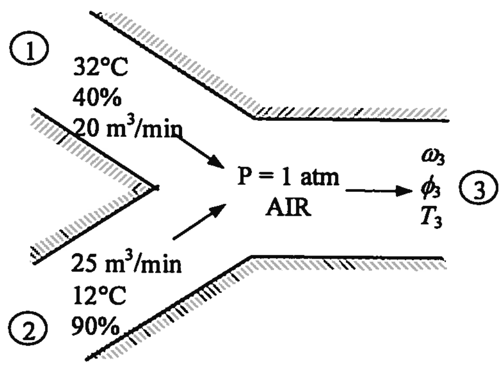
14-102

~~14-107~~ Two airstreams are mixed steadily. The specific humidity, the relative humidity, the dry-bulb temperature, and the volume flow rate of the mixture are to be determined.

Assumptions 1 Steady operating conditions exist 2 Dry air and water vapor are ideal gases. 3 The kinetic and potential energy changes are negligible. 4 The mixing section is adiabatic.

Properties Properties of each inlet stream are determined from the psychrometric chart (Fig. A-31) to be

$$h_1 = 62.7 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0119 \text{ kg } H_2O\text{/kg dry air}$$
$$v_1 = 0.882 \text{ m}^3\text{/kg dry air}$$



and

$$h_2 = 31.9 \text{ kJ/kg dry air}$$
$$\omega_2 = 0.0079 \text{ kg } H_2O\text{/kg dry air}$$
$$v_2 = 0.819 \text{ m}^3\text{/kg dry air}$$

Analysis The mass flow rate of dry air in each stream is

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{20 \text{ m}^3\text{/min}}{0.882 \text{ m}^3\text{/kg dry air}} = 22.7 \text{ kg/min}$$

$$\dot{m}_{a2} = \frac{\dot{V}_2}{v_2} = \frac{25 \text{ m}^3\text{/min}}{0.819 \text{ m}^3\text{/kg dry air}} = 30.5 \text{ kg/min}$$

From the conservation of mass,

$$\dot{m}_{a3} = \dot{m}_{a1} + \dot{m}_{a2} = (22.7 + 30.5) \text{ kg/min} = 53.2 \text{ kg/min}$$

The specific humidity and the enthalpy of the mixture can be determined from Eqs. 14-24, which are obtained by combining the conservation of mass and energy equations for the adiabatic mixing of two streams:

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

$$\frac{22.7}{30.5} = \frac{0.0079 - \omega_3}{\omega_3 - 0.0119} = \frac{31.9 - h_3}{h_3 - 62.7}$$

which yields,

$$\omega_3 = \mathbf{0.0096 \text{ kg } H_2O\text{/kg dry air}}$$
$$h_3 = 45.0 \text{ kJ/kg dry air}$$

These two properties fix the state of the mixture. Other properties of the mixture are determined from the psychrometric chart:

$$T_3 = \mathbf{20.6°C}$$
$$\phi_3 = \mathbf{63.4\%}$$
$$v_3 = 0.845 \text{ m}^3\text{/kg dry air}$$

Finally, the volume flow rate of the mixture is determined from

$$\dot{V}_3 = \dot{m}_{a3} v_3 = (53.2 \text{ kg/min})(0.845 \text{ m}^3\text{/kg}) = \mathbf{45.0 \text{ m}^3\text{/min}}$$

15–7C Is the air–fuel ratio expressed on a mole basis identical to the air–fuel ratio expressed on a mass basis?

15–8 Trace amounts of sulfur (S) in coal are burned in the presence of diatomic oxygen (O_2) to form sulfur dioxide (SO_2). Determine the minimum mass of oxygen required in the reactants and the mass of sulfur dioxide in the products when 1 kg of sulfur is burned.

Theoretical and Actual Combustion Processes

15–9C What are the causes of incomplete combustion?

15–10C Which is more likely to be found in the products of an incomplete combustion of a hydrocarbon fuel, CO or OH? Why?

15–11C What does 100 percent theoretical air represent?

15–12C Are complete combustion and theoretical combustion identical? If not, how do they differ?

15–13C Consider a fuel that is burned with (*a*) 130 percent theoretical air and (*b*) 70 percent excess air. In which case is the fuel burned with more air?

15–14 Propane fuel (C_3H_8) is burned in the presence of air. Assuming that the combustion is theoretical—that is, only nitrogen (N_2), water vapor (H_2O), and carbon dioxide (CO_2) are present in the products—determine (*a*) the mass fraction of carbon dioxide and (*b*) the mole and mass fractions of the water vapor in the products.

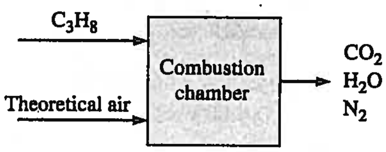


FIGURE P15–14

15–15 The fuel mixer in a natural gas burner mixes methane (CH_4) with air to form a combustible mixture at the outlet. Determine the mass flow rates at the two inlets needed to produce 0.01 kg/s of an ideal combustion mixture at the outlet.

15–16 n-Octane (C_8H_{18}) is burned with stoichiometric amount of oxygen. Calculate the mass fractions of each of the products and the mass of water in the products per unit mass of fuel burned.

15–17 Acetylene (C_2H_2) is burned with 10 percent excess oxygen in a cutting torch. Determine the mass fraction of each of the products. Calculate the mass of oxygen used per unit mass of acetylene burned.

15–18 Determine the fuel-air ratio when coal from Colorado which has an ultimate analysis (by mass) as 79.61 percent C, 4.66 percent H_2, 4.76 percent O_2, 1.83 percent N_2, 0.52 percent S, and 8.62 percent ash (non-combustibles) is burned with 50 percent excess air. *Answer:* 0.0576 kg fuel/kg air

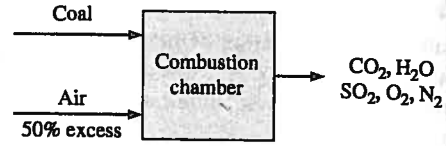


FIGURE P15–18

15–19 Propane (C_3H_8) is burned with 75 percent excess air during a combustion process. Assuming complete combustion, determine the air–fuel ratio. *Answer:* 27.5 kg air/kg fuel

15–20 Acetylene (C_2H_2) is burned with stoichiometric amount of air during a combustion process. Assuming complete combustion, determine the air–fuel ratio on a mass and on a mole basis.

15–21 Ethylene (C_2H_4) is burned with 200 percent theoretical air during a combustion process. Assuming complete combustion and a total pressure of 100 kPa, determine (*a*) the air–fuel ratio and (*b*) the dew-point temperature of the products. *Answers:* (*a*) 29.6 kg air/kg fuel, (*b*) 38.1°C

15–22 Propylene (C_3H_6) is burned with 50 percent excess air during a combustion process. Assuming complete combustion and a total pressure of 105 kPa, determine (*a*) the air–fuel ratio and (*b*) the temperature at which the water vapor in the products will start condensing.

15–23 Butane (C_4H_{10}) is burned in 200 percent theoretical air. For complete combustion, how many kmol of water must be sprayed into the combustion chamber per kmol of fuel if the products of combustion are to have a dew-point temperature of 60°C when the product pressure is 100 kPa?

15–24 A fuel mixture of 20 percent by mass methane (CH_4) and 80 percent by mass ethanol (C_2H_6O), is burned completely with theoretical air. If the total flow rate of the fuel is 31 kg/s, determine the required flow rate of air. *Answer:* 330 kg/s

15–25 Octane (C_8H_{18}) is burned with 250 percent theoretical air, which enters the combustion chamber at 25°C. Assuming complete combustion and a total pressure of 1 atm, determine (*a*) the air–fuel ratio and (*b*) the dew-point temperature of the products.

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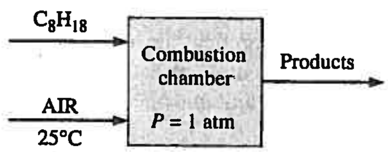


FIGURE P15–25

15–26 Gasoline (assumed C_8H_{18}) is burned steadily with air in a jet engine. If the air–fuel ratio is 18 kg air/kg fuel, determine the percentage of theoretical air used during this process.

15–27 n-Butane fuel (C_4H_{10}) is burned with stoichiometric amount of air. Determine the mass fraction of each product. Also, calculate the mass of carbon dioxide in the products and mass of air required per unit of fuel mass burned.

15–28 A coal from Pennsylvania which has an ultimate analysis (by mass) as 84.36 percent C, 1.89 percent H_2, 4.40 percent O_2, 0.63 percent N_2, 0.89 percent S, and 7.83 percent ash (non-combustibles) is burned with stoichiometric amount of air. Calculate the mole fractions of the products, the apparent molecular weight of the product gas, and the air-fuel ratio required neglecting the ash constituent.

15–29 Methyl alcohol (CH_3OH) is burned with stoichiometric amount of air. Calculate the mole fractions of each of the products, and the apparent molar mass of the product gas. Also, calculate the mass of water in the products per unit mass of fuel burned. *Answers:* 0.116 (CO_2), 0.231 (H_2O), 0.653 (N_2), 27.5 kg/kmol, 1.13 kg H_2O/kg fuel

15–30 A coal from Utah which has an ultimate analysis (by mass) as 61.40 percent C, 5.79 percent H_2, 25.31 percent O_2, 1.09 percent N_2, 1.41 percent S, and 5.00 percent ash (non-combustibles) is burned with stoichiometric amount of air, but the combustion is incomplete with 5 percent of the carbon in the fuel forming carbon monoxide. Calculate the mass fraction and the apparent molecular weight of the products, and the mass of air required per unit mass of fuel burned.

15–31 Propane fuel (C_3H_8) is burned with 30 percent excess air. Determine the mole fractions of each of the products. Also, calculate the mass of water in the products per unit mass of the fuel and the air-fuel ratio.

15–32 A certain natural gas has the following volumetric analysis: 65 percent CH_4, 8 percent H_2, 18 percent N_2, 3 percent O_2, and 6 percent CO_2. This gas is now burned completely with the stoichiometric amount of dry air. What is the air–fuel ratio for this combustion process?

15–33 Repeat Prob. 15–32 by replacing the dry air by moist air that enters the combustion chamber at 25°C, 1 atm, and 85 percent relative humidity.

15–34 A gaseous fuel with a volumetric analysis of 60 percent CH_4, 30 percent H_2, and 10 percent N_2 is burned to completion with 130 percent theoretical air. Determine (*a*) the air–fuel ratio and (*b*) the fraction of water vapor that would condense if the product gases were cooled to 20°C at 1 atm. *Answers:* (*a*) 18.6 kg air/kg fuel, (*b*) 88 percent

15–35 EES Reconsider Prob. 15–34. Using EES (or other) software, study the effects of varying the percentages of CH_4, H_2, and N_2 making up the fuel and the product gas temperature in the range 5 to 150°C.

15–36 Carbon (C) is burned with dry air. The volumetric analysis of the products is 10.06 percent CO_2, 0.42 percent CO, 10.69 percent O_2, and 78.83 percent N_2. Determine (*a*) the air–fuel ratio and (*b*) the percentage of theoretical air used.

15–37 Methane (CH_4) is burned with dry air. The volumetric analysis of the products on a dry basis is 5.20 percent CO_2, 0.33 percent CO, 11.24 percent O_2, and 83.23 percent N_2. Determine (*a*) the air–fuel ratio and (*b*) the percentage of theoretical air used. *Answers:* (*a*) 34.5 kg air/kg fuel, (*b*) 200 percent

15–38 Methyl alcohol (CH_3OH) is burned with 50 percent excess air. The combustion is incomplete with 10 percent of the carbon in the fuel forming carbon monoxide. Calculate the mole fraction of carbon monoxide and the apparent molecular weight of the products.

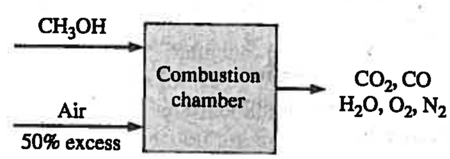


FIGURE P15–38

15–39 n-Octane (C_8H_{18}) is burned with 100 percent excess air with 15 percent of the carbon in the fuel forming carbon monoxide. Calculate the mole fractions of the products and the dew-point temperature of the water vapor in the products when the products are at 1 atm pressure. *Answers:* 0.0548 (CO_2), 0.0097 (CO), 0.0725 (H_2O), 0.1056 (O_2), 0.7575 (N_2), 39.9°C

Enthalpy of Formation and Enthalpy of Combustion

15–40C What is enthalpy of combustion? How does it differ from the enthalpy of reaction?

15–41C What is enthalpy of formation? How does it differ from the enthalpy of combustion?

15–42C What are the higher and the lower heating values of a fuel? How do they differ? How is the heating value of a fuel related to the enthalpy of combustion of that fuel?

15–43C When are the enthalpy of formation and the enthalpy of combustion identical?

15–44C Does the enthalpy of formation of a substance change with temperature?

15–45C The $\bar{h}_f^\circ$ of N_2 is listed as zero. Does this mean that N_2 contains no chemical energy at the standard reference state?

15–46C Which contains more chemical energy, 1 kmol of H_2 or 1 kmol of H_2O?

15–47 Determine the enthalpy of combustion of methane (CH_4) at 25°C and 1 atm, using the enthalpy of formation data from Table A–26. Assume that the water in the products is in the liquid form. Compare your result to the value listed in Table A–27. *Answer:* −890,330 kJ/kmol

15–48 Reconsider Prob. 15–47. Using EES (or other) software, study the effect of temperature on the enthalpy of combustion. Plot the enthalpy of combustion as a function of temperature over the range 25 to 600°C.

15–49 Repeat Prob. 15–47 for gaseous ethane (C_2H_6).

15–50 Repeat Prob. 15–47 for liquid octane (C_8H_{18}).

15–51 Ethane (C_2H_6) is burned at atmospheric pressure with stoichiometric amount of air as the oxidizer. Determine the heat rejected, in kJ/kmol fuel, when the products and reactants are at 25°C, and the water appears in the products as water vapor.

15–52 What is the minimum pressure of the products of Prob. 15–51 which will assure that the water in the products will be in vapor form?

15–53 Calculate the higher and lower heating values of a coal from Utah which has an ultimate analysis (by mass) as 61.40 percent C, 5.79 percent H_2, 25.31 percent O_2, 1.09 percent N_2, 1.41 percent S, and 5.00 percent ash (non-combustibles). The enthalpy of formation of SO_2 is −297,100 kJ/kmol. *Answers:* 30,000 kJ/kg, 28,700 kJ/kg

First-Law Analysis of Reacting Systems

15–54C Derive an energy balance relation for a reacting closed system undergoing a quasi-equilibrium constant pressure expansion or compression process.

15–55C Consider a complete combustion process during which both the reactants and the products are maintained at the same state. Combustion is achieved with (*a*) 100 percent theoretical air, (*b*) 200 percent theoretical air, and (*c*) the chemically correct amount of pure oxygen. For which case will the amount of heat transfer be the highest? Explain.

15–56C Consider a complete combustion process during which the reactants enter the combustion chamber at 20°C and the products leave at 700°C. Combustion is achieved with (*a*) 100 percent theoretical air, (*b*) 200 percent theoretical air, and (*c*) the chemically correct amount of pure oxygen. For which case will the amount of heat transfer be the lowest? Explain.

15–57 Propane fuel (C_3H_8) is burned with an air-fuel ratio of 18 in an atmospheric pressure heating furnace. Determine the heat transfer per kilogram of fuel burned when the temperature of the products is such that liquid water just begins to form in the products.

15–58 n-Octane gas (C_8H_{18}) is burned with 100 percent excess air in a constant pressure burner. The air and fuel enter this burner steadily at standard conditions and the products of combustion leave at 257°C. Calculate the heat transfer, in kJ/kg fuel, during this combustion.

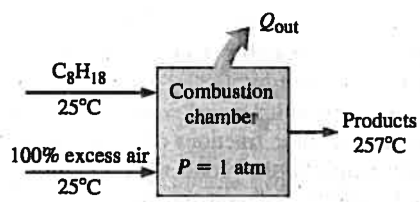


FIGURE P15–58

15–59 A coal from Texas which has an ultimate analysis (by mass) as 39.25 percent C, 6.93 percent H_2, 41.11 percent O_2, 0.72 percent N_2, 0.79 percent S, and 11.20 percent ash (non-combustibles) is burned steadily with 40 percent excess air in a power plant boiler. The coal and air enter this boiler at standard conditions and the products of combustion in the smokestack are at 127°C. Calculate the heat transfer, in kJ/kg fuel, in this boiler. Include the effect of the sulfur in the energy analysis by noting that sulfur dioxide has an enthalpy of formation of −297,100 kJ/kmol and an average specific heat at constant pressure of c_p = 41.7 kJ/kmol · K.

15–60 Methane (CH_4) is burned completely with the stoichiometric amount of air during a steady-flow combustion process. If both the reactants and the products are maintained at 25°C and 1 atm and the water in the products exists in the liquid form, determine the heat transfer from the combustion chamber during this process. What would your answer be if combustion were achieved with 100 percent excess air? *Answer:* 890,330 kJ/kmol

15–61 Liquid propane (C_3H_8) enters a combustion chamber at 25°C at a rate of 1.2 kg/min where it is mixed and burned with 150 percent excess air that enters the combustion chamber at 12°C. If the combustion is complete and the exit temperature of the combustion gases is 1200 K, determine (*a*) the mass flow rate of air and (*b*) the rate of heat transfer from the combustion chamber. *Answers:* (*a*) 47.1 kg/min, (*b*) 5194 kJ/min

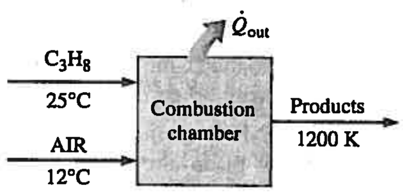


FIGURE P15–61

15–62 Liquid octane (C_8H_{18}) at 25°C is burned completely during a steady-flow combustion process with 180 percent theoretical air that enters the combustion chamber at 25°C. If the products leave at 1400 K, determine (*a*) the air–fuel ratio and (*b*) the heat transfer from the combustion chamber during this process.

15–63 Benzene gas (C_6H_6) at 25°C is burned during a steady-flow combustion process with 95 percent theoretical air that enters the combustion chamber at 25°C. All the hydrogen in the fuel burns to H_2O, but part of the carbon burns to CO. If the products leave at 1000 K, determine (*a*) the mole fraction of the CO in the products and (*b*) the heat transfer from the combustion chamber during this process. *Answers:* (*a*) 2.1 percent, (*b*) 2,112,800 kJ/kmol C_6H_6

15–64 Octane gas (C_8H_{18}) at 25°C is burned steadily with 30 percent excess air at 25°C, 1 atm, and 60 percent relative humidity. Assuming combustion is complete and the products leave the combustion chamber at 600 K, determine the heat transfer for this process per unit mass of octane.

15–65 Reconsider Prob. 15–64. Using EES (or other) software, investigate the effect of the amount of excess air on the heat transfer for the combustion process. Let the excess air vary from 0 to 200 percent. Plot the heat transfer against excess air, and discuss the results.

15–66 Ethane gas (C_2H_6) at 25°C is burned in a steady-flow combustion chamber at a rate of 5 kg/h with the stoichiometric amount of air, which is preheated to 500 K before entering the combustion chamber. An analysis of the combustion gases reveals that all the hydrogen in the fuel burns to H_2O but only 95 percent of the carbon burns to CO_2, the remaining 5 percent forming CO. If the products leave the combustion chamber at 800 K, determine the rate of heat transfer from the combustion chamber. *Answer:* 200,170 kJ/h

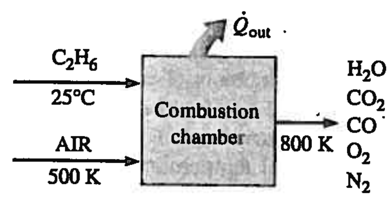


FIGURE P15–66

15–67 A constant-volume tank contains a mixture of 120 g of methane (CH_4) gas and 600 g of O_2 at 25°C and 200 kPa. The contents of the tank are now ignited, and the methane gas burns completely. If the final temperature is 1200 K, determine (*a*) the final pressure in the tank and (*b*) the heat transfer during this process.

15–68 Reconsider Prob. 15–67. Using EES (or other) software, investigate the effect of the final temperature on the final pressure and the heat transfer for the combustion process. Let the final temperature vary from 500 to 1500 K. Plot the final pressure and heat transfer against the final temperature, and discuss the results.

15–69 Propane fuel (C_3H_8) is burned in a space heater with 50 percent excess air. The fuel and air enter this heater steadily at 1 atm and 17°C, while the combustion products leave at 1 atm and 97°C. Calculate the heat transferred in this heater, in kJ/kmol fuel. *Answer:* 1,953,000 kJ/kmol fuel

15–70 One kmol of methane (CH_4) undergoes complete combustion with stoichiometric amount of air in a rigid container. Initially, the air and methane are at 100 kPa and 25°C. The products of combustion are at 447°C. How much heat is rejected from the container, in kJ/kmol fuel?

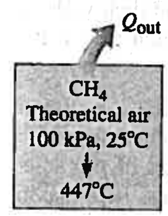


FIGURE P15–70

15–71 The effective mass-specific heat product (mc_v) of a constant volume bomb calorimeter is 100 kJ/K. Wheat straw that is being considered as an alternative fuel is tested in the calorimeter. Ten grams of this straw are placed in the calorimeter. After charging the calorimeter with oxygen and burning the straw, it is found that the temperature of the calorimeter has increased by 1.8°C. Determine the heating value of this straw. How does this compare to the higher heating value of propane fuel?

15–72 A constant-volume tank contains a mixture of 1 kmol of benzene (C_6H_6) gas and 30 percent excess air at 25°C and 1 atm. The contents of the tank are now ignited, and all the hydrogen in the fuel burns to H_2O but only 92 percent of the carbon burns to CO_2, the remaining 8 percent forming CO. If the final temperature in the tank is 1000 K, determine the heat transfer from the combustion chamber during this process.

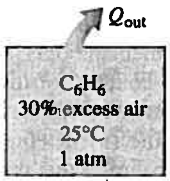


FIGURE P15–72

15–73 To supply heated air to a house, a high-efficiency gas furnace burns gaseous propane (C_3H_8) with a combustion efficiency of 96 percent. Both the fuel and 140 percent theoretical air are supplied to the combustion chamber at 25°C and 100 kPa, and the combustion is complete. Because this is a high-efficiency furnace, the product gases are cooled to 25°C and 100 kPa before leaving the furnace. To maintain the house at the desired temperature, a heat transfer rate of 31,650 kJ/h is required from the furnace. Determine the volume of water condensed from the product gases per day. *Answer:* 8.7 L/day

Adiabatic Flame Temperature

15–74C A fuel is completely burned first with the stoichiometric amount of air and then with the stoichiometric amount of pure oxygen. For which case will the adiabatic flame temperature be higher?

15–75C A fuel at 25°C is burned in a well-insulated steady-flow combustion chamber with air that is also at 25°C. Under what conditions will the adiabatic flame temperature of the combustion process be a maximum?

15–76 Hydrogen (H_2) at 7°C is burned with 20 percent excess air that is also at 7°C during an adiabatic steady-flow combustion process. Assuming complete combustion, determine the exit temperature of the product gases. *Answer:* 2251 K

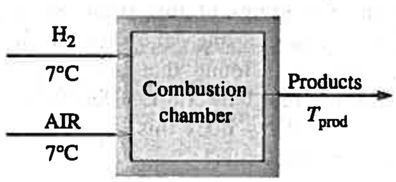


FIGURE P15–76

15–77 Reconsider Prob. 15–76. Using EES (or other) software, modify this problem to include the fuels butane, ethane, methane, and propane as well as H_2; to include the effects of inlet air and fuel temperatures; and the percent theoretical air supplied. Select a range of input parameters and discuss the results for your choices.

15–78 What is the adiabatic flame temperature of methane (CH_4) when it is burned with 30 percent excess air?

15–79 Liquid octane (C_8H_{18}) is burned in the constant pressure, adiabatic combustor of an aircraft engine with 40 percent excess air. The air enters this combustor at 600 kPa and 307°C, and the fuel is injected into the combustor at 25°C. Estimate the temperature at which the products of combustion leave the combustor. *Answer:* 2113 K

15–80 A large railroad has experimented with burning powdered coal in a gas turbine combustor. Fifty percent excess air was introduced to the combustor at 1380 kPa and 127°C while the powdered coal was injected at 25°C. The combustion was adiabatic and at constant pressure. Based on a coal from Colorado which has an ultimate analysis (by mass) as 79.61 percent C, 4.66 percent H_2, 4.76 percent O_2, 1.83 percent N_2, 0.52 percent S, and 8.62 percent ash (noncombustibles), what is the estimated temperature of the combustion products? Neglect the effect of the sulfur in the energy balance.

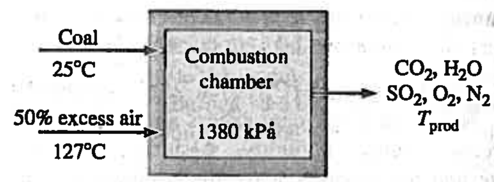


FIGURE P15–80

15–81 The combustion products of Prob. 15–80 are expanded in an isentropic turbine to 140 kPa. Calculate the work produced by this turbine, in kJ/kg fuel.

15–82 Ethyl alcohol (C_2H_5OH (*g*)) is burned with 200 percent excess air in an adiabatic, constant volume container. Initially, air and ethyl alcohol are at 100 kPa and 25°C. Assuming complete combustion, determine the final temperature and pressure of the products of combustion. *Answers:* 1435 K, 493 kPa

15–83 An adiabatic constant-volume tank contains a mixture of 1 kmol of hydrogen (H_2) gas and the stoichiometric amount of air at 25°C and 1 atm. The contents of the tank are now ignited. Assuming complete combustion, determine the final temperature in the tank.

Entropy Change and Second-Law Analysis of Reacting Systems

15–84C Express the increase of entropy principle for chemically reacting systems.

15–85C How are the absolute entropy values of ideal gases at pressures different from 1 atm determined?

15–86C What does the Gibbs function of formation g_f° of a compound represent?

15–87 One kmol of H_2 at 25°C and 1 atm is burned steadily with 0.5 kmol of O_2 at the same state. The H_2O formed during the process is then brought to 25°C and 1 atm, the conditions of the surroundings. Assuming combustion is complete, determine the reversible work and exergy destruction for this process.

15–88 Ethylene (C_2H_4) gas enters an adiabatic combustion chamber at 25°C and 1 atm and is burned with 20 percent excess air that enters at 25°C and 1 atm. The combustion is complete, and the products leave the combustion chamber at 1 atm pressure. Assuming T_0 = 25°C, determine (*a*) the temperature of the products, (*b*) the entropy generation, and (*c*) the exergy destruction. *Answers:* (*a*) 2269.6 K, (*b*) 1311.3 kJ/kmol · K, (*c*) 390,760 kJ/kmol

15–89 Liquid octane (C_8H_{18}) enters a steady-flow combustion chamber at 25°C and 1 atm at a rate of 0.25 kg/min. It is burned with 50 percent excess air that also enters at 25°C and 1 atm. After combustion, the products are allowed to cool to 25°C. Assuming complete combustion and that all the H_2O in the products is in liquid form, determine (*a*) the heat transfer rate from the combustion chamber, (*b*) the entropy generation rate, and (*c*) the exergy destruction rate. Assume that T_0 = 298 K and the products leave the combustion chamber at 1 atm pressure.

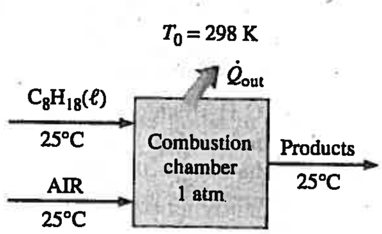


FIGURE P15–89

15–90 Benzene gas (C_6H_6) at 1 atm and 25°C is burned during a steady-flow combustion process with 95 percent theoretical air that enters the combustion chamber at 25°C and 1 atm. All the hydrogen in the fuel burns to H_2O, but part of the carbon burns to CO. Heat is lost to the surroundings at 25°C, and the products leave the combustion chamber at 1 atm and 850 K. Determine (*a*) the heat transfer from the combustion chamber and (*b*) the exergy destruction.

15–91 Liquid propane (C_3H_8) enters a steady-flow combustion chamber at 25°C and 1 atm at a rate of 0.4 kg/min where it is mixed and burned with 150 percent excess air that enters the combustion chamber at 12°C. If the combustion products leave at 1200 K and 1 atm, determine (*a*) the mass flow rate of air, (*b*) the rate of heat transfer from the combustion chamber, and (*c*) the rate of entropy generation during this process. Assume T_0 = 25°C. *Answers:* (*a*) 15.7 kg/min, (*b*) 1732 kJ/min, (*c*) 34.2 kJ/min · K

15–92 Reconsider Prob. 15–91. Using EES (or other) software, study the effect of varying the surroundings temperature from 0 to 38°C on the rate of exergy destruction, and plot it as a function of surroundings temperature.

15–93 n-Octane (C_8H_{18}) is burned in an automobile engine with 200 percent excess air. Air enters this engine at 1 atm and 25°C. Liquid fuel at 25°C is mixed with this air before combustion. The exhaust products leave the exhaust system at 1 atm and 77°C. What is the maximum amount of work, in kJ/kg fuel, that can be produced by this engine? Take T_0 = 25°C.

15–94 The automobile engine of Prob. 15-97 is to be converted to natural gas (methane, CH_4) fuel. Assuming that all factors remain the same, what is the maximum work that can be produced by the modified engine, in kJ/kg fuel? *Answer:* 51,050 kJ/kg fuel

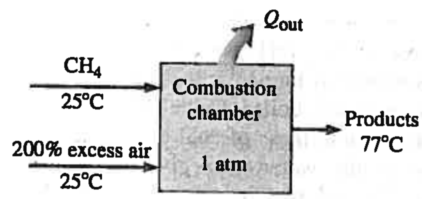


FIGURE P15–94

15–95 n-Octane (C_8H_{18}) is burned in the constant pressure combustor of an aircraft engine with 30 percent excess air. Air enters this combustor at 600 kPa and 327°C, liquid fuel is injected at 25°C, and the products of combustion leave at 600 kPa and 1227°C. Determine the entropy generation and exergy destruction per unit mass of fuel during this combustion process. Take T_0 = 25°C.

Review Problems

15–96 A 1-g sample of a certain fuel is burned in a bomb calorimeter that contains 2 kg of water in the presence of 100 g of air in the reaction chamber. If the water temperature rises by 2.5°C when equilibrium is established, determine the heating value of the fuel, in kJ/kg.

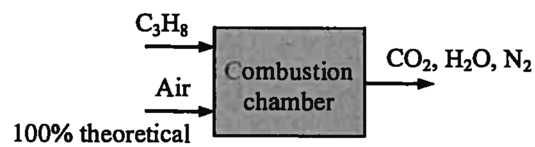
15.14

[redacted] Propane is burned with theoretical amount of air. The mass fraction of carbon dioxide and the mole and mass fractions of the water vapor in the products are to be determined.

Properties The molar masses of C_3H_8, O_2, N_2, CO_2, and H_2O are 44, 32, 28, 44, and 18 kg/kmol, respectively (Table A-1).

Analysis (*a*) The reaction in terms of undetermined coefficients is

$$C_3H_8 + x(O_2 + 3.76N_2) \longrightarrow yCO_2 + zH_2O + pN_2$$



Balancing the carbon in this reaction gives

$$y = 3$$

and the hydrogen balance gives

$$2z = 8 \longrightarrow z = 4$$

The oxygen balance produces

$$2x = 2y + z \longrightarrow x = y + z/2 = 3 + 4/2 = 5$$

A balance of the nitrogen in this reaction gives

$$2 \times 3.76x = 2p \longrightarrow p = 3.76x = 3.76 \times 5 = 18.8$$

In balanced form, the reaction is

$$C_3H_8 + 5O_2 + 18.8N_2 \longrightarrow 3CO_2 + 4H_2O + 18.8N_2$$

The mass fraction of carbon dioxide is determined from

$$\begin{aligned}\text{mf}_{CO2} &= \frac{m_{CO2}}{m_{\text{products}}} = \frac{N_{CO2}M_{CO2}}{N_{CO2}M_{CO2} + N_{H2O}M_{H2O} + N_{N2}M_{N2}} \\ &= \frac{(3\text{ kmol})(44\text{ kg/kmol})}{(3\text{ kmol})(44\text{ kg/kmol}) + (4\text{ kmol})(18\text{ kg/kmol}) + (18.8\text{ kmol})(28\text{ kg/kmol})} \\ &= \frac{132\text{ kg}}{730.4\text{ kg}} = \mathbf{0.181}\end{aligned}$$

(*b*) The mole and mass fractions of water vapor are

$$y_{H2O} = \frac{N_{H2O}}{N_{\text{products}}} = \frac{N_{H2O}}{N_{CO2} + N_{H2O} + N_{N2}} = \frac{4\text{ kmol}}{3\text{ kmol} + 4\text{ kmol} + 18.8\text{ kmol}} = \frac{4\text{ kmol}}{25.8\text{ kmol}} = \mathbf{0.155}$$

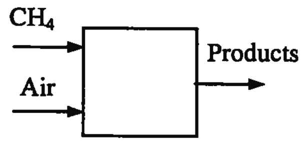
$$\begin{aligned}\text{mf}_{H2O} &= \frac{m_{H2O}}{m_{\text{products}}} = \frac{N_{H2O}M_{H2O}}{N_{CO2}M_{CO2} + N_{H2O}M_{H2O} + N_{N2}M_{N2}} \\ &= \frac{(4\text{ kmol})(18\text{ kg/kmol})}{(3\text{ kmol})(44\text{ kg/kmol}) + (4\text{ kmol})(18\text{ kg/kmol}) + (18.8\text{ kmol})(28\text{ kg/kmol})} \\ &= \frac{72\text{ kg}}{730.4\text{ kg}} = \mathbf{0.0986}\end{aligned}$$

15.15

15-16 Methane is burned with air. The mass flow rates at the two inlets are to be determined.

Properties The molar masses of CH_4, O_2, N_2, CO_2, and H_2O are 16, 32, 28, 44, and 18 kg/kmol, respectively (Table A-1).

Analysis The stoichiometric combustion equation of CH_4 is



$$CH_4 + a_{th}[O_2 + 3.76N_2] \longrightarrow CO_2 + 2H_2O + 3.76a_{th}N_2$$

O_2 balance: $$a_{th} = 1 + 1 \longrightarrow a_{th} = 2$$

Substituting, $$CH_4 + 2[O_2 + 3.76N_2] \longrightarrow CO_2 + 2H_2O + 7.52N_2$$

The masses of the reactants are

$$m_{CH4} = N_{CH4}M_{CH4} = (1\text{ kmol})(16\text{ kg/kmol}) = 16\text{ kg}$$
$$m_{O2} = N_{O2}M_{O2} = (2\text{ kmol})(32\text{kg/kmol}) = 64\text{ kg}$$
$$m_{N2} = N_{N2}M_{N2} = (2\times 3.76\text{ kmol})(28\text{ kg/kmol}) = 211\text{ kg}$$

The total mass is

$$m_{total} = m_{CH4} + m_{O2} + N_{N2} = 16 + 64 + 211 = 291\text{ kg}$$

Then the mass fractions are

$$\text{mf}_{CH4} = \frac{m_{CH4}}{m_{total}} = \frac{16\text{ kg}}{291\text{ kg}} = 0.05498$$
$$\text{mf}_{O2} = \frac{m_{O2}}{m_{total}} = \frac{64\text{ kg}}{291\text{ kg}} = 0.2199$$
$$\text{mf}_{N2} = \frac{m_{N2}}{m_{total}} = \frac{211\text{ kg}}{291\text{ kg}} = 0.7251$$

For a mixture flow of 0.01 kg/s, the mass flow rates of the reactants are

$$\dot{m}_{CH4} = \text{mf}_{CH4}\dot{m} = (0.05498)(0.01\text{kg/s}) = \mathbf{0.0005498\ kg/s}$$
$$\dot{m}_{air} = \dot{m} - \dot{m}_{CH4} = 0.01 - 0.0005498 = \mathbf{0.009450\ kg/s}$$

15.17

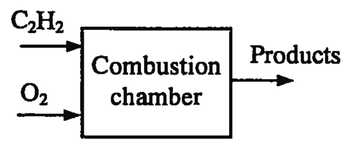
~~15-18~~ Acetylene is burned with 10 percent excess oxygen. The mass fractions of each of the products and the mass of oxygen used per unit mass of fuel burned are to be determined.

Assumptions 1 Combustion is complete. 2 The combustion products contain CO_2, H_2O, and O_2. 3 Combustion gases are ideal gases.

Properties The molar masses of C, H_2, and O_2 are 12 kg/kmol, 2 kg/kmol, and 32 kg/kmol, respectively (Table A-1).

Analysis The stoichiometric combustion equation is

$$C_2H_2 + 2.5O_2 \longrightarrow 2CO_2 + H_2O$$



The combustion equation with 10% excess oxygen is

$$C_2H_2 + 2.75O_2 \longrightarrow 2CO_2 + H_2O + 0.25O_2$$

The mass of each product and the total mass are

$$m_{CO2} = N_{CO2}M_{CO2} = (2 \text{ kmol})(44 \text{ kg/kmol}) = 88 \text{ kg}$$
$$m_{H2O} = N_{H2O}M_{H2O} = (1 \text{ kmol})(18 \text{ kg/kmol}) = 18 \text{ kg}$$
$$m_{O2} = N_{O2}M_{O2} = (0.25 \text{ kmol})(32 \text{ kg/kmol}) = 8 \text{ kg}$$
$$m_{total} = m_{CO2} + m_{H2O} + m_{O2} = 88 + 18 + 8 = 114 \text{ kg}$$

Then the mass fractions are

$$\text{mf}_{CO2} = \frac{m_{CO2}}{m_{total}} = \frac{88 \text{ kg}}{114 \text{ kg}} = \mathbf{0.7719}$$

$$\text{mf}_{H2O} = \frac{m_{H2O}}{m_{total}} = \frac{18 \text{ kg}}{114 \text{ kg}} = \mathbf{0.1579}$$

$$\text{mf}_{O2} = \frac{m_{O2}}{m_{total}} = \frac{8 \text{ kg}}{114 \text{ kg}} = \mathbf{0.0702}$$

The mass of oxygen per unit mass of fuel burned is determined from

$$\frac{m_{O2}}{m_{C2H2}} = \frac{(2.75 \times 32) \text{ kg}}{(1 \times 26) \text{ kg}} = \mathbf{3.385 \text{ kg } O_2/\text{kg } C_2H_2}$$

15.19

[redacted]0 Propane is burned with 75 percent excess air during a combustion process. The AF ratio is to be determined.

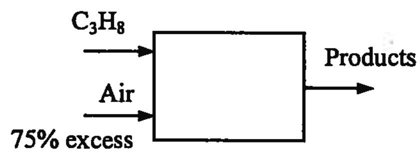
Assumptions 1 Combustion is complete. 2 The combustion products contain CO_2, H_2O, O_2, and N_2 only.

Properties The molar masses of C, H_2, and air are 12 kg/kmol, 2 kg/kmol, and 29 kg/kmol, respectively (Table A-1).

Analysis The combustion equation in this case can be written as

$$C_3H_8 + 1.75a_{th}[O_2 + 3.76N_2] \longrightarrow 3CO_2 + 4H_2O + 0.75a_{th}O_2 + (1.75 \times 3.76)a_{th}N_2$$

where a_{th} is the stoichiometric coefficient for air. We have automatically accounted for the 75% excess air by using the factor $1.75a_{th}$ instead of a_{th} for air. The stoichiometric amount of oxygen ($a_{th}O_2$) will be used to oxidize the fuel, and the remaining excess amount ($0.75a_{th}O_2$) will appear in the products as free oxygen. The coefficient a_{th} is determined from the O_2 balance,



O_2 balance: $\quad 1.75a_{th} = 3 + 2 + 0.75a_{th} \longrightarrow a_{th} = 5$

Substituting,

$$C_3H_8 + 8.75[O_2 + 3.76N_2] \longrightarrow 3CO_2 + 4H_2O + 3.75O_2 + 32.9N_2$$

The air-fuel ratio is determined by taking the ratio of the mass of the air to the mass of the fuel,

$$AF = \frac{m_{air}}{m_{fuel}} = \frac{(8.75 \times 4.76\ \text{kmol})(29\ \text{kg/kmol})}{(3\ \text{kmol})(12\ \text{kg/kmol}) + (4\ \text{kmol})(2\ \text{kg/kmol})} = \mathbf{27.5\ kg\ air/kg\ fuel}$$

15.40

15-40 n-Octane is burned with 100% excess air. The combustion is incomplete. The mole fractions of products and the dew-point temperature of the water vapor in the products are to be determined.

Assumptions **1** Combustion is complete. **2** The combustion products contain CO_2, CO, H_2O, O_2, and N_2 only.

Properties The molar masses of C, H_2, O_2, N_2 and air are 12 kg/kmol, 2 kg/kmol, 32 kg/kmol, 28 kg/kmol, and 29 kg/kmol, respectively (Table A-1).

Analysis The combustion reaction for stoichiometric air is

$$C_8H_{18} + 12.5[O_2 + 3.76N_2] \longrightarrow 8CO_2 + 9H_2O + (12.5\times3.76)N_2$$

The combustion equation with 100% excess air and incomplete combustion is

$$C_8H_{18} + 2\times12.5[O_2 + 3.76N_2] \longrightarrow (0.85\times8)\,CO_2 + (0.15\times8)\,CO + 9H_2O + x\,O_2 + (2\times12.5\times3.76)\,N_2$$

The coefficient for CO is determined from a mass balance,

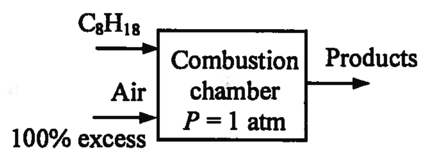
O_2 balance: $\quad 25 = 0.85\times8 + 0.5\times0.15\times8 + 0.5\times9 + x \longrightarrow x = 13.1$

Substituting,

$$C_8H_{18} + 25[O_2 + 3.76N_2] \longrightarrow 6.8\,CO_2 + 1.2\,CO + 9\,H_2O + 13.1\,O_2 + 94\,N_2$$

The mole fractions of the products are

$$N_{prod} = 6.8 + 1.2 + 9 + 13.1 + 94 = 124.1\text{ kmol}$$



$$y_{CO2} = \frac{N_{CO2}}{N_{prod}} = \frac{6.8\text{ kmol}}{124.1\text{ kmol}} = \mathbf{0.0548}$$

$$y_{CO} = \frac{N_{CO}}{N_{prod}} = \frac{1.2\text{ kmol}}{124.1\text{ kmol}} = \mathbf{0.0097}$$

$$y_{H2O} = \frac{N_{H2O}}{N_{prod}} = \frac{9\text{ kmol}}{124.1\text{ kmol}} = \mathbf{0.0725}$$

$$y_{O2} = \frac{N_{O2}}{N_{prod}} = \frac{13.1\text{ kmol}}{124.1\text{ kmol}} = \mathbf{0.1056}$$

$$y_{N2} = \frac{N_{N2}}{N_{prod}} = \frac{94\text{ kmol}}{124.1\text{ kmol}} = \mathbf{0.7575}$$

The dew-point temperature of a gas-vapor mixture is the saturation temperature of the water vapor in the product gases corresponding to its partial pressure. That is,

$$P_v = \left(\frac{N_v}{N_{prod}}\right)P_{prod} = \left(\frac{9\text{ kmol}}{124.1\text{ kmol}}\right)(101.325\text{ kPa}) = 7.348\text{ kPa}$$

Thus,

$$T_{dp} = T_{sat@7.348\text{ kPa}} = \mathbf{39.9°C} \qquad \text{(Table A-5 or EES)}$$

15.57

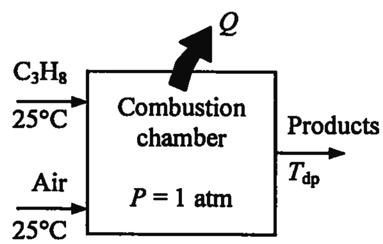
[redacted] Propane is burned with an air-fuel ratio of 18. The heat transfer per kilogram of fuel burned when the temperature of the products is such that liquid water just begins to form in the products is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Air and combustion gases are ideal gases. **3** Kinetic and potential energies are negligible. **4** Combustion is complete. **5** The reactants are at 25°C and 1 atm. **6** The fuel is in vapor phase.

Properties The molar masses of propane and air are 44 kg/kmol and 29 kg/kmol, respectively (Table A-1).

Analysis The mass of air per kmol of fuel is

$$\begin{aligned} m_{\text{air}} &= (\text{AF})m_{\text{fuel}} \\ &= (18\text{ kg air/kg fuel})(1\times 44\text{ kg/kmol fuel}) \\ &= 792\text{ kg air/kmol fuel} \end{aligned}$$



The mole number of air per kmol of fuel is then

$$N_{\text{air}} = \frac{m_{\text{air}}}{M_{\text{air}}} = \frac{792\text{ kg air/kmol fuel}}{29\text{ kg air/kmol air}} = 27.31\text{ kmol air/kmol fuel}$$

The combustion equation can be written as

$$C_3H_8 + (27.31/4.76)(O_2 + 3.76N_2) \longrightarrow 3CO_2 + 4H_2O + xO_2 + (27.31/4.76)\times 3.76N_2$$

The coefficient for CO is obtained from O_2 balance:

$$(27.31/4.76) = 3 + 2 + x \longrightarrow x = 0.7374$$

Substituting,

$$C_3H_8 + 5.7374(O_2 + 3.76N_2) \longrightarrow 3CO_2 + 4H_2O + 0.7374O_2 + 21.57N_2$$

The mole fraction of water in the products is

$$y_v = \frac{N_{\text{H2O}}}{N_{\text{prod}}} = \frac{4\text{ kmol}}{(3+4+0.7374+21.57)\text{ kmol}} = \frac{4\text{ kmol}}{29.31\text{ kmol}} = 0.1365$$

The partial pressure of water vapor at 1 atm total pressure is

$$P_v = y_v P = (0.1365)(101.325\text{ kPa}) = 13.83\text{ kPa}$$

When this mixture is at the dew-point temperature, the water vapor pressure is the same as the saturation pressure. Then,

$$T_{\text{dp}} = T_{\text{sat@13.83 kPa}} = 52.3°\text{C} \cong 325\text{ K}$$

The heat transfer for this combustion process is determined from the energy balance $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{\text{out}} = \sum N_P\left(\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ\right)_P - \sum N_R\left(\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ\right)_R$$

Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

Substance	$\overline{h}_f^\circ$ kJ/kmol	$\overline{h}_{298K}$ kJ/kmol	$\overline{h}_{325K}$ kJ/kmol
C_3H_8	-103,850	---	---
O_2	0	8682	9473
N_2	0	8669	9452
H_2O (*g*)	-241,820	9904	10,808
CO_2	-393,520	9364	10,378

Substituting,

$$
\begin{aligned}
-\overline{Q}_{out} &= (3)(-393{,}520 + 10{,}378 - 9364) + (4)(-241{,}820 + 10{,}808 - 9904) + (0.7374)(0 + 9473 - 8682) \\
&\quad + (21.57)(0 + 9452 - 8669) - (1)(-103{,}850) - 0 \\
&= -2{,}019{,}860 \text{ kJ/kmol } C_3H_8
\end{aligned}
$$

or

$$\overline{Q}_{out} = 2{,}019{,}860 \text{ kJ/kmol } C_3H_8$$

Then the heat transfer per kg of fuel is

$$Q_{out} = \frac{\overline{Q}_{out}}{M_{fuel}} = \frac{2{,}019{,}860 \text{ kJ/kmol fuel}}{44 \text{ kg/kmol}} = \mathbf{45{,}900\ kJ/kg\ C_3H_8}$$

15.58

15-59 n-Octane is burned with 100 percent excess air. The heat transfer per kilogram of fuel burned for a product temperature of 257°C is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Air and combustion gases are ideal gases. **3** Kinetic and potential energies are negligible. **4** Combustion is complete. **5** The fuel is in vapor phase.

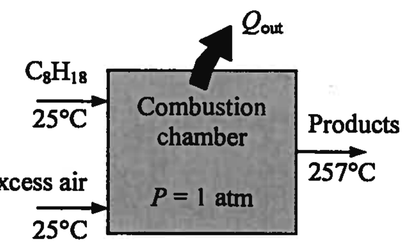
Properties The molar masses of propane and air are 44 kg/kmol and 29 kg/kmol, respectively (Table A-1).

Analysis The combustion reaction for stoichiometric air is

$$C_8H_{18} + 12.5[O_2 + 3.76N_2] \longrightarrow 8CO_2 + 9H_2O + (12.5\times3.76)N_2$$

The combustion equation with 100% excess air is

$$C_8H_{18} + 25[O_2 + 3.76N_2] \longrightarrow 8CO_2 + 9H_2O + 12.5\,O_2 + 94N_2$$



The heat transfer for this combustion process is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{out} = \sum N_P\left(\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ\right)_P - \sum N_R\left(\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ\right)_R$$

Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

Substance	$\bar{h}_f^\circ$ kJ/kmol	$\bar{h}_{298K}$ kJ/kmol	$\bar{h}_{530K}$ kJ/kmol
C_8H_{18} (g)	-208,450	---	---
O_2	0	8682	15,708
N_2	0	8669	15,469
H_2O (g)	-241,820	9904	17,889
CO_2	-393,520	9364	19,029

Substituting,

$$\begin{aligned}-\bar{Q}_{out} &= (8)(-393{,}520 + 19{,}029 - 9364) + (9)(-241{,}820 + 17{,}889 - 9904) + (12.5)(0 + 15{,}708 - 8682)\\ &\quad + (94)(0 + 15{,}469 - 8669) - (1)(-208{,}450) - 0 - 0\\ &= -4{,}239{,}880 \text{ kJ/kmol } C_8H_{18}\end{aligned}$$

or $\quad \bar{Q}_{out} = 4{,}239{,}880 \text{ kJ/kmol } C_8H_{18}$

Then the heat transfer per kg of fuel is

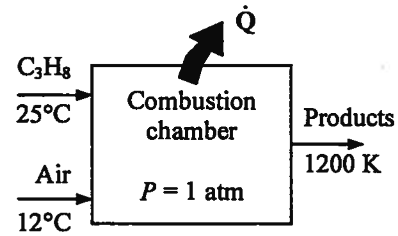
$$Q_{out} = \frac{\bar{Q}_{out}}{M_{fuel}} = \frac{4{,}239{,}880 \text{ kJ/kmol fuel}}{114 \text{ kg/kmol}} = \mathbf{37{,}200\ kJ/kg\ C_8H_{18}}$$

15.61

~~15-62~~ Liquid propane is burned with 150 percent excess air during a steady-flow combustion process. The mass flow rate of air and the rate of heat transfer from the combustion chamber are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Air and combustion gases are ideal gases. **3** Kinetic and potential energies are negligible. **4** Combustion is complete.

Properties The molar masses of propane and air are 44 kg/kmol and 29 kg/kmol, respectively (Table A-1).



Analysis The fuel is burned completely with excess air, and thus the products will contain only CO_2, H_2O, N_2, and some free O_2. Considering 1 kmol of C_3H_8, the combustion equation can be written as

$$C_3H_8(\ell)+2.5a_{th}(O_2+3.76N_2)\longrightarrow 3CO_2+4H_2O+1.5a_{th}O_2+(2.5)(3.76a_{th})N_2$$

where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$2.5a_{th}=3+2+1.5a_{th} \longrightarrow a_{th}=5$$

Thus,

$$C_3H_8(\ell)+12.5(O_2+3.76N_2)\longrightarrow 3CO_2+4H_2O+7.5O_2+47N_2$$

(*a*) The air-fuel ratio for this combustion process is

$$\text{AF}=\frac{m_{\text{air}}}{m_{\text{fuel}}}=\frac{(12.5\times 4.76\text{ kmol})(29\text{ kg/kmol})}{(3\text{ kmol})(12\text{ kg/kmol})+(4\text{ kmol})(2\text{ kg/kmol})}=39.22\text{ kg air/kg fuel}$$

Thus, $\dot{m}_{\text{air}}=(\text{AF})(\dot{m}_{\text{fuel}})=(39.22\text{ kg air/kg fuel})(1.2\text{ kg fuel/min})=\mathbf{47.1\ kg\ air/min}$

(*b*) The heat transfer for this combustion process is determined from the energy balance $E_{in}-E_{out}=\Delta E_{system}$ applied on the combustion chamber with $W=0$. It reduces to

$$-Q_{\text{out}}=\sum N_P\left(\overline{h}_f^\circ+\overline{h}-\overline{h}^\circ\right)_P-\sum N_R\left(\overline{h}_f^\circ+\overline{h}-\overline{h}^\circ\right)_R$$

Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

Substance	$\overline{h}_f^\circ$ kJ/kmol	$\overline{h}_{285\text{ K}}$ kJ/kmol	$\overline{h}_{298\text{ K}}$ kJ/kmol	$\overline{h}_{1200\text{ K}}$ kJ/kmol
C_3H_8 (ℓ)	-118,910	---	---	---
O_2	0	8296.5	8682	38,447
N_2	0	8286.5	8669	36,777
H_2O (g)	-241,820	---	9904	44,380
CO_2	-393,520	---	9364	53,848

The $\overline{h}_f^\circ$ of liquid propane is obtained by adding $\overline{h}_{fg}$ of propane at 25°C to $\overline{h}_f^\circ$ of gas propane.

Substituting,

$$\begin{aligned}-Q_{\text{out}}&=(3)(-393{,}520+53{,}848-9364)+(4)(-241{,}820+44{,}380-9904)+(7.5)(0+38{,}447-8682)\\&\quad+(47)(0+36{,}777-8669)-(1)(-118{,}910+h_{298}-h_{298})-(12.5)(0+8296.5-8682)\\&\quad-(47)(0+8286.5-8669)\\&=-190{,}464\text{ kJ/kmol }C_3H_8\end{aligned}$$

or $\quad Q_{\text{out}}=190{,}464\text{ kJ/kmol }C_3H_8$

Then the rate of heat transfer for a mass flow rate of 1.2 kg/min for the propane becomes

$$\dot{Q}_{\text{out}}=\dot{N}Q_{\text{out}}=\left(\frac{\dot{m}}{N}\right)Q_{\text{out}}=\left(\frac{1.2\text{ kg/min}}{44\text{ kg/kmol}}\right)(190{,}464\text{ kJ/kmol})=\mathbf{5194\ kJ/min}$$

15.88

15-92 Ethylene gas is burned steadily with 20 percent excess air. The temperature of products, the entropy generation, and the exergy destruction (or irreversibility) are to be determined.

Assumptions **1** Combustion is complete. **2** Steady operating conditions exist. **3** Air and the combustion gases are ideal gases. **4** Changes in kinetic and potential energies are negligible.

Analysis (*a*) The fuel is burned completely with the excess air, and thus the products will contain only CO_2, H_2O, N_2, and some free O_2. Considering 1 kmol of C_2H_4, the combustion equation can be written as

$$C_2H_4(g)+1.2a_{th}(O_2+3.76N_2)\longrightarrow 2CO_2+2H_2O+0.2a_{th}O_2+(1.2)(3.76)a_{th}N_2$$

where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$1.2a_{th}=2+1+0.2a_{th} \quad\longrightarrow\quad a_{th}=3$$

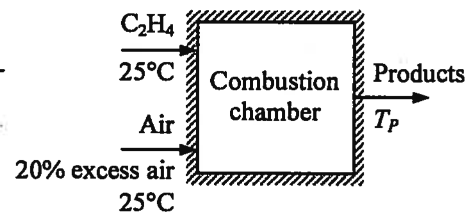
Thus, $$C_2H_4(g)+3.6(O_2+3.76N_2)\longrightarrow 2CO_2+2H_2O+0.6O_2+13.54N_2$$

Under steady-flow conditions, the exit temperature of the product gases can be determined from the steady-flow energy equation, which reduces to

$$\sum N_P\left(\bar{h}_f^\circ+\bar{h}-\bar{h}^\circ\right)_P=\sum N_R\bar{h}_{f,R}^\circ=\left(N\bar{h}_f^\circ\right)_{C_2H_4}$$

since all the reactants are at the standard reference state, and for O_2 and N_2. From the tables,

Substance	$\bar{h}_f^\circ$ kJ/kmol	$\bar{h}_{298\text{ K}}$ kJ/kmol
C_2H_4 (g)	52,280	---
O_2	0	8682
N_2	0	8669
H_2O (g)	-241,820	9904
CO_2	-393,520	9364



Substituting,

$$(2)(-393{,}520+\bar{h}_{CO_2}-9364)+(2)(-241{,}820+\bar{h}_{H_2O}-9904)$$
$$+(0.6)(0+\bar{h}_{O_2}-8682)+(13.54)(0+\bar{h}_{N_2}-8669)=(1)(52{,}280)$$

or, $$2\bar{h}_{CO_2}+2\bar{h}_{H_2O}+0.6\bar{h}_{O_2}+13.54\bar{h}_{N_2}=1{,}484{,}083\text{ kJ}$$

By trial and error,

$$T_P=\mathbf{2269.6\ K}$$

(*b*) The entropy generation during this adiabatic process is determined from

$$S_{gen}=S_P-S_R=\sum N_P\bar{s}_P-\sum N_R\bar{s}_R$$

The C_2H_4 is at 25°C and 1 atm, and thus its absolute entropy is 219.83 kJ/kmol·K (Table A-26). The entropy values listed in the ideal gas tables are for 1 atm pressure. Both the air and the product gases are at a total pressure of 1 atm, but the entropies are to be calculated at the partial pressure of the components which is equal to $P_i=y_i P_{total}$, where y_i is the mole fraction of component i. Also,

$$S_i = N_i \bar{s}_i (T, P_i) = N_i \left(\bar{s}_i^\circ (T, P_0) - R_u \ln(y_i P_m) \right)$$

The entropy calculations can be presented in tabular form as

	N_i	y_i	$\bar{s}_i^\circ(T,1\text{atm})$	$R_u \ln(y_i P_m)$	$N_i \bar{s}_i$
C_2H_4	1	1.00	219.83	---	219.83
O_2	3.6	0.21	205.14	-12.98	784.87
N_2	13.54	0.79	191.61	-1.96	2620.94
					S_R = 3625.64 kJ/K
CO_2	2	0.1103	316.881	-18.329	670.42
H_2O	2	0.1103	271.134	-18.329	578.93
O_2	0.6	0.0331	273.467	-28.336	181.08
N_2	13.54	0.7464	256.541	-2.432	3506.49
					S_P = 4936.92 kJ/K

Thus,

$$S_{gen} = S_P - S_R = 4936.92 - 3625.64 = \mathbf{1311.28\ kJ/kmol \cdot K}$$

and

(*c*) $X_{destroyed} = T_0 S_{gen} = (298\text{ K})(1311.28\text{ kJ/kmol}\cdot\text{K } C_2H_4) = \mathbf{390{,}760\ \ kJ}$ (per kmol C_2H_4)

15.89

~~15-93~~ Liquid octane is burned steadily with 50 percent excess air. The heat transfer rate from the combustion chamber, the entropy generation rate, and the reversible work and exergy destruction rate are to be determined.

Assumptions **1** Combustion is complete. **2** Steady operating conditions exist. **3** Air and the combustion gases are ideal gases. **4** Changes in kinetic and potential energies are negligible.

Analysis (*a*) The fuel is burned completely with the excess air, and thus the products will contain only CO_2, H_2O, N_2, and some free O_2. Considering 1 kmol C_8H_{18}, the combustion equation can be written as

$$C_8H_{18}(\ell)+1.5a_{th}(O_2+3.76N_2)\longrightarrow 8CO_2+9H_2O+0.5a_{th}O_2+(1.5)(3.76)a_{th}N_2$$

where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$1.5a_{th}=8+4.5+0.5a_{th} \longrightarrow a_{th}=12.5$$

Thus,

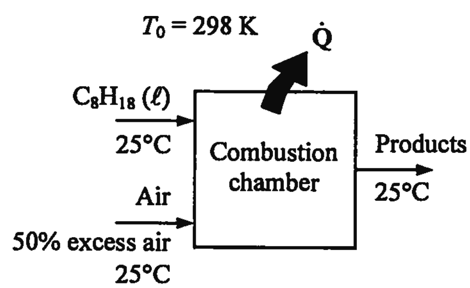
$$C_8H_{18}(\ell)+18.75(O_2+3.76N_2)\longrightarrow 8CO_2+9H_2O+6.25O_2+70.5N_2$$

Under steady-flow conditions the energy balance $E_{in}-E_{out}=\Delta E_{system}$ applied on the combustion chamber with $W = 0$ reduces to

$$-Q_{out}=\sum N_P\left(\bar{h}_f^\circ+\bar{h}-\bar{h}^\circ\right)_P-\sum N_R\left(\bar{h}_f^\circ+\bar{h}-\bar{h}^\circ\right)_R=\sum N_P\bar{h}_{f,P}^\circ-\sum N_R\bar{h}_{f,R}^\circ$$

since all of the reactants are at 25°C. Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

Substance	$\bar{h}_f^\circ$ kJ/kmol
C_8H_{18} (ℓ)	-249,950
O_2	0
N_2	0
H_2O (l)	-285,830
CO_2	-393,520



Substituting,

$$-Q_{out}=(8)(-393{,}520)+(9)(-285{,}830)+0+0-(1)(-249{,}950)-0-0=-5{,}470{,}680 \text{ kJ/kmol of } C_8H_{18}$$

or

$$Q_{out}=5{,}470{,}680 \text{ kJ/kmol of } C_8H_{18}$$

The C_8H_{18} is burned at a rate of 0.25 kg/min or

$$\dot{N}=\frac{\dot{m}}{M}=\frac{0.25\text{ kg/min}}{[(8)(12)+(18)(1)]\text{ kg/kmol}}=2.193\times10^{-3}\text{ kmol/min}$$

Thus,

$$\dot{Q}_{out}=\dot{N}Q_{out}=(2.193\times10^{-3}\text{ kmol/min})(5{,}470{,}680\text{ kJ/kmol})=\mathbf{11{,}997\text{ kJ/min}}$$

The heat transfer for this process is also equivalent to the enthalpy of combustion of liquid C_8H_{18}, which could easily be de determined from Table A-27 to be $\bar{h}_C$ = 5,470,740 kJ/kmol C_8H_{18}.

(*b*) The entropy generation during this process is determined from

$$S_{\text{gen}} = S_P - S_R + \frac{Q_{\text{out}}}{T_{\text{surr}}} \longrightarrow S_{\text{gen}} = \sum N_P \bar{s}_P - \sum N_R \bar{s}_R + \frac{Q_{\text{out}}}{T_{\text{surr}}}$$

The C_8H_{18} is at 25°C and 1 atm, and thus its absolute entropy is $\bar{s}_{C_8H_{18}}$ = 360.79 kJ/kmol.K (Table A-26). The entropy values listed in the ideal gas tables are for 1 atm pressure. Both the air and the product gases are at a total pressure of 1 atm, but the entropies are to be calculated at the partial pressure of the components which is equal to $P_i = y_i P_{\text{total}}$, where y_i is the mole fraction of component *i*. Also,

$$S_i = N_i \bar{s}_i(T, P_i) = N_i\left(\bar{s}_i^\circ(T, P_0) - R_u \ln(y_i P_m)\right)$$

The entropy calculations can be presented in tabular form as

	N_i	y_i	$\bar{s}_i^\circ(T,1\text{atm})$	$R_u \ln(y_i P_m)$	$N_i \bar{s}_i$
C_8H_{18}	1	1.00	360.79	---	360.79
O_2	18.75	0.21	205.14	-12.98	4089.75
N_2	70.50	0.79	191.61	-1.96	13646.69
				S_R =	18,097.23 kJ/K
CO_2	8	0.0944	213.80	-19.62	1867.3
H_2O (ℓ)	9	---	69.92	---	629.3
O_2	6.25	0.0737	205.04	-21.68	1417.6
N_2	70.50	0.8319	191.61	-1.53	13,616.3
				S_P =	17,531 kJ/K

Thus,

$$S_{\text{gen}} = S_P - S_R + \frac{Q_{\text{surr}}}{T_{\text{surr}}} = 17{,}531 - 18{,}097 + \frac{5{,}470{,}523 \text{ kJ}}{298 \text{ K}} = 17{,}798 \text{ kJ/kmol}\cdot\text{K}$$

and

$$\dot{S}_{\text{gen}} = \dot{N} S_{\text{gen}} = (2.193\times10^{-3} \text{ kmol/min})(17{,}798 \text{ kJ/kmol}\cdot\text{K}) = \mathbf{39.03 \text{ kJ/min}\cdot\text{K}}$$

(*c*) The exergy destruction rate associated with this process is determined from

$$\dot{X}_{\text{destroyed}} = T_0 \dot{S}_{\text{gen}} = (298 \text{ K})(39.03 \text{ kJ/min}\cdot\text{K}) = 11{,}632 \text{ kJ/min} = \mathbf{193.9 \text{ kW}}$$