Thermo 1 (MEP 261)

Thermodynamics An Engineering Approach

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Sheet 8:Chapter 9

9–2C How does the thermal efficiency of an ideal cycle, in general, compare to that of a Carnot cycle operating between the same temperature limits?

Solution It is less than the thermal efficiency of a Carnot cycle.

9–3C What does the area enclosed by the cycle represent on a *P*-*v* diagram? How about on a *T*-*s* diagram?

Solution It represents the net work on both diagrams.

9–4C What is the difference between air-standard assumptions and the cold-air-standard assumptions?

Solution The cold air standard assumptions involve the additional assumption that air can be treated as an ideal gas with constant specific heats at room temperature

9–5C How are the combustion and exhaust processes modeled under the air-standard assumptions?

Solution Under the air standard assumptions, the combustion process is modeled as a heat addition process, and the exhaust process as a heat rejection process.

9–6C What are the air-standard assumptions?

Solution The air standard assumptions are: (1) the working fluid is air which behaves as an ideal gas, (2) all the processes are internally reversible, (3) the combustion process is replaced by the heat addition process, and (4) the exhaust process is replaced by the heat rejection process which returns the working fluid to its original state.

9–7C What is the difference between the clearance volume and the displacement volume of reciprocating engines?

Solution The clearance volume is the minimum volume formed in the cylinder whereas the displacement volume is the volume displaced by the piston as the piston moves between the top dead center and the bottom dead center.

9–8C Define the compression ratio for reciprocating engines.

Solution It is the ratio of the maximum to minimum volumes in the cylinder.

9–9C How is the mean effective pressure for reciprocating engines defined?

Solution The MEP is the fictitious pressure which, if acted on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle.

9–12C What is the difference between spark-ignition and compression-ignition engines?

Solution The SI and CI engines differ from each other in the way combustion is initiated; by a spark in SI engines, and by compressing the air above the self-ignition temperature of the fuel in CI engines.

9–13C Define the following terms related to reciprocating engines: stroke, bore, top dead center, and clearance volume.

Solution Stroke is the distance between the TDC and the BDC, bore is the diameter of the cylinder, TDC is the position of the piston when it forms the smallest volume in the cylinder, and clearance volume is the minimum volume formed in the cylinder.

9–14 An air-standard cycle with variable specific heats is executed in a closed system and is composed of the following four processes:

1-2 Isentropic compression from 100 kPa and 27°C to 800 kPa

2-3 *v* = *constant* heat addition to 1800 K

3-4 Isentropic expansion to 100 kPa

4-1 *P* = *constant* heat rejection to initial state

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

(*b*) Calculate the net work output per unit mass.

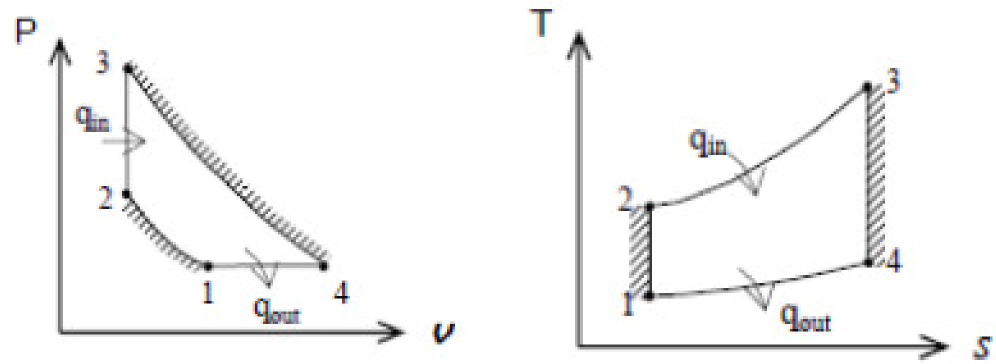
(*c*) Determine the thermal efficiency.

Solution The four processes of an air-standard cycle are described. The cycle is to be shown on *P*-*v* and *T*-*s* diagrams, and the net work output and the thermal efficiency are to be determined.

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

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

Analysis (*b*) The properties of air at various states are



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

$$P_{r_2} = \frac{P_2}{P_1} P_{r_1} = \frac{800 \text{ kPa}}{100 \text{ kPa}} (1.386) = 11.088 \longrightarrow \begin{array}{l} u_2 = 389.22 \text{ kJ/kg} \\ T_2 = 539.8 \text{ K} \end{array}$$

$$T_3 = 1800 \text{ K} \longrightarrow \begin{array}{l} u_3 = 1487.2 \text{ kJ/kg} \\ P_{r_3} = 1310 \end{array}$$

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow P_3 = \frac{T_3}{T_2} P_2 = \frac{1800 \text{ K}}{539.8 \text{ K}} (800 \text{ kPa}) = 2668 \text{ kPa}$$

$$P_{r_4} = \frac{P_4}{P_3} P_{r_3} = \frac{100 \text{ kPa}}{2668 \text{ kPa}} (1310) = 49.10 \longrightarrow h_4 = 828.1 \text{ kJ/kg}$$

From energy balances,

$$q_{\text{in}} = u_3 - u_2 = 1487.2 - 389.2 = 1098.0 \text{ kJ/kg}$$

$$q_{\text{out}} = h_4 - h_1 = 828.1 - 300.19 = 527.9 \text{ kJ/kg}$$

$$w_{\text{net,out}} = q_{\text{in}} - q_{\text{out}} = 1098.0 - 527.9 = \mathbf{570.1 \text{ kJ/kg}}$$

(*c*) Then the thermal efficiency becomes

$$\eta_{\text{th}} = \frac{w_{\text{net,out}}}{q_{\text{in}}} = \frac{570.1 \text{kJ/kg}}{1098.0 \text{kJ/kg}} = \mathbf{51.9\%}$$

9–16 An air-standard cycle is executed in a closed system and is composed of the following four processes:

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

2-3 *P* = *constant* heat addition in amount of 2800 kJ/kg

3-4 *v* = *constant* heat rejection to 100 kPa

4-1 *P* = *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.

Assume constant specific heats at room temperature.

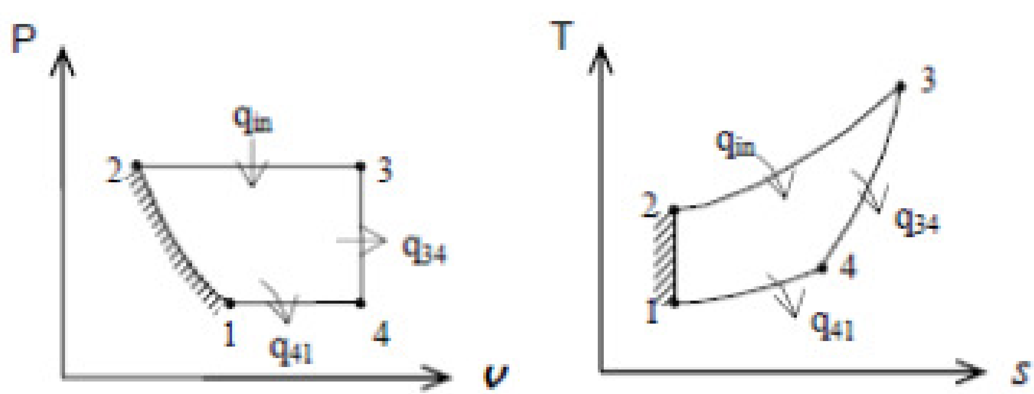
Answers: (*b*) 3360 K, (*c*) 21.0 percent

Solution The four processes of an air-standard cycle are described. The cycle is to be shown on *P*-*v* and *T*-*s* diagrams, and the maximum temperature in the cycle and the thermal efficiency are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** 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, c_v = 0.718 kJ/kg·K, and k = 1.4 (Table A-2).

Analysis (*b*) From the ideal gas isentropic relations and energy balance,



$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (300\text{ K})\left(\frac{1000\text{ kPa}}{100\text{ kPa}}\right)^{0.4/1.4} = 579.2\text{ K}$$

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2)$$

$$2800\text{ kJ/kg} = (1.005\text{ kJ/kg}\cdot\text{K})(T_3 - 579.2) \longrightarrow T_{max} = T_3 = \mathbf{3360\ \ K}$$

(c) $$\frac{P_3 v_3}{T_3} = \frac{P_4 v_4}{T_4} \longrightarrow T_4 = \frac{P_4}{P_3}T_3 = \frac{100\text{ kPa}}{1000\text{ kPa}}(3360\text{ K}) = 336\text{ K}$$

$$\begin{aligned} q_{out} &= q_{34,out} + q_{41,out} = (u_3 - u_4) + (h_4 - h_1) \\ &= c_v(T_3 - T_4) + c_p(T_4 - T_1) \\ &= (0.718\text{ kJ/kg}\cdot\text{K})(3360 - 336)\text{K} + (1.005\text{ kJ/kg}\cdot\text{K})(336 - 300)\text{K} \\ &= 2212\text{ kJ/kg} \end{aligned}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{2212\text{ kJ/kg}}{2800\text{ kJ/kg}} = \mathbf{21.0\%}$$

Discussion The assumption of constant specific heats at room temperature is not realistic in this case as the temperature changes involved are too large.

9–20 An air-standard cycle with variable specific heats is executed in a closed system with 0.003 kg of air and consists of the following three processes:

1-2 v = *constant* heat addition from 95 kPa and 17°C to 380 kPa

2-3 Isentropic expansion to 95 kPa

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

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

(*b*) Calculate the net work per cycle, in kJ.

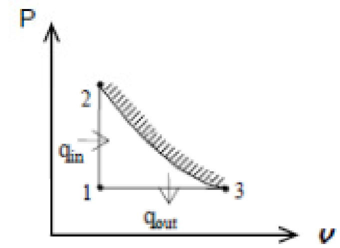
(*c*) Determine the thermal efficiency.

Solution The three processes of an air-standard cycle are described. The cycle is to be shown on *P-v* and *T-s* diagrams, and the net work per cycle and the thermal efficiency are to be determined.

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

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

Analysis (*b*) The properties of air at various states are

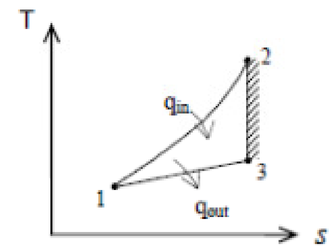


$$T_1 = 290 \text{ K} \longrightarrow \begin{array}{l} u_1 = 206.91 \text{ kJ/kg} \\ h_1 = 290.16 \text{ kJ/kg} \end{array}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow T_2 = \frac{P_2}{P_1} T_1 = \frac{380 \text{ kPa}}{95 \text{ kPa}} (290 \text{ K}) = 1160 \text{ K}$$

$$\longrightarrow u_2 = 897.91 \text{ kJ/kg}, \ P_{r_2} = 207.2$$

$$P_{r_3} = \frac{P_3}{P_2} P_{r_2} = \frac{95 \text{ kPa}}{380 \text{ kPa}} (207.2) = 51.8 \longrightarrow h_3 = 840.38 \text{ kJ/kg}$$



$$Q_{in} = m(u_2 - u_1) = (0.003 \text{ kg})(897.91 - 206.91)\text{kJ/kg} = 2.073 \text{ kJ}$$

$$Q_{out} = m(h_3 - h_1) = (0.003 \text{ kg})(840.38 - 290.16)\text{kJ/kg} = 1.651 \text{ kJ}$$

$$W_{net,out} = Q_{in} - Q_{out} = 2.073 - 1.651 = \mathbf{0.422 \text{ kJ}}$$

(c) $$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{0.422 \text{ kJ}}{2.073 \text{ kJ}} = \mathbf{20.4\%}$$

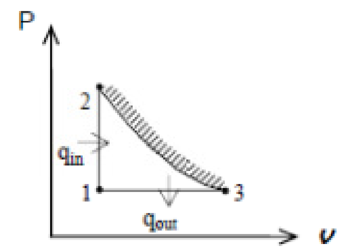
9–21 Repeat Problem 9–20 using constant specific heats at room temperature.

Solution The three processes of an air-standard cycle are described. The cycle is to be shown on *P-v* and *T-s* diagrams, and the net work per cycle and the thermal efficiency are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** 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, c_v = 0.718 kJ/kg·K, and k = 1.4 (Table A-2).

Analysis (*b*) From the isentropic relations and energy balance,

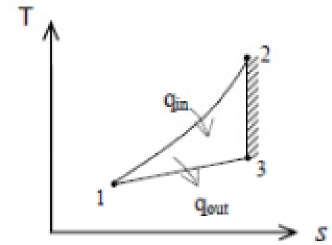


$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow T_2 = \frac{P_2}{P_1} T_1 = \frac{380\text{ kPa}}{95\text{ kPa}}(290\text{ K}) = 1160\text{ K}$$

$$T_3 = T_2\left(\frac{P_3}{P_2}\right)^{(k-1)/k} = (1160\text{ K})\left(\frac{95\text{ kPa}}{380\text{ kPa}}\right)^{0.4/1.4} = 780.6\text{ K}$$

$$Q_{in} = m(u_2 - u_1) = mc_v(T_2 - T_1)$$

$$= (0.003\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(1160 - 290)\text{K} = 1.87\text{ kJ}$$



$$Q_{out} = m(h_3 - h_1) = mc_p(T_3 - T_1)$$

$$= (0.003\text{ kg})(1.005\text{ kJ/kg}\cdot\text{K})(780.6 - 290)\text{K} = 1.48\text{ kJ}$$

$$W_{net,out} = Q_{in} - Q_{out} = 1.87 - 1.48 = \mathbf{0.39\text{ kJ}}$$

(*c*) $$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{0.39\text{kJ}}{1.87\text{kJ}} = \mathbf{20.9\%}$$

9–22 Consider a Carnot cycle executed in a closed system with 0.003 kg of air. The temperature limits of the cycle are 300 and 900 K, and the minimum and maximum pressures that occur during the cycle are 20 and 2000 kPa. Assuming constant specific heats, determine the net work output per cycle.

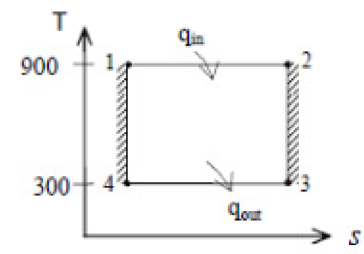
Solution A Carnot cycle with the specified temperature limits is considered. The net work output per cycle is to be determined.

Assumption 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, c_v = 0.718 kJ/kg·K, R = 0.287 kJ/kg.K, and k = 1.4 (Table A-2).

Analysis The minimum pressure in the cycle is P_3 and the maximum pressure is P_1. Then,

$$\frac{T_2}{T_3} = \left(\frac{P_2}{P_3}\right)^{(k-1)/k}$$



or,

$$P_2 = P_3\left(\frac{T_2}{T_3}\right)^{k/(k-1)} = (20\text{ kPa})\left(\frac{900\text{ K}}{300\text{ K}}\right)^{1.4/0.4} = 935.3\text{ kPa}$$

The heat input is determined from

$$s_2 - s_1 = c_p \ln\frac{T_2}{T_1}^{\nearrow 0} - R\ln\frac{P_2}{P_1} = -(0.287\text{ kJ/kg}\cdot\text{K})\ln\frac{935.3\text{ kPa}}{2000\text{ kPa}} = 0.2181\text{ kJ/kg}\cdot\text{K}$$

$$Q_{in} = mT_H(s_2 - s_1) = (0.003\text{ kg})(900\text{ K})(0.2181\text{ kJ/kg}\cdot\text{K}) = 0.5889\text{ kJ}$$

Then,

$$\eta_{th} = 1 - \frac{T_L}{T_H} = 1 - \frac{300\text{ K}}{900\text{ K}} = 66.7\%$$

$$W_{net,out} = \eta_{th}Q_{in} = (0.667)(0.5889\text{ kJ}) = \mathbf{0.393\ kJ}$$

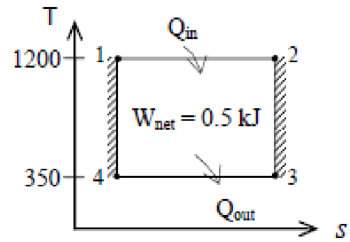
9–23 An air-standard Carnot cycle is executed in a closed system between the temperature limits of 350 and 1200 K. The pressures before and after the isothermal compression are 150 and 300 kPa, respectively. If the net work output per cycle is 0.5 kJ, determine (*a*) the maximum pressure in the cycle, (*b*) the heat transfer to air, and (*c*) the mass of air. Assume variable specific heats for air. *Answers:* (*a*) 30,013 kPa, (*b*) 0.706 kJ, (*c*) 0.00296 kg

Solution A Carnot cycle with specified temperature limits is considered. The maximum pressure in the cycle, the heat transfer to the working fluid, and the mass of the working fluid are to be determined.

Assumption Air is an ideal gas with variable specific heats.

Analysis (*a*) In a Carnot cycle, the maximum pressure occurs at the beginning of the expansion process, which is state 1.

$$T_1 = 1200\text{ K} \longrightarrow P_{r_1} = 238$$
$$T_4 = 350\text{ K} \longrightarrow P_{r_4} = 2.379 \qquad \text{(Table A-17)}$$



$$P_1 = \frac{P_{r_1}}{P_{r_4}} P_4 = \frac{238}{2.379}(300\text{ kPa}) = \mathbf{30{,}013\ kPa} = P_{\max}$$

(*b*) The heat input is determined from

$$\eta_{\text{th}} = 1 - \frac{T_L}{T_H} = 1 - \frac{350\text{ K}}{1200\text{ K}} = 70.83\%$$

$$Q_{\text{in}} = W_{\text{net,out}} / \eta_{\text{th}} = (0.5\text{ kJ})/(0.7083) = \mathbf{0.706\ kJ}$$

(*c*) The mass of air is

$$s_4 - s_3 = \left(s_4^\circ - s_3^\circ\right)^{\phi 0} - R\ln\frac{P_4}{P_3} = -(0.287\text{ kJ/kg}\cdot\text{K})\ln\frac{300\text{ kPa}}{150\text{ kPa}}$$
$$= -0.199\text{ kJ/kg}\cdot\text{K} = s_1 - s_2$$

$$w_{\text{net,out}} = (s_2 - s_1)(T_H - T_L) = (0.199\text{kJ/kg}\cdot\text{K})(1200 - 350)\text{K} = 169.15\text{kJ/kg}$$

$$m = \frac{W_{\text{net,out}}}{w_{\text{net,out}}} = \frac{0.5\text{ kJ}}{169.15\text{ kJ/kg}} = \mathbf{0.00296\ kg}$$

9–24 Repeat Problem 9–23 using helium as the working fluid.

Solution A Carnot cycle with specified temperature limits is considered. The maximum pressure in the cycle, the heat transfer to the working fluid, and the mass of the working fluid are to be determined.

Assumption Helium is an ideal gas with constant specific heats.

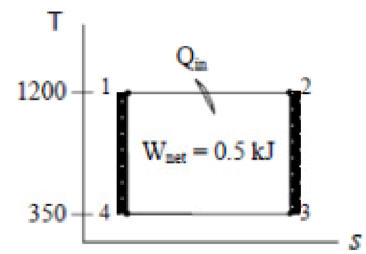
Properties The properties of helium at room temperature are $R = 2.0769$ kJ/kg.K and $k = 1.667$ (Table A-2).

Analysis (*a*) In a Carnot cycle, the maximum pressure occurs at the beginning of the expansion process, which is state 1.

$$\frac{T_1}{T_4} = \left(\frac{P_1}{P_4}\right)^{(k-1)/k}$$

or,

$$P_1 = P_4\left(\frac{T_1}{T_4}\right)^{k/(k-1)} = (300\text{ kPa})\left(\frac{1200\text{ K}}{350\text{ K}}\right)^{1.667/0.667} = \mathbf{6524\ kPa}$$



(*b*) The heat input is determined from

$$\eta_{th} = 1 - \frac{T_L}{T_H} = 1 - \frac{350\text{ K}}{1200\text{ K}} = 70.83\%$$

$$Q_{in} = W_{net,out} / \eta_{th} = (0.5\text{ kJ})/(0.7083) = \mathbf{0.706\ kJ}$$

(*c*) The mass of helium is determined from

$$s_4 - s_3 = c_p \ln\frac{T_4}{T_3}^{\nearrow 0} - R\ln\frac{P_4}{P_3} = -(2.0769\text{ kJ/kg}\cdot\text{K})\ln\frac{300\text{ kPa}}{150\text{ kPa}}$$

$$= -1.4396\text{ kJ/kg}\cdot\text{K} = s_1 - s_2$$

$$w_{net,out} = (s_2 - s_1)(T_H - T_L) = (1.4396\text{ kJ/kg}\cdot\text{K})(1200 - 350)\text{K} = 1223.7\text{ kJ/kg}$$

$$m = \frac{W_{net,out}}{w_{net,out}} = \frac{0.5\text{ kJ}}{1223.7\text{ kJ/kg}} = \mathbf{0.000409\ kg}$$

9–25 Consider a Carnot cycle executed in a closed system with air as the working fluid. The maximum pressure in the cycle is 800 kPa while the maximum temperature is 750 K. If the entropy increase during the isothermal heat rejection process is 0.25 kJ/kg · K and the net work output is 100 kJ/kg, determine (a) the minimum pressure in the cycle, (b) the heat rejection from the cycle, and (c) the thermal efficiency of the cycle. (d) If an actual heat engine cycle operates between the same temperature limits and produces 5200 kW of power for an air flow rate of 90 kg/s, determine the second law efficiency of this cycle.

Solution A Carnot cycle executed in a closed system with air as the working fluid is considered. The minimum pressure in the cycle, the heat rejection from the cycle, the thermal efficiency of the cycle, and the second-law efficiency of an actual cycle operating between the same temperature limits are to be determined.

Assumption Air is an ideal gas with constant specific heats.

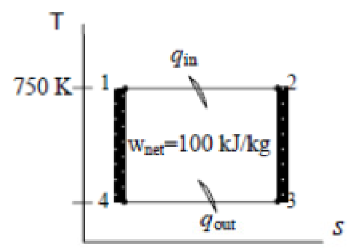
Properties The properties of air at room temperatures are $R = 0.287$ kJ/kg.K and $k = 1.4$ (Table A-2).

Analysis (*a*) The minimum temperature is determined from

$$w_{\text{net}} = (s_2 - s_1)(T_H - T_L) \longrightarrow 100 \text{ kJ/kg} = (0.25 \text{ kJ/kg}\cdot\text{K})(750 - T_L)\text{K} \longrightarrow T_L = 350 \text{ K}$$

The pressure at state 4 is determined from

$$\frac{T_1}{T_4} = \left(\frac{P_1}{P_4}\right)^{(k-1)/k}$$



or

$$P_1 = P_4\left(\frac{T_1}{T_4}\right)^{k/(k-1)}$$

$$800 \text{ kPa} = P_4\left(\frac{750 \text{ K}}{350 \text{ K}}\right)^{1.4/0.4} \longrightarrow P_4 = 110.1 \text{ kPa}$$

The minimum pressure in the cycle is determined from

$$\Delta s_{12} = -\Delta s_{34} = c_p \ln\frac{T_4}{T_3}^{\nearrow 0} - R\ln\frac{P_4}{P_3}$$

$$-0.25 \text{ kJ/kg}\cdot\text{K} = -(0.287 \text{ kJ/kg}\cdot\text{K})\ln\frac{110.1 \text{ kPa}}{P_3} \longrightarrow P_3 = \mathbf{46.1 \text{ kPa}}$$

(*b*) The heat rejection from the cycle is

$$q_{\text{out}} = T_L \Delta s_{12} = (350 \text{ K})(0.25 \text{ kJ/kg.K}) = \mathbf{87.5 \text{ kJ/kg}}$$

(*c*) The thermal efficiency is determined from

$$\eta_{\text{th}} = 1 - \frac{T_L}{T_H} = 1 - \frac{350 \text{ K}}{750 \text{ K}} = \mathbf{0.533}$$

(*d*) The power output for the Carnot cycle is

$$\dot{W}_{\text{Carnot}} = \dot{m}w_{\text{net}} = (90 \text{ kg/s})(100 \text{ kJ/kg}) = 9000 \text{ kW}$$

Then, the second-law efficiency of the actual cycle becomes

$$\eta_{\text{II}} = \frac{\dot{W}_{\text{actual}}}{\dot{W}_{\text{Carnot}}} = \frac{5200 \text{ kW}}{9000 \text{ kW}} = \mathbf{0.578}$$

9–26C What four processes make up the ideal Otto cycle?

Solution The four processes that make up the Otto cycle are (1) isentropic compression, (2) v = constant heat addition, (3) isentropic expansion, and (4) v = constant heat rejection.

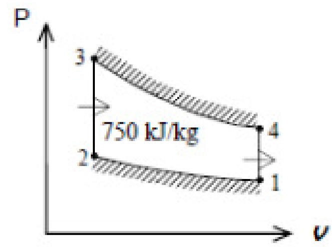
9–34 An ideal Otto cycle has a compression ratio of 8. At the beginning of the compression process, air is at 95 kPa and 27°C, and 750 kJ/kg of heat is transferred to air during the constant-volume heat-addition process. Taking into account the variation of specific heats with temperature, determine (*a*) the pressure and temperature at the end of the heat-addition process, (*b*) the net work output, (*c*) the thermal efficiency, and (*d*) the mean effective pressure for the cycle. *Answers:* (*a*) 3898 kPa, 1539 K, (*b*) 392.4 kJ/kg, (*c*) 52.3 percent, (*d*) 495 kPa

Solution An ideal Otto cycle with air as the working fluid has a compression ratio of 8. The pressure and temperature at the end of the heat addition process, the net work output, the thermal efficiency, and the mean effective pressure for the cycle are to be determined.

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

Properties The gas constant of air is $R = 0.287$ kJ/kg.K. The properties of air are given in Table A-17.

Analysis (*a*) Process 1–2: isentropic compression.



$$T_1 = 300\text{K} \longrightarrow \begin{array}{l} u_1 = 214.07\text{kJ/kg} \\ v_{r_1} = 621.2 \end{array}$$

$$v_{r_2} = \frac{v_2}{v_1} v_{r_1} = \frac{1}{r} v_{r_1} = \frac{1}{8}(621.2) = 77.65 \longrightarrow \begin{array}{l} T_2 = 673.1\text{K} \\ u_2 = 491.2 \text{ kJ/kg} \end{array}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow P_2 = \frac{v_1}{v_2}\frac{T_2}{T_1} P_1 = (8)\left(\frac{673.1 \text{ K}}{300 \text{ K}}\right)(95 \text{ kPa}) = 1705 \text{ kPa}$$

Process 2–3: v= constant heat addition.

$$q_{23,\text{in}} = u_3 - u_2 \longrightarrow u_3 = u_2 + q_{23,\text{in}} = 491.2 + 750 = 1241.2 \text{ kJ/kg} \longrightarrow \begin{array}{l} T_3 = \mathbf{1539 \text{ K}} \\ v_{r_3} = 6.588 \end{array}$$

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow P_3 = \frac{T_3}{T_2} P_2 = \left(\frac{1539 \text{ K}}{673.1 \text{ K}}\right)(1705 \text{ kPa}) = \mathbf{3898 \text{ kPa}}$$

(*b*) Process 3-4: isentropic expansion.

$$v_{r_4} = \frac{v_1}{v_2} v_{r_3} = r v_{r_3} = (8)(6.588) = 52.70 \longrightarrow \begin{array}{l} T_4 = 774.5 \text{ K} \\ u_4 = 571.69 \text{ kJ/kg} \end{array}$$

Process 4-1: v= constant heat rejection.

$$q_{\text{out}} = u_4 - u_1 = 571.69 - 214.07 = 357.62 \text{ kJ/kg}$$

$$w_{\text{net,out}} = q_{\text{in}} - q_{\text{out}} = 750 - 357.62 = \mathbf{392.4 \text{ kJ/kg}}$$

(*c*)

$$\eta_{\text{th}} = \frac{w_{\text{net,out}}}{q_{\text{in}}} = \frac{392.4 \text{ kJ/kg}}{750 \text{ kJ/kg}} = \mathbf{52.3\%}$$

(*d*)

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{K})}{95\text{kPa}} = 0.906\text{m}^3/\text{kg} = v_{\max}$$

$$v_{\min} = v_2 = \frac{v_{\max}}{r}$$

$$\text{MEP} = \frac{w_{\text{net,out}}}{v_1 - v_2} = \frac{w_{\text{net,out}}}{v_1(1-1/r)} = \frac{392.4 \text{ kJ/kg}}{(0.906 \text{ m}^3/\text{kg})(1-1/8)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{495.0 \text{ kPa}}$$

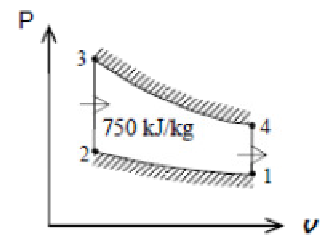
9–36 Repeat Problem 9–34 using constant specific heats at room temperature.

Solution An ideal Otto cycle with air as the working fluid has a compression ratio of 8. The pressure and temperature at the end of the heat addition process, the net work output, the thermal efficiency, and the mean effective pressure for the cycle are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** 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, c_v = 0.718 kJ/kg·K, R = 0.287 kJ/kg·K, and $k = 1.4$ (Table A-2).

Analysis (*a*) Process 1–2: isentropic compression.



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (300\text{K})(8)^{0.4} = 689\text{ K}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow P_2 = \frac{v_1}{v_2}\frac{T_2}{T_1}P_1 = (8)\left(\frac{689\text{ K}}{300\text{ K}}\right)(95\text{ kPa}) = 1745\text{ kPa}$$

Process 2–3: v = constant heat addition.

$$q_{23,\text{in}} = u_3 - u_2 = c_v(T_3 - T_2)$$

$$750\text{ kJ/kg} = (0.718\text{ kJ/kg}\cdot\text{K})(T_3 - 689)\text{K}$$

$$T_3 = \mathbf{1734\ K}$$

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow P_3 = \frac{T_3}{T_2}P_2 = \left(\frac{1734\text{ K}}{689\text{ K}}\right)(1745\text{ kPa}) = \mathbf{4392\ kPa}$$

(*b*) Process 3–4: isentropic expansion.

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{k-1} = (1734\text{ K})\left(\frac{1}{8}\right)^{0.4} = 755\text{ K}$$

Process 4-1: v = constant heat rejection.

$$q_{\text{out}} = u_4 - u_1 = c_v(T_4 - T_1) = (0.718\text{ kJ/kg}\cdot\text{K})(755 - 300)\text{K} = 327\text{ kJ/kg}$$

$$w_{\text{net,out}} = q_{\text{in}} - q_{\text{out}} = 750 - 327 = \mathbf{423\ kJ/kg}$$

(*c*) $$\eta_{\text{th}} = \frac{w_{\text{net,out}}}{q_{\text{in}}} = \frac{423\text{kJ/kg}}{750\text{kJ/kg}} = \mathbf{56.4\%}$$

(*d*) $$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{ K})}{95\text{ kPa}} = 0.906\text{ m}^3/\text{kg} = v_{\text{max}}$$

$$v_{\text{min}} = v_2 = \frac{v_{\text{max}}}{r}$$

$$\text{MEP} = \frac{w_{\text{net,out}}}{v_1 - v_2} = \frac{w_{\text{net,out}}}{v_1(1-1/r)} = \frac{423\text{ kJ/kg}}{(0.906\text{ m}^3/\text{kg})(1-1/8)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{534\ kPa}$$

9–37 The compression ratio of an air-standard Otto cycle is 9.5. Prior to the isentropic compression process, the air is at 100 kPa, 35°C, and 600 cm^3. The temperature at the end of the isentropic expansion process is 800 K. Using specific heat values at room temperature, determine (*a*) the highest temperature and pressure in the cycle; (*b*) the amount of heat transferred in, in kJ; (*c*) the thermal efficiency; and (*d*) the mean effective pressure. *Answers:* (*a*) 1969 K, 6072 kPa, (*b*) 0.59 kJ, (c) 59.4 percent, (*d*) 652 kPa

Solution An ideal Otto cycle with air as the working fluid has a compression ratio of 9.5. The highest pressure and temperature in the cycle, the amount of heat transferred, the thermal efficiency, and the mean effective pressure are to be determined.

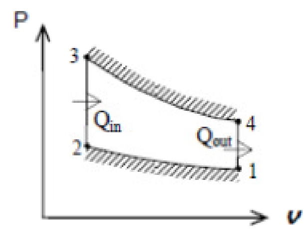
Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg·K, c_v = 0.718 kJ/kg·K, R = 0.287 kJ/kg·K, and $k = 1.4$ (Table A-2).

Analysis (*a*) Process 1–2: isentropic compression.

$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (308\text{ K})(9.5)^{0.4} = 757.9\text{ K}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow P_2 = \frac{v_1}{v_2}\frac{T_2}{T_1}P_1 = (9.5)\left(\frac{757.9\text{ K}}{308\text{ K}}\right)(100\text{ kPa}) = 2338\text{ kPa}$$



Process 3–4: isentropic expansion.

$$T_3 = T_4\left(\frac{v_4}{v_3}\right)^{k-1} = (800\text{ K})(9.5)^{0.4} = \mathbf{1969\ K}$$

Process 2-3: v = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow P_3 = \frac{T_3}{T_2}P_2 = \left(\frac{1969\text{ K}}{757.9\text{ K}}\right)(2338\text{ kPa}) = \mathbf{6072\ kPa}$$

(*b*)
$$m = \frac{P_1 V_1}{RT_1} = \frac{(100\text{ kPa})(0.0006\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(308\text{ K})} = 6.788\times10^{-4}\text{ kg}$$

$$Q_{in} = m(u_3 - u_2) = mc_v(T_3 - T_2) = (6.788\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(1969 - 757.9)\text{K} = \mathbf{0.590\ kJ}$$

(c) Process 4–1: v = constant heat rejection.

$$Q_{out} = m(u_4 - u_1) = mc_v(T_4 - T_1) = -(6.788\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(800 - 308)\text{K} = \mathbf{0.240\ kJ}$$

$$W_{net} = Q_{in} - Q_{out} = 0.590 - 0.240 = 0.350\text{ kJ}$$

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{0.350\text{ kJ}}{0.590\text{ kJ}} = \mathbf{59.4\%}$$

(*d*)
$$V_{min} = V_2 = \frac{V_{max}}{r}$$

$$\text{MEP} = \frac{W_{net,out}}{V_1 - V_2} = \frac{W_{net,out}}{V_1(1 - 1/r)} = \frac{0.350\text{ kJ}}{(0.0006\text{ m}^3)(1 - 1/9.5)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{652\ kPa}$$

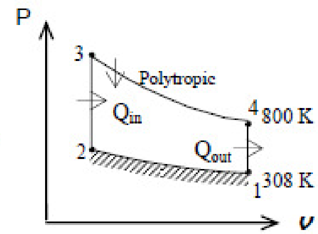
9–38 Repeat Problem 9–37, but replace the isentropic expansion process by a polytropic expansion process with the polytropic exponent $n = 1.35$.

Solution An Otto cycle with air as the working fluid has a compression ratio of 9.5. The highest pressure and temperature in the cycle, the amount of heat transferred, the thermal efficiency, and the mean effective pressure are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** 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, c_v = 0.718 kJ/kg·K, R = 0.287 kJ/kg·K, and $k = 1.4$ (Table A-2).

Analysis (*a*) Process 1–2: isentropic compression.



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (308\text{ K})(9.5)^{0.4} = 757.9\text{ K}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow P_2 = \frac{v_1}{v_2}\frac{T_2}{T_1}P_1 = (9.5)\left(\frac{757.9\text{ K}}{308\text{ K}}\right)(100\text{ kPa}) = 2338\text{ kPa}$$

Process 3–4: polytropic expansion.

$$m = \frac{P_1 V_1}{RT_1} = \frac{(100\text{ kPa})(0.0006\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(308\text{ K})} = 6.788\times10^{-4}\text{ kg}$$

$$T_3 = T_4\left(\frac{v_4}{v_3}\right)^{n-1} = (800\text{ K})(9.5)^{0.35} = \mathbf{1759\text{ K}}$$

$$W_{34} = \frac{mR(T_4 - T_3)}{1-n} = \frac{(6.788\times10^{-4})(0.287\text{ kJ/kg}\cdot\text{K})(800-1759)\text{K}}{1-1.35} = 0.5338\text{ kJ}$$

Then energy balance for process 3–4 gives

$$E_{in} - E_{out} = \Delta E_{system}$$

$$Q_{34,in} - W_{34,out} = m(u_4 - u_3)$$

$$Q_{34,in} = m(u_4 - u_3) + W_{34,out} = mc_v(T_4 - T_3) + W_{34,out}$$

$$Q_{34,in} = (6.788\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(800-1759)\text{K} + 0.5338\text{ kJ} = 0.0664\text{ kJ}$$

That is, 0.066 kJ of heat is added to the air during the expansion process (This is not realistic, and probably is due to assuming constant specific heats at room temperature).

(*b*) Process 2–3: v = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow P_3 = \frac{T_3}{T_2}P_2 = \left(\frac{1759\text{ K}}{757.9\text{ K}}\right)(2338\text{ kPa}) = \mathbf{5426\text{ kPa}}$$

$$Q_{23,in} = m(u_3 - u_2) = mc_v(T_3 - T_2)$$

$$Q_{23,in} = (6.788\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(1759-757.9)\text{K} = 0.4879\text{ kJ}$$

Therefore,

$$Q_{in} = Q_{23,in} + Q_{34,in} = 0.4879 + 0.0664 = \mathbf{0.5543\text{ kJ}}$$

(*c*) Process 4-1: v = constant heat rejection.

$$Q_{out} = m(u_4 - u_1) = mc_v(T_4 - T_1) = (6.788\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(800-308)\text{K} = 0.2398\text{ kJ}$$

$$W_{net,out} = Q_{in} - Q_{out} = 0.5543 - 0.2398 = 0.3145\text{ kJ}$$

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{0.3145\text{ kJ}}{0.5543\text{ kJ}} = \mathbf{56.7\%}$$

(*d*) $$V_{min} = V_2 = \frac{V_{max}}{r}$$

$$\text{MEP} = \frac{W_{net,out}}{V_1 - V_2} = \frac{W_{net,out}}{V_1(1-1/r)} = \frac{0.3145\text{ kJ}}{(0.0006\text{ m}^3)(1-1/9.5)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{586\text{ kPa}}$$

9–42C How does a diesel engine differ from a gasoline engine?

Solution A diesel engine differs from the gasoline engine in the way combustion is initiated. In diesel engines combustion is initiated by compressing the air above the self-ignition temperature of the fuel whereas it is initiated by a spark plug in a gasoline engine.

9–43C How does the ideal Diesel cycle differ from the ideal Otto cycle?

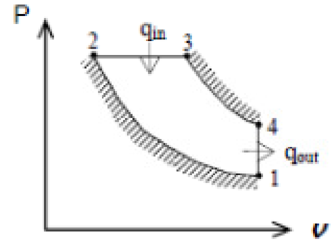
Solution The Diesel cycle differs from the Otto cycle in the heat addition process only; it takes place at constant volume in the Otto cycle, but at constant pressure in the Diesel cycle.

9–47 An air-standard Diesel cycle has a compression ratio of 16 and a cutoff ratio of 2. At the beginning of the compression process, air is at 95 kPa and 27°C. Accounting for the variation of specific heats with temperature, determine
(*a*) the temperature after the heat-addition process, (*b*) the thermal efficiency, and (*c*) the mean effective pressure.
Answers: (*a*) 1724.8 K, (*b*) 56.3 percent, (*c*) 675.9 kPa

Solution An air-standard Diesel cycle with a compression ratio of 16 and a cutoff ratio of 2 is considered. The temperature after the heat addition process, the thermal efficiency, and the mean effective pressure are to be determined.

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

Properties The gas constant of air is R = 0.287 kJ/kg.K. The properties of air are given in Table A-17.



Analysis (*a*) Process 1–2: isentropic compression.

$$T_1 = 300\text{K} \longrightarrow \begin{array}{l} u_1 = 214.07\text{kJ/kg} \\ v_{r_1} = 621.2 \end{array}$$

$$v_{r_2} = \frac{v_2}{v_1} v_{r_1} = \frac{1}{r} v_{r_1} = \frac{1}{16}(621.2) = 38.825 \longrightarrow \begin{array}{l} T_2 = 862.4\text{ K} \\ h_2 = 890.9\text{ kJ/kg} \end{array}$$

Process 2–3: P = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow T_3 = \frac{v_3}{v_2} T_2 = 2T_2 = (2)(862.4\text{ K}) = \mathbf{1724.8\text{ K}} \longrightarrow \begin{array}{l} h_3 = 1910.6\text{ kJ/kg} \\ v_{r_3} = 4.546 \end{array}$$

(*b*) $$q_{in} = h_3 - h_2 = 1910.6 - 890.9 = 1019.7\text{kJ/kg}$$

Process 3–4: isentropic expansion.

$$v_{r_4} = \frac{v_4}{v_3} v_{r_3} = \frac{v_4}{2v_2} v_{r_3} = \frac{r}{2} v_{r_3} = \frac{16}{2}(4.546) = 36.37 \longrightarrow u_4 = 659.7\text{kJ/kg}$$

Process 4–1: v = constant heat rejection.

$$q_{out} = u_4 - u_1 = 659.7 - 214.07 = 445.63\text{ kJ/kg}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{445.63\text{ kJ/kg}}{1019.7\text{ kJ/kg}} = \mathbf{56.3\%}$$

(*c*) $$w_{net,out} = q_{in} - q_{out} = 1019.7 - 445.63 = 574.07\text{ kJ/kg}$$

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{ K})}{95\text{ kPa}} = 0.906\text{ m}^3/\text{kg} = v_{max}$$

$$v_{min} = v_2 = \frac{v_{max}}{r}$$

$$\text{MEP} = \frac{w_{net,out}}{v_1 - v_2} = \frac{w_{net,out}}{v_1(1 - 1/r)} = \frac{574.07\text{ kJ/kg}}{(0.906\text{ m}^3/\text{kg})(1 - 1/16)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{675.9\text{ kPa}}$$

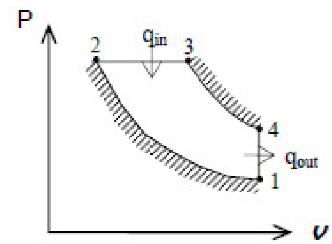
9–48 Repeat Problem 9–47 using constant specific heats at room temperature.

Solution An air-standard Diesel cycle with a compression ratio of 16 and a cutoff ratio of 2 is considered. The temperature after the heat addition process, the thermal efficiency, and the mean effective pressure are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** 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, c_v = 0.718 kJ/kg·K, R = 0.287 kJ/kg·K, and k = 1.4 (Table A-2).

Analysis (*a*) Process 1–2: isentropic compression.



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (300\text{K})(16)^{0.4} = 909.4\text{K}$$

Process 2–3: P = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow T_3 = \frac{v_3}{v_2}T_2 = 2T_2 = (2)(909.4\text{K}) = \mathbf{1818.8K}$$

(*b*)
$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2) = (1.005\text{ kJ/kg}\cdot\text{K})(1818.8 - 909.4)\text{K} = 913.9\text{ kJ/kg}$$

Process 3–4: isentropic expansion.

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{k-1} = T_3\left(\frac{2v_2}{v_4}\right)^{k-1} = (1818.8\text{K})\left(\frac{2}{16}\right)^{0.4} = 791.7\text{K}$$

Process 4–1: v = constant heat rejection.

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1) = (0.718\text{kJ/kg}\cdot\text{K})(791.7 - 300)\text{K} = 353\text{kJ/kg}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{353\text{ kJ/kg}}{913.9\text{ kJ/kg}} = \mathbf{61.4\%}$$

(*c*)
$$w_{net.out} = q_{in} - q_{out} = 913.9 - 353 = 560.9\text{kJ/kg}$$

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{ kPa}\cdot\text{m}^3\text{/kg}\cdot\text{K})(300\text{ K})}{95\text{ kPa}} = 0.906\text{ m}^3\text{/kg} = v_{max}$$

$$v_{min} = v_2 = \frac{v_{max}}{r}$$

$$\text{MEP} = \frac{w_{net,out}}{v_1 - v_2} = \frac{w_{net,out}}{v_1(1-1/r)} = \frac{560.9\text{ kJ/kg}}{(0.906\text{ m}^3\text{/kg})(1-1/16)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{660.4\ kPa}$$

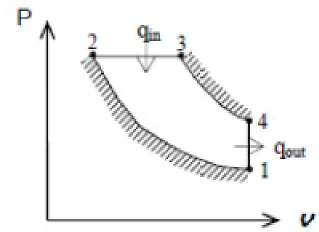
9–51 An ideal diesel engine has a compression ratio of 20 and uses air as the working fluid. The state of air at the beginning of the compression process is 95 kPa and 20°C. If the maximum temperature in the cycle is not to exceed 2200 K, determine (*a*) the thermal efficiency and (*b*) the mean effective pressure. Assume constant specific heats for air at room temperature. *Answers:* (*a*) 63.5 percent, (*b*) 933 kPa

Solution An ideal diesel engine with air as the working fluid has a compression ratio of 20. The thermal efficiency and the mean effective pressure are to be determined.

Assumptions 1 The air-standard assumptions are applicable. 2 Kinetic and potential energy changes are negligible. 3 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, c_v = 0.718 kJ/kg·K, R = 0.287 kJ/kg·K, and k = 1.4 (Table A-2).

Analysis (*a*) Process 1–2: isentropic compression.



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (293\text{ K})(20)^{0.4} = 971.1\text{ K}$$

Process 2–3: P = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow \frac{v_3}{v_2} = \frac{T_3}{T_2} = \frac{2200\text{K}}{971.1\text{K}} = 2.265$$

Process 3–4: isentropic expansion.

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{k-1} = T_3\left(\frac{2.265 v_2}{v_4}\right)^{k-1} = T_3\left(\frac{2.265}{r}\right)^{k-1} = (2200\text{ K})\left(\frac{2.265}{20}\right)^{0.4} = 920.6\text{ K}$$

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2) = (1.005\text{ kJ/kg}\cdot\text{K})(2200 - 971.1)\text{K} = 1235\text{ kJ/kg}$$

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1) = (0.718\text{ kJ/kg}\cdot\text{K})(920.6 - 293)\text{K} = 450.6\text{ kJ/kg}$$

$$w_{net,out} = q_{in} - q_{out} = 1235 - 450.6 = 784.4\text{ kJ/kg}$$

$$\eta_{th} = \frac{w_{net,out}}{q_{in}} = \frac{784.4\text{ kJ/kg}}{1235\text{ kJ/kg}} = \mathbf{63.5\%}$$

(*b*)
$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293\text{ K})}{95\text{ kPa}} = 0.885\text{ m}^3/\text{kg} = v_{max}$$

$$v_{min} = v_2 = \frac{v_{max}}{r}$$

$$\text{MEP} = \frac{w_{net,out}}{v_1 - v_2} = \frac{w_{net,out}}{v_1(1 - 1/r)} = \frac{784.4\text{ kJ/kg}}{(0.885\text{ m}^3/\text{kg})(1 - 1/20)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{933\text{ kPa}}$$

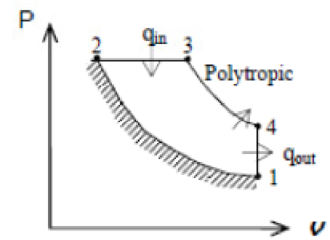
9–52 Repeat Problem 9–51, but replace the isentropic expansion process by polytropic expansion process with the polytropic exponent $n = 1.35$.

Solution A diesel engine with air as the working fluid has a compression ratio of 20. The thermal efficiency and the mean effective pressure are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** 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, c_v = 0.718 kJ/kg·K, and k = 1.4 (Table A-2).

Analysis (a) Process 1−2: isentropic compression.



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (293\text{ K})(20)^{0.4} = 971.1\text{ K}$$

Process 2−3: P = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow \frac{v_3}{v_2} = \frac{T_3}{T_2} = \frac{2200\text{ K}}{971.1\text{ K}} = 2.265$$

Process 3−4: polytropic expansion.

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{n-1} = T_3\left(\frac{2.265 v_2}{v_4}\right)^{n-1} = T_3\left(\frac{2.265}{r}\right)^{n-1} = (2200\text{ K})\left(\frac{2.265}{20}\right)^{0.35} = 1026\text{ K}$$

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2) = (1.005\text{ kJ/kg}\cdot\text{K})(2200 - 971.1)\text{ K} = 1235\text{ kJ/kg}$$

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1) = (0.718\text{ kJ/kg}\cdot\text{K})(1026 - 293)\text{ K} = 526.3\text{ kJ/kg}$$

Note that q_{out} in this case does not represent the entire heat rejected since some heat is also rejected during the polytropic process, which is determined from an energy balance in process 3−4:

$$w_{34,out} = \frac{R(T_4 - T_3)}{1-n} = \frac{(0.287\text{ kJ/kg}\cdot\text{K})(1026 - 2200)\text{ K}}{1 - 1.35} = 963\text{ kJ/kg}$$

$$E_{in} - E_{out} = \Delta E_{system}$$

$$q_{34,in} - w_{34,out} = u_4 - u_3 \longrightarrow q_{34,in} = w_{34,out} + c_v(T_4 - T_3)$$
$$= 963\text{ kJ/kg} + (0.718\text{ kJ/kg}\cdot\text{K})(1026 - 2200)\text{ K}$$
$$= 120.1\text{ kJ/kg}$$

which means that 120.1 kJ/kg of heat is transferred to the combustion gases during the expansion process. This is unrealistic since the gas is at a much higher temperature than the surroundings, and a hot gas loses heat during polytropic expansion. The cause of this unrealistic result is the constant specific heat assumption. If we were to use u data from the air table, we would obtain

$$q_{34,in} = w_{34,out} + (u_4 - u_3) = 963 + (781.3 - 1872.4) = -128.1\text{ kJ/kg}$$

which is a heat loss as expected. Then q_{out} becomes

$$q_{out} = q_{34,out} + q_{41,out} = 128.1 + 526.3 = 654.4\text{ kJ/kg}$$

and

$$w_{net,out} = q_{in} - q_{out} = 1235 - 654.4 = 580.6\text{ kJ/kg}$$

$$\eta_{th} = \frac{w_{net,out}}{q_{in}} = \frac{580.6\text{ kJ/kg}}{1235\text{ kJ/kg}} = \mathbf{47.0\%}$$

(b)

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{ kPa}\cdot\text{m}^3\text{/kg}\cdot\text{K})(293\text{ K})}{95\text{ kPa}} = 0.885\text{ m}^3\text{/kg} = v_{max}$$

$$v_{min} = v_2 = \frac{v_{max}}{r}$$

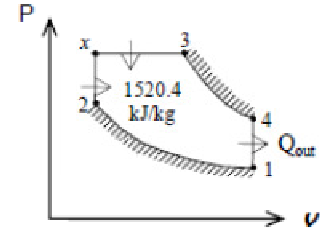
$$\text{MEP} = \frac{w_{net,out}}{v_1 - v_2} = \frac{w_{net,out}}{v_1(1 - 1/r)} = \frac{580.6\text{ kJ/kg}}{(0.885\text{ m}^3\text{/kg})(1 - 1/20)}\left(\frac{1\text{ kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{691\text{ kPa}}$$

9–56 The compression ratio of an ideal dual cycle is 14. Air is at 100 kPa and 300 K at the beginning of the compression process and at 2200 K at the end of the heat-addition process. Heat transfer to air takes place partly at constant volume and partly at constant pressure, and it amounts to 1520.4 kJ/kg. Assuming variable specific heats for air, determine (*a*) the fraction of heat transferred at constant volume and (*b*) the thermal efficiency of the cycle.

Solution An ideal dual cycle with air as the working fluid has a compression ratio of 14. The fraction of heat transferred at constant volume and the thermal efficiency of the cycle are to be determined.

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

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



Analysis (a) Process 1–2: isentropic compression.

$$T_1 = 300\text{ K} \longrightarrow \begin{array}{l} u_1 = 214.07\text{ kJ/kg} \\ v_{r_1} = 621.2 \end{array}$$

$$v_{r_2} = \frac{v_2}{v_1} v_{r_1} = \frac{1}{r} v_{r_1} = \frac{1}{14}(621.2) = 44.37 \longrightarrow \begin{array}{l} T_2 = 823.1\text{ K} \\ u_2 = 611.2\text{ kJ/kg} \end{array}$$

Process 2–x, x–3: heat addition,

$$T_3 = 2200\text{ K} \longrightarrow \begin{array}{l} h_3 = 2503.2\text{ kJ/kg} \\ v_{r_3} = 2.012 \end{array}$$

$$q_{in} = q_{x-2,in} + q_{3-x,in} = (u_x - u_2) + (h_3 - h_x)$$
$$1520.4 = (u_x - 611.2) + (2503.2 - h_x)$$

By trial and error, we get T_x = 1300 K and h_x = 1395.97, u_x = 1022.82 kJ /kg.

Thus,

$$q_{2-x,in} = u_x - u_2 = 1022.82 - 611.2 = 411.62\text{ kJ/kg}$$

and

$$\text{ratio} = \frac{q_{2-x,in}}{q_{in}} = \frac{411.62\text{ kJ/kg}}{1520.4\text{ kJ/kg}} = \mathbf{27.1\%}$$

(b)
$$\frac{P_3 v_3}{T_3} = \frac{P_x v_x}{T_x} \longrightarrow \frac{v_3}{v_x} = \frac{T_3}{T_x} = \frac{2200\text{ K}}{1300\text{ K}} = 1.692 = r_c$$

$$v_{r_4} = \frac{v_4}{v_3} v_{r_3} = \frac{v_4}{1.692 v_2} v_{r_3} = \frac{r}{1.692} v_{r_3} = \frac{14}{1.692}(2.012) = 16.648 \longrightarrow u_4 = 886.3\text{ kJ/kg}$$

Process 4-1: v = constant heat rejection.

$$q_{out} = u_4 - u_1 = 886.3 - 214.07 = 672.23\text{ kJ/kg}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{672.23\text{ kJ/kg}}{1520.4\text{ kJ/kg}} = 55.8\%$$

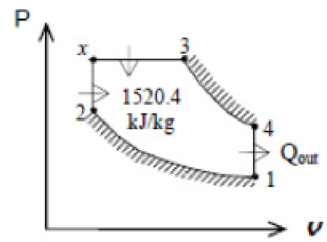
9–58 Repeat Problem 9–56 using constant specific heats at room temperature. Is the constant specific heat assumption reasonable in this case?

Solution An ideal dual cycle with air as the working fluid has a compression ratio of 14. The fraction of heat transferred at constant volume and the thermal efficiency of the cycle are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** 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, c_v = 0.718 kJ/kg·K, and k = 1.4 (Table A-2).

Analysis (a) Process 1–2: isentropic compression.



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (300\text{ K})(14)^{0.4} = 862\text{ K}$$

Process 2–x, x–3: heat addition,

$$q_{in} = q_{2-x,in} + q_{3-x,in} = (u_x - u_2) + (h_3 - h_x)$$
$$= c_v(T_x - T_2) + c_p(T_3 - T_x)$$
$$1520.4\text{ kJ/kg} = (0.718\text{ kJ/kg}\cdot\text{K})(T_x - 862) + (1.005\text{ kJ/kg}\cdot\text{K})(2200 - T_x)$$

Solving for T_x we get T_x = 250 K which is impossible. Therefore, constant specific heats at room temperature turned out to be an unreasonable assumption in this case because of the very high temperatures changes involved.

9–60C 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?

Solution The efficiencies of the Carnot and the Stirling cycles would be the same, the efficiency of the Otto cycle would be less.

9–61C 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?

Solution The efficiencies of the Carnot and the Ericsson cycles would be the same, the efficiency of the Diesel cycle would be less.

9–65 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

Solution An ideal steady-flow Ericsson engine with air as the working fluid is considered. The maximum pressure in the cycle, the net work output, and the thermal efficiency of the cycle are to be determined.

Assumption Air is an ideal gas.

Properties The gas constant of air is $R = 0.287$ kJ/kg.K (Table A-1).

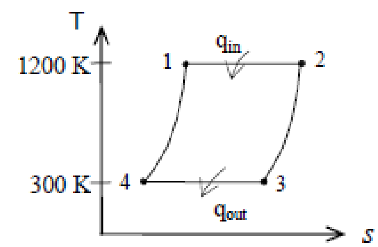
Analysis (*a*) The entropy change during process 3-4 is

$$s_4 - s_3 = -\frac{q_{34,\text{out}}}{T_0} = -\frac{150\text{ kJ/kg}}{300\text{ K}} = -0.5\text{ kJ/kg}\cdot\text{K}$$

and

$$s_4 - s_3 = c_p \ln\frac{T_4}{T_3}^{\nearrow 0} - R\ln\frac{P_4}{P_3}$$

$$= -(0.287\text{ kJ/kg}\cdot\text{K})\ln\frac{P_4}{120\text{ kPa}} = -0.5\text{ kJ/kg}\cdot\text{K}$$



It yields $\quad P_4 = \mathbf{685.2\text{ kPa}}$

(*b*) For reversible cycles, $\frac{q_{\text{out}}}{q_{\text{in}}} = \frac{T_L}{T_H} \longrightarrow q_{\text{in}} = \frac{T_H}{T_L} q_{\text{out}} = \frac{1200\text{ K}}{300\text{ K}}(150\text{ kJ/kg}) = 600\text{ kJ/kg}$

Thus, $\quad w_{\text{net,out}} = q_{\text{in}} - q_{\text{out}} = 600 - 150 = \mathbf{450\text{ kJ/kg}}$

(*c*) The thermal efficiency of this totally reversible cycle is determined from

$$\eta_{\text{th}} = 1 - \frac{T_L}{T_H} = 1 - \frac{300\text{K}}{1200\text{K}} = \mathbf{75.0\%}$$

9–66 An ideal Stirling engine using helium as the working fluid operates between temperature limits of 300 and 2000 K and pressure limits of 150 kPa and 3 MPa. Assuming the mass of the helium used in the cycle is 0.12 kg, determine (*a*) the thermal efficiency of the cycle, (*b*) the amount of heat transfer in the regenerator, and (*c*) the work output per cycle.

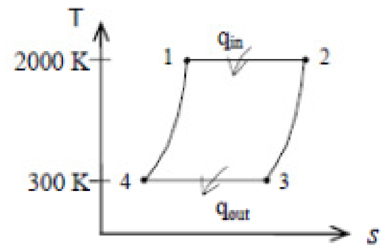
Solution An ideal Stirling engine with helium as the working fluid operates between the specified temperature and pressure limits. The thermal efficiency of the cycle, the amount of heat transfer in the regenerator, and the work output per cycle are to be determined.

Assumption Helium is an ideal gas with constant specific heats.

Properties The gas constant and the specific heat of helium at room temperature are $R = 2.0769$ kJ/kg.K, $c_v = 3.1156$ kJ/kg.K and $c_p = 5.1926$ kJ/kg.K (Table A-2).

Analysis (*a*) The thermal efficiency of this totally reversible cycle is determined from

$$\eta_{th} = 1 - \frac{T_L}{T_H} = 1 - \frac{300\text{ K}}{2000\text{ K}} = \mathbf{85.0\%}$$



(*b*) The amount of heat transferred in the regenerator is

$$Q_{regen} = Q_{41,in} = m(u_1 - u_4) = mc_v(T_1 - T_4)$$
$$= (0.12\text{ kg})(3.1156\text{ kJ/kg}\cdot\text{K})(2000 - 300)\text{K}$$
$$= \mathbf{635.6\ kJ}$$

(*c*) The net work output is determined from

$$\frac{P_3 \upsilon_3}{T_3} = \frac{P_1 \upsilon_1}{T_1} \longrightarrow \frac{\upsilon_3}{\upsilon_1} = \frac{T_3 P_1}{T_1 P_3} = \frac{(300\text{ K})(3000\text{ kPa})}{(2000\text{ K})(150\text{ kPa})} = 3 = \frac{\upsilon_2}{\upsilon_1}$$

$$s_2 - s_1 = c_v \ln\frac{T_2}{T_1}^{\nearrow 0} + R\ln\frac{\upsilon_2}{\upsilon_1} = (2.0769\text{ kJ/kg}\cdot\text{K})\ln(3) = 2.282\text{ kJ/kg}\cdot\text{K}$$

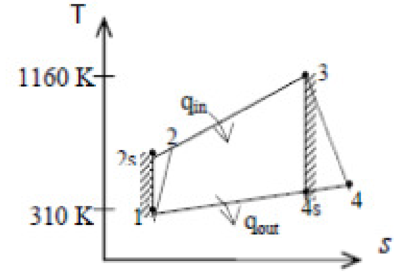
$$Q_{in} = mT_H(s_2 - s_1) = (0.12\text{ kg})(2000\text{ K})(2.282\text{ kJ/kg}\cdot\text{K}) = 547.6\text{ kJ}$$

$$W_{net,out} = \eta_{th} Q_{in} = (0.85)(547.6\text{ kJ}) = \mathbf{465.5\ kJ}$$

9–73 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

Solution 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 variable specific heats.



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

Analysis (*a*) Noting that process 1–2 is isentropic,

$$T_1 = 310 \text{ K} \longrightarrow \begin{array}{l} h_1 = 310.24 \text{ kJ/kg} \\ P_{r_1} = 1.5546 \end{array}$$

$$P_{r_2} = \frac{P_2}{P_1} P_{r_1} = (8)(1.5546) = 12.44 \longrightarrow h_{2s} = 562.58 \text{ kJ/kg and } T_{2s} = 557.25 \text{ K}$$

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

$$= 310.24 + \frac{562.58 - 310.24}{0.75} = 646.7 \text{ kJ/kg}$$

$$T_3 = 1160 \text{ K} \longrightarrow \begin{array}{l} h_3 = 1230.92 \text{ kJ/kg} \\ P_{r_3} = 207.2 \end{array}$$

$$P_{r_4} = \frac{P_4}{P_3} P_{r_3} = \left(\frac{1}{8}\right)(207.2) = 25.90 \longrightarrow h_{4s} = 692.19 \text{ kJ/kg and } T_{4s} = 680.3 \text{ K}$$

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

$$= 1230.92 - (0.82)(1230.92 - 692.19)$$

$$= 789.16 \text{ kJ/kg}$$

Thus, $T_4 = \mathbf{770.1\ K}$

(*b*) $q_{in} = h_3 - h_2 = 1230.92 - 646.7 = 584.2 \text{ kJ/kg}$

$q_{out} = h_4 - h_1 = 789.16 - 310.24 = 478.92 \text{ kJ/kg}$

$w_{net,out} = q_{in} - q_{out} = 584.2 - 478.92 = \mathbf{105.3\ kJ/kg}$

(*c*) $$\eta_{th} = \frac{w_{net,out}}{q_{in}} = \frac{105.3 \text{ kJ/kg}}{584.2 \text{ kJ/kg}} = \mathbf{18.0\%}$$

9–75 Repeat Problem 9–73 using constant specific heats at room temperature.

Solution 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).

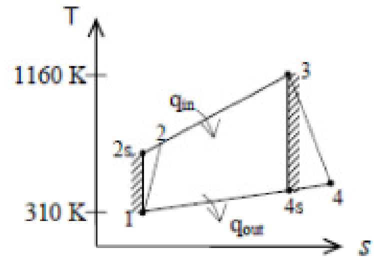
Analysis (*a*) Using the compressor and turbine efficiency relations,

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

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

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

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



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

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

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

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

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

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

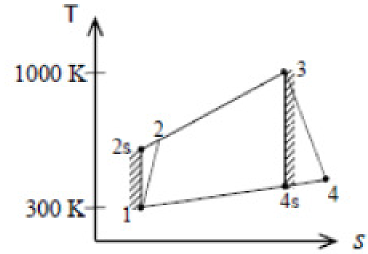
(*c*) $$\eta_{th} = \frac{w_{net,out}}{q_{in}} = \frac{91.3\text{ kJ/kg}}{517.3\text{ kJ/kg}} = \mathbf{17.6\%}$$

9–76 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

Solution A gas turbine power plant that operates on the simple Brayton cycle with air as the working fluid has a specified pressure ratio. The required mass flow rate of air is to be determined for two cases.

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 isentropic relations,

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (300\text{ K})(12)^{0.4/1.4} = 610.2\text{ K}$$

$$T_{4s} = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1000\text{ K})\left(\frac{1}{12}\right)^{0.4/1.4} = 491.7\text{ K}$$

$$w_{s,C,in} = h_{2s} - h_1 = c_p(T_{2s} - T_1) = (1.005\text{ kJ/kg}\cdot\text{K})(610.2 - 300)\text{K} = 311.75\text{ kJ/kg}$$

$$w_{s,T,out} = h_3 - h_{4s} = c_p(T_3 - T_{4s}) = (1.005\text{ kJ/kg}\cdot\text{K})(1000 - 491.7)\text{K} = 510.84\text{ kJ/kg}$$

$$w_{s,net,out} = w_{s,T,out} - w_{s,C,in} = 510.84 - 311.75 = 199.1\text{ kJ/kg}$$

$$\dot{m}_s = \frac{\dot{W}_{net,out}}{w_{s,net,out}} = \frac{70{,}000\text{ kJ/s}}{199.1\text{ kJ/kg}} = \mathbf{352\ kg/s}$$

(*b*) The net work output is determined to be

$$w_{a,net,out} = w_{a,T,out} - w_{a,C,in} = \eta_T w_{s,T,out} - w_{s,C,in}/\eta_C$$
$$= (0.85)(510.84) - 311.75/0.85 = 67.5\text{ kJ/kg}$$

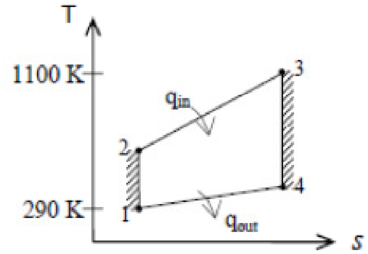
$$\dot{m}_a = \frac{\dot{W}_{net,out}}{w_{a,net,out}} = \frac{70{,}000\text{ kJ/s}}{67.5\text{ kJ/kg}} = \mathbf{1037\ kg/s}$$

9–77 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.

Solution A stationary gas-turbine power plant operates on a simple ideal Brayton cycle with air as the working fluid. The power delivered by this plant is to be determined assuming constant and variable specific heats.

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.

Analysis (*a*) Assuming constant specific heats,



$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (290\ \text{K})(8)^{0.4/1.4} = 525.3\ \text{K}$$

$$T_{4s} = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1100\ \text{K})\left(\frac{1}{8}\right)^{0.4/1.4} = 607.2\ \text{K}$$

$$\eta_{th} = 1-\frac{q_{out}}{q_{in}} = 1-\frac{c_p(T_4-T_1)}{c_p(T_3-T_2)} = 1-\frac{T_4-T_1}{T_3-T_2} = 1-\frac{607.2-290}{1100-525.3} = 0.448$$

$$\dot{W}_{net,out} = \eta_{th}\dot{Q}_{in} = (0.448)(35{,}000\ \text{kW}) = \mathbf{15{,}680\ kW}$$

(*b*) Assuming variable specific heats (Table A-17),

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

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

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

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

$$\eta_{th} = 1-\frac{q_{out}}{q_{in}} = 1-\frac{h_4-h_1}{h_3-h_2} = 1-\frac{651.37-290.16}{1161.07-526.11} = 0.431$$

$$\dot{W}_{net,out} = \eta_T\dot{Q}_{in} = (0.431)(35{,}000\ \text{kW}) = \mathbf{15{,}085\ kW}$$

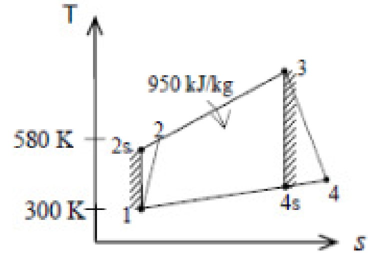
9–78 Air enters the compressor of a gas-turbine engine at 300 K and 100 kPa, where it is compressed to 700 kPa and 580 K. Heat is transferred to air in the amount of 950 kJ/kg before it enters the turbine. For a turbine efficiency of 86 percent, determine (*a*) the fraction of the turbine work output used to drive the compressor and (*b*) the thermal efficiency. Assume variable specific heats for air.

Solution An actual gas-turbine power plant operates at specified conditions. The fraction of the turbine work output used to drive the compressor 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 variable specific heats.

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

Analysis (a) Using the isentropic relations,



$$T_1 = 300 \text{ K} \longrightarrow h_1 = 300.19 \text{ kJ/kg}$$

$$T_2 = 580 \text{ K} \longrightarrow h_2 = 586.04 \text{ kJ/kg}$$

$$r_p = \frac{P_2}{P_1} = \frac{700}{100} = 7$$

$$q_{\text{in}} = h_3 - h_2 \longrightarrow h_3 = 950 + 586.04 = 1536.04 \text{kJ/kg}$$

$$\rightarrow P_{r_3} = 474.11$$

$$P_{r_4} = \frac{P_4}{P_3} P_{r_3} = \left(\frac{1}{7}\right)(474.11) = 67.73 \longrightarrow h_{4s} = 905.83 \text{ kJ/kg}$$

$$w_{\text{C,in}} = h_2 - h_1 = 586.04 - 300.19 = 285.85 \text{ kJ/kg}$$

$$w_{\text{T,out}} = \eta_T (h_3 - h_{4s}) = (0.86)(1536.04 - 905.83) = 542.0 \text{ kJ/kg}$$

Thus, $r_{\text{bw}} = \dfrac{w_{\text{C,in}}}{w_{\text{T,out}}} = \dfrac{285.85 \text{ kJ/kg}}{542.0 \text{ kJ/kg}} = \mathbf{52.7\%}$

(b) $w_{\text{net.out}} = w_{\text{T,out}} - w_{\text{C,in}} = 542.0 - 285.85 = 256.15 \text{ kJ/kg}$

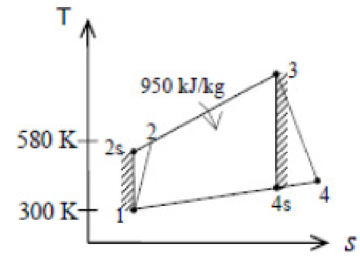
$$\eta_{\text{th}} = \frac{w_{\text{net,out}}}{q_{\text{in}}} = \frac{256.15 \text{ kJ/kg}}{950 \text{ kJ/kg}} = \mathbf{27.0\%}$$

9–79 Repeat Problem 9–78 using constant specific heats at room temperature.

Solution A gas-turbine power plant operates at specified conditions. The fraction of the turbine work output used to drive the compressor 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 constant specific heats,

$$r_p = \frac{P_2}{P_1} = \frac{700}{100} = 7$$

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2) \longrightarrow T_3 = T_2 + q_{in}/c_p$$
$$= 580\text{ K} + (950\text{ kJ/kg})/(1.005\text{ kJ/kg}\cdot\text{K})$$
$$= 1525.3\text{ K}$$

$$T_{4s} = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1525.3\text{ K})\left(\frac{1}{7}\right)^{0.4/1.4} = 874.8\text{ K}$$

$$w_{C,in} = h_2 - h_1 = c_p(T_2 - T_1) = (1.005\text{kJ/kg}\cdot\text{K})(580 - 300)\text{K} = 281.4\text{ kJ/kg}$$

$$w_{T,out} = \eta_T(h_3 - h_{4s}) = \eta_T c_p(T_3 - T_{4s}) = (0.86)(1.005\text{ kJ/kg}\cdot\text{K})(1525.3 - 874.8)\text{K} = 562.2\text{ kJ/kg}$$

Thus, $$r_{bw} = \frac{w_{C,in}}{w_{T,out}} = \frac{281.4\text{ kJ/kg}}{562.2\text{ kJ/kg}} = \mathbf{50.1\%}$$

(b) $$w_{net,out} = w_{T,out} - w_{C,in} = 562.2 - 281.4 = 280.8\text{ kJ/kg}$$

$$\eta_{th} = \frac{w_{net,out}}{q_{in}} = \frac{280.8\text{ kJ/kg}}{950\text{ kJ/kg}} = \mathbf{29.6\%}$$

9–82 A gas-turbine power plant operates on the simple Brayton cycle with air as the working fluid and delivers 32 MW of power. The minimum and maximum temperatures in the cycle are 310 and 900 K, and the pressure of air at the compressor exit is 8 times the value at the compressor inlet. Assuming an isentropic efficiency of 80 percent for the compressor and 86 percent for the turbine, determine the mass flow rate of air through the cycle. Account for the variation of specific heats with temperature.

Solution A 32-MW gas-turbine power plant operates on a simple Brayton cycle with air as the working fluid. The mass flow rate of air through the cycle is 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 variable specific heats.

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

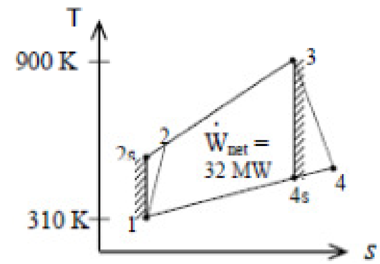
Analysis Using variable specific heats,

$$T_1 = 310 \text{ K} \longrightarrow \begin{array}{l} h_1 = 310.24 \text{ kJ/kg} \\ P_{r_1} = 1.5546 \end{array}$$

$$P_{r_2} = \frac{P_2}{P_1} P_{r_1} = (8)(1.5546) = 12.44 \longrightarrow h_{2s} = 562.26 \text{ kJ/kg}$$

$$T_3 = 900 \text{ K} \longrightarrow \begin{array}{l} h_3 = 932.93 \text{ kJ/kg} \\ P_{r_3} = 75.29 \end{array}$$

$$P_{r_4} = \frac{P_4}{P_3} P_{r_3} = \left(\frac{1}{8}\right)(75.29) = 9.411 \longrightarrow h_{4s} = 519.32 \text{ kJ/kg}$$



$$w_{\text{net,out}} = w_{\text{T,out}} - w_{\text{C,in}} = \eta_T (h_3 - h_{4s}) - (h_{2s} - h_1)/\eta_C$$
$$= (0.86)(932.93 - 519.32) - (562.26 - 310.24)/(0.80) = 40.68 \text{ kJ/kg}$$

and $$\dot{m} = \frac{\dot{W}_{\text{net,out}}}{w_{\text{net,out}}} = \frac{32{,}000 \text{ kJ/s}}{40.68 \text{ kJ/kg}} = \mathbf{786.6\ kg/s}$$

9–83 Repeat Problem 9–82 using constant specific heats at room temperature.

Solution A 32-MW gas-turbine power plant operates on a simple Brayton cycle with air as the working fluid. The mass flow rate of air through the cycle is to be determined.

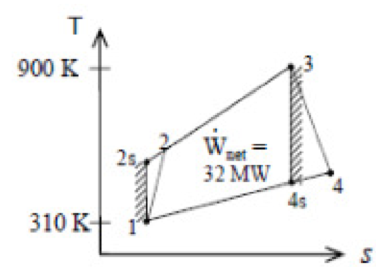
Assumptions **1** Steady operating conditions exist. **2** The air-standard assumptions are applicable. **3** Kinetic and potential energy changes are negligible. **4** Air is an ideal gas with constant specific heats.

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

Analysis Using constant specific heats,

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

$$T_{4s} = T_3 \left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (900 \text{ K})\left(\frac{1}{8}\right)^{0.4/1.4} = 496.8 \text{ K}$$



$$w_{\text{net,out}} = w_{\text{T,out}} - w_{\text{C,in}} = \eta_T c_p (T_3 - T_{4s}) - c_p (T_{2s} - T_1)/\eta_C$$
$$= (1.005 \text{ kJ/kg}\cdot\text{K})[(0.86)(900 - 496.8) - (561.5 - 310)/(0.80)]\text{K}$$
$$= 32.5 \text{ kJ/kg}$$

and

$$\dot{m} = \frac{\dot{W}_{\text{net,out}}}{w_{\text{net,out}}} = \frac{32{,}000 \text{ kJ/s}}{32.5 \text{ kJ/kg}} = \mathbf{984.6\ kg/s}$$

9–85C How does regeneration affect the efficiency of a Brayton cycle, and how does it accomplish it?

Solution 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.

9–87C Define the effectiveness of a regenerator used in gas-turbine cycles.

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

9–93 An ideal Brayton cycle with regeneration has a pressure ratio of 10. Air enters the compressor at 300 K and the turbine at 1200 K. If the effectiveness of the regenerator is 100 percent, determine the net work output and the thermal efficiency of the cycle. Account for the variation of specific heats with temperature.

Solution An ideal Brayton cycle with regeneration is considered. The effectiveness of the regenerator is 100%. The net work output and the thermal efficiency of the cycle are to be determined.

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 Noting that this is an ideal cycle and thus the compression and expansion processes are isentropic, we have

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

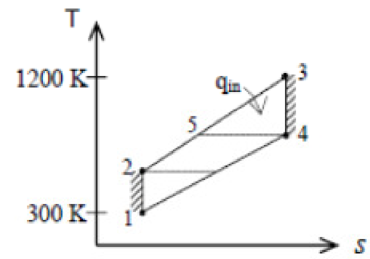
$$P_{r_2} = \frac{P_2}{P_1} P_{r_1} = (10)(1.386) = 13.86 \longrightarrow h_2 = 579.87 \text{ kJ/kg}$$

$$T_3 = 1200 \text{ K} \longrightarrow \begin{matrix} h_3 = 1277.79 \text{ kJ/kg} \\ P_{r_3} = 238 \end{matrix}$$

$$P_{r_4} = \frac{P_4}{P_3} P_{r_3} = \left(\frac{1}{10}\right)(238) = 23.8 \longrightarrow h_4 = 675.85 \text{ kJ/kg}$$

$$w_{C,in} = h_2 - h_1 = 579.87 - 300.19 = 279.68 \text{ kJ/kg}$$

$$w_{T,out} = h_3 - h_4 = 1277.79 - 675.85 = 601.94 \text{ kJ/kg}$$



Thus,

$$w_{net} = w_{T,out} - w_{C,in} = 601.94 - 279.68 = \mathbf{322.26 \text{ kJ/kg}}$$

Also, $\varepsilon = 100\% \longrightarrow h_5 = h_4 = 675.85 \text{ kJ/kg}$

$$q_{in} = h_3 - h_5 = 1277.79 - 675.85 = 601.94 \text{ kJ/kg}$$

and

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{322.26 \text{ kJ/kg}}{601.94 \text{ kJ/kg}} = \mathbf{53.5\%}$$