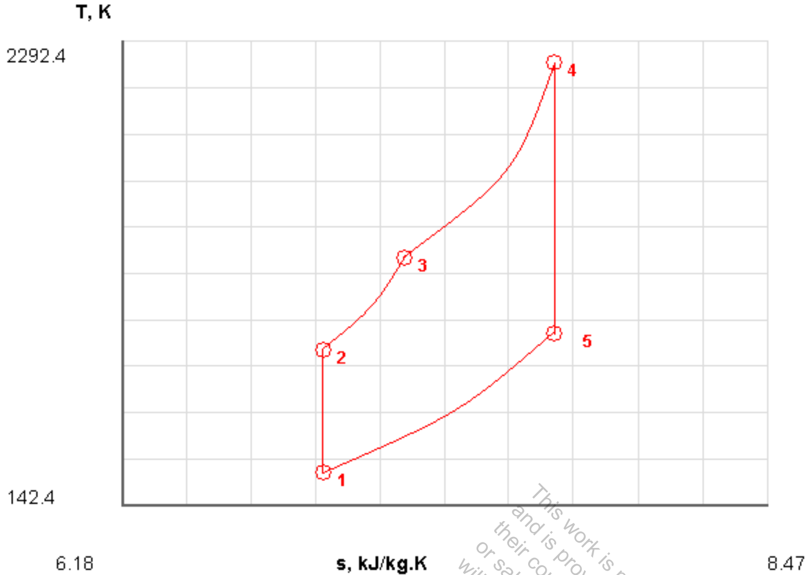
7-5-1 [OGB] An ideal dual cycle has a compression ratio of 14 and uses air as working fluid. The state of air at the beginning of the compression process is 100 kPa and 300 K. The pressure ratio is 1.5 during the constant-volume heat addition process. If the maximum temperature in the cycle is 2200 K, determine (a) the thermal efficiency and (b) the mean effective pressure. Use the PG model.

SOLUTION



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Given:

$$c_v = 0.717 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1):

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287)(300)}{100} = 0.861 \ \frac{\text{m}^3}{\text{kg}};$$

State-2 (given $s_2 = s_1, r$):

$$T_2 = T_1 r^{k-1} = (300)(14)^{1.4-1} = 862 \text{ K};$$

$$p_2 = p_1 r^k = (100)(14)^{1.4} = 4023 \text{ kPa};$$

$$v_2 = \frac{v_1}{14} = \frac{0.861}{14} = 0.0615 \ \frac{\text{m}^3}{\text{kg}};$$

State-3 (given $p_3 = 1.5p_2, v_3 = v_2$):

$$T_3 = \frac{T_2 p_3}{p_2} = 1.5T_2 = 1293 \text{ K};$$

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State-4 (given $p_4 = p_3, T_4$):

$$v_4 = \frac{RT_4}{p_4} = 0.10464 \ \frac{\text{m}^3}{\text{kg}};$$

State-5 (given $s_5 = s_4, v_5 = v_1$):

$$\frac{v_5}{v_4} = \frac{v_1}{v_4} = \frac{0.861}{0.10464} = 8.23;$$

$$T_5 = \frac{T_4}{\left(\frac{v_5}{v_4}\right)^{1.4-1}} = \frac{2200}{(8.23)^{1.4-1}} = 947 \text{ K};$$

An energy analysis for the heat addition and rejection processes yields:
Process 2-4:

$$q_{\text{in}} = q_{23} + q_{34};$$

$$\Rightarrow q_{\text{in}} = c_v \left(T_3 - T_2\right) + c_p \left(T_4 - T_3\right);$$

$$\Rightarrow q_{\text{in}} = (0.71)(1293 - 862) + (1.005)(2200 - 1293);$$

$$\Rightarrow q_{\text{in}} = 1221 \ \frac{\text{kJ}}{\text{kg}};$$

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Process 5-1:

$$q_{\text{out}} = -q_{51};$$

$$\Rightarrow q_{\text{out}} = u_5 - u_1;$$

$$\Rightarrow q_{\text{out}} = mc_v \left(T_5 - T_1\right);$$

$$\Rightarrow q_{\text{out}} = (0.717)(947 - 300);$$

$$\Rightarrow q_{\text{out}} = 464.5 \ \frac{\text{kJ}}{\text{kg}};$$

Therefore, the net work, efficiency and MEP can be calculated as:

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}};$$

$$\Rightarrow w_{\text{net}} = 1221 - 464.5;$$

$$\Rightarrow w_{\text{net}} = 756.5 \ \frac{\text{kJ}}{\text{kg}};$$

(a) $\eta_{\text{th}} = \dfrac{w_{\text{net}}}{q_{in}};$

$$\Rightarrow \eta_{\text{th}} = \frac{756.5}{1221};$$

$$\Rightarrow \eta_{\text{th}} = 62\%$$

(b) $\text{MEP} = \dfrac{w_{\text{net}}}{v_1 - v_2};$

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$$\Rightarrow \text{MEP} = \frac{w_{\text{net}}}{v_1(1-r)};$$

$$\Rightarrow \text{MEP} = \frac{756.5}{(0.861)\left(1-\frac{1}{14}\right)};$$

$$\Rightarrow \text{MEP} = 946 \text{ kPa}$$

TEST Solution:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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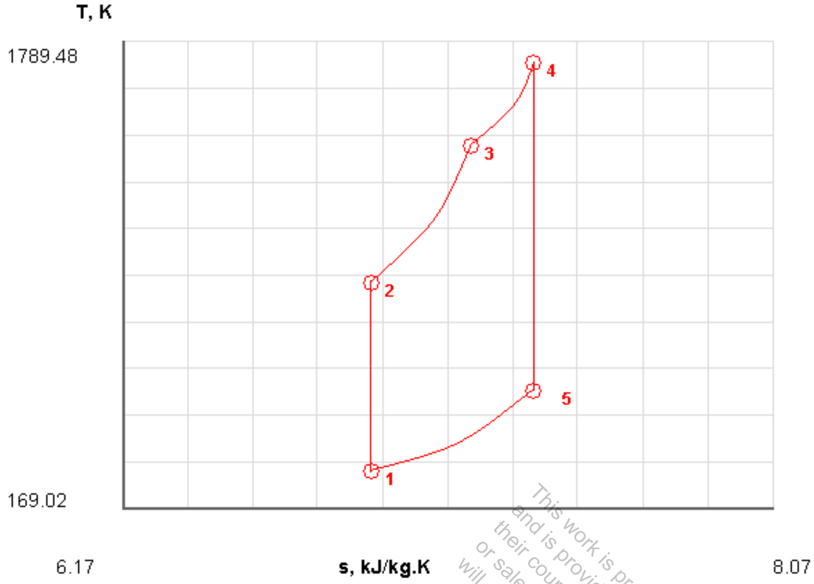
7-5-2 [OGS] At the beginning of the compression process of an air standard dual cycle with a compression ratio of 18, p = 100 kPa and T = 300 K. The pressure ratio for the constant volume part of the heating process is 1.5 and the volume ratio of the constant pressure part is 1.2. Determine (a) the thermal efficiency and (b) the MEP. Use the PG model.

SOLUTION



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Given:

$$c_v = 0.717 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1):

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287)(300)}{100} = 0.861 \ \frac{\text{m}^3}{\text{kg}};$$

State-2 (given $s_1 = s_2, r$):

$$T_2 = T_1 r^{k-1} = (300)(18)^{1.4-1} = 953 \text{ K};$$

$$p_2 = p_1 r^k = (100)(18)^{1.4} = 5719.8 \text{ kPa};$$

$$v_2 = \frac{v_1}{18} = 0.0478 \ \frac{\text{m}^3}{\text{kg}};$$

State-3 (given $p_3 = 1.5 p_2, v_2 = v_3$):

$$T_3 = \frac{p_3}{p_2} T_2 = (1.5)(953) = 1430 \text{ K};$$

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State-4 (given $p_4 = p_3, v_4 = 1.2v_3$):

$$T_4 = \frac{v_4}{v_3}T_3 = (1.2)(1430) = 1716 \text{ K};$$

State-5 (given $s_5 = s_4, v_5 = v_1$):

$$\frac{v_5}{v_4} = \frac{v_1}{v_4} = \frac{0.861}{0.05736} = 15.01;$$

$$T_5 = \frac{T_4}{\left(\frac{v_5}{v_4}\right)^{1.4-1}} = \frac{1716}{(15.01)^{1.4-1}} = 581 \text{ K};$$

An energy analysis for the heat addition and rejection processes yields:
Process 2-4:

$$q_{\text{in}} = q_{23} + q_{34};$$

$$\Rightarrow q_{\text{in}} = c_v\left(T_3 - T_2\right) + c_p\left(T_4 - T_3\right);$$

$$\Rightarrow q_{\text{in}} = (0.717)(1430-953) + (1.005)(1716-1430);$$

$$\Rightarrow q_{\text{in}} = 629 \ \frac{\text{kJ}}{\text{kg}};$$

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Process 5-1:

$$q_{\text{out}} = -q_{51};$$

$$\Rightarrow q_{\text{out}} = u_5 - u_1;$$

$$\Rightarrow q_{\text{out}} = c_v\left(T_5 - T_1\right);$$

$$\Rightarrow q_{\text{out}} = (0.717)(581-300);$$

$$\Rightarrow q_{\text{out}} = 201 \ \frac{\text{kJ}}{\text{kg}};$$

Therefore, the net work, efficiency and MEP are calculated as:

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}};$$

$$\Rightarrow w_{\text{net}} = 629 - 201;$$

$$\Rightarrow w_{\text{net}} = 428 \ \frac{\text{kJ}}{\text{kg}};$$

(a) $\eta_{\text{th}} = \dfrac{w_{\text{net}}}{q_{\text{in}}};$

$$\Rightarrow \eta_{\text{th}} = \frac{428}{629};$$

$$\Rightarrow \eta_{\text{th}} = 68\%$$

(b) $\text{MEP} = \dfrac{w_{\text{net}}}{v_1 - v_2};$

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$$\Rightarrow \text{MEP} = \frac{w_{\text{net}}}{v_1 - v_2};$$

$$\Rightarrow \text{MEP} = \frac{w_{\text{net}}}{v_1\left(1 - r\right)};$$

$$\Rightarrow \text{MEP} = \frac{428}{\left(0.861\right)\left(1 - \frac{1}{18}\right)};$$

$$\Rightarrow \text{MEP} = 526 \text{ kPa} = 0.526 \text{ MPa}$$

TEST Solution:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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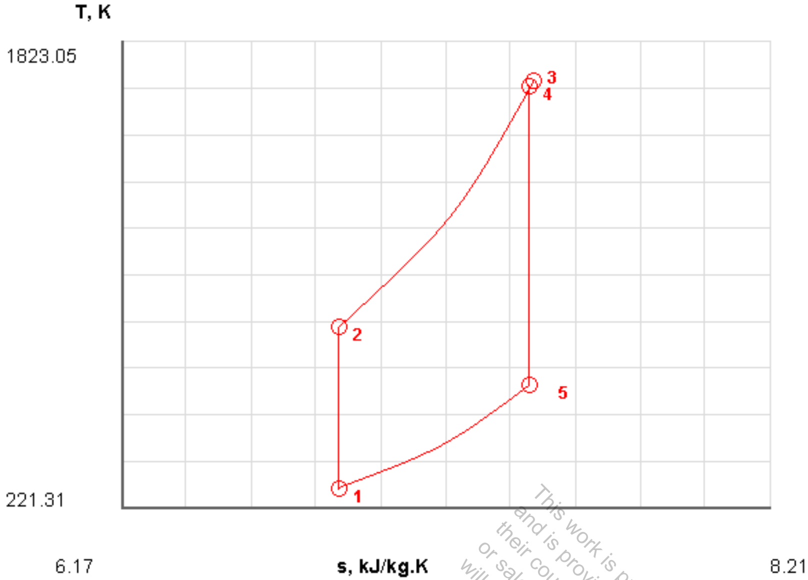
7-5-3 [OGN] An air standard dual cycle has a compression ratio of 17. At the beginning of compression, P_1 = 100 kPa and T_1 = 15°C and volume is 0.5 ft^3. The pressure doubles during the constant volume heat addition process. For maximum cycle temperature of 1400°C, determine (a) the thermal efficiency (η_{th}) and (b) the MEP. Assume variable c_p (IG model).

SOLUTION



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Given:

$$R = 0.287 \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

State-1 (given $p_1, T_1, \cancel{V}_1$):

$$v_1 = 0.826 \frac{\text{m}^3}{\text{kg}};$$

$$u_1 = -92.71 \frac{\text{kJ}}{\text{kg}};$$

$$m_1 = \frac{p_1 \cancel{V}_1}{RT_1} = \frac{(100)(0.01415)}{(0.287)(288)} = 0.01712 \text{ kg};$$

State-2 (given $s_2 = s_1, r$):

$$v_2 = \frac{v_1}{17} = 0.0486 \frac{\text{m}^3}{\text{kg}};$$

$$u_2 = 333.47 \frac{\text{kJ}}{\text{kg}};$$

$$T_2 = 845.94 \text{ K};$$

$$p_2 = 4990.7 \text{ kPa};$$

State-3 (given $p_3 = 2p_2, v_3 = v_2$):

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$T_3 = 1691.8 \text{ K};$

$u_3 = 1088.22 \ \dfrac{\text{kJ}}{\text{kg}};$

State-4 (given $p_4 = p_3, T_4$):

$u_4 = 1070.6 \ \dfrac{\text{kJ}}{\text{kg}};$

$v_4 = 0.0481 \ \dfrac{\text{m}^3}{\text{kg}};$

State-5 (given $s_5 = s_4, v_5 = v_1$):

$u_5 = 174.76 \ \dfrac{\text{kJ}}{\text{kg}};$

$T_5 = 647.09 \text{ K};$

$p_5 = 224.56 \text{ kPa};$

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An energy analysis for the heat addition and rejection processes yields:
Process 2-4:

$Q_{\text{in}} = Q_{23} + Q_{34};$

$\Rightarrow Q_{\text{in}} = m(u_3 - u_2) + m(u_4 - u_3);$

$\Rightarrow Q_{\text{in}} = (0.01712)(754.7 - 17.67);$

$\Rightarrow Q_{\text{in}} = 12.62 \text{ kJ};$

Process 5-1:

$Q_{\text{out}} = -Q_{51};$

$\Rightarrow Q_{\text{out}} = m(u_5 - u_1);$

$\Rightarrow Q_{\text{out}} = (0.01712)(174.76 + 92.71);$

$\Rightarrow Q_{\text{out}} = 4.58 \text{ kJ};$

Therefore, the net work, efficiency and MEP can be calculated as:

$W_{\text{net}} = Q_{\text{in}} - Q_{\text{out}};$

$\Rightarrow W_{\text{net}} = 12.62 - 4.58;$

$\Rightarrow W_{\text{net}} = 8.04;$

(a) $\eta_{\text{th}} = \dfrac{W_{\text{net}}}{Q_{\text{in}}};$

$\Rightarrow \eta_{\text{th}} = \dfrac{8.04}{12.62};$

$\Rightarrow \eta_{\text{th}} = 63\%$

(b) $\text{MEP} = \dfrac{W_{\text{net}}}{V_d};$

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$$\Rightarrow \text{MEP} = \frac{W_{\text{net}}}{m(v_1 - v_2)};$$

$$\Rightarrow \text{MEP} = \frac{W_{\text{net}}}{mv_2(r-1)};$$

$$\Rightarrow \text{MEP} = \frac{8.04}{(0.01712)(0.0486)(16)};$$

$$\Rightarrow \text{MEP} = 603.9 \text{ kPa}$$

TEST Solution:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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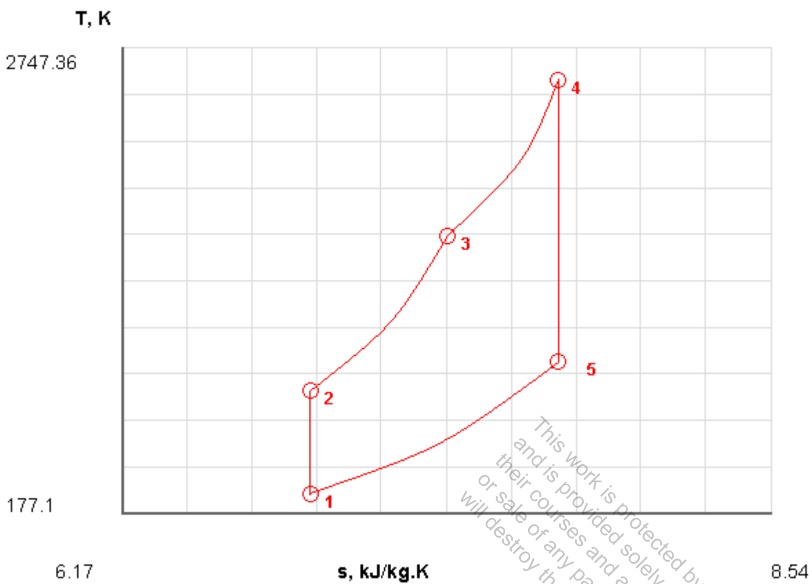
7-5-4 [OGA] An air standard dual cycle has a compression ratio of 15 and a cutoff ratio of 1.5. At the beginning of compression, p_1 = 1 bar and T_1 = 290 K. The pressure doubles during the constant volume heat addition process. If the mass of air is 0.5 kg, determine (a) the net work (W_{net}) of the cycle, (b) the thermal efficiency (η_{th}) and (c) the MEP. Use the PG model. (d) What-if Scenario: What would the net work and efficiency be if the compression ratio were increased to 18? Explain the changes with the help of a *T-s* diagram.

SOLUTION



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Given:

$$c_v = 0.717 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1, m_1):

$$v_2 = \frac{RT_1}{p_1} = \frac{(0.287)(290)}{100} = 0.8323 \ \frac{\text{m}^3}{\text{kg}};$$

State-2 (given $s_2 = s_1, r$): Use of isentropic relations leads to

$$T_2 = T_1 r^{k-1} = (290)(15)^{1.4-1} = 856.7 \text{ K};$$

$$p_2 = p_1 r^k = (100)(15)^{1.4} = 4431.3 \text{ kPa};$$

$$v_2 = \frac{v_1}{15} = \frac{0.8323}{15} = 0.05548 \ \frac{\text{m}^3}{\text{kg}};$$

State-3 (given $p_3 = 2p_2, v_3 = v_2$):

$$T_3 = \frac{T_2 p_3}{p_2} = 2T_2 = 1713.4 \text{ K};$$

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State-4 (given $p_4 = p_3, r_c$):

$$T_4 = \frac{v_4 T_3}{v_3} = 1.5 T_3 = 2570 \text{ K};$$

State-5 (given r and T_4):

$$\frac{v_5}{v_4} = \frac{v_1}{v_4} = \frac{0.8323}{0.08323} = 10;$$

$$T_5 = \frac{T_4}{\left(\frac{v_5}{v_4}\right)^{k-1}} = \frac{2570}{(10)^{1.4-1}} = 1023.1 \text{ K};$$

An energy analysis for the heat addition and rejection processes yields:
Process 2-4:

$$Q_{\text{in}} = Q_{23} + Q_{34};$$
$$\Rightarrow Q_{\text{in}} = mc_v(T_3 - T_2) + mc_p(T_4 - T_3);$$
$$\Rightarrow Q_{\text{in}} = (0.5)(0.717)(1713.4 - 856.7) + (0.5)(1.003)(2570 - 1713.4);$$
$$\Rightarrow Q_{\text{in}} = 736.7 \text{ kJ};$$

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Process 5-1:

$$Q_{\text{out}} = -Q_{51};$$
$$\Rightarrow Q_{\text{out}} = m(u_5 - u_1);$$
$$\Rightarrow Q_{\text{out}} = mc_v(T_5 - T_1);$$
$$\Rightarrow Q_{\text{out}} = (0.5)(0.717)(1021.9 - 290);$$
$$\Rightarrow Q_{\text{out}} = 262.4 \text{ kJ};$$

Therefore, the net work, efficiency and MEP can be calculated as:

(a) $W_{\text{net}} = Q_{\text{in}} - Q_{\text{out}};$

$$\Rightarrow W_{\text{net}} = 736.7 - 262.4;$$
$$\Rightarrow W_{\text{net}} = 474.3 \text{ kJ}$$

(b) $\eta_{\text{th}} = \frac{W_{\text{net}}}{Q_H};$

$$\Rightarrow \eta_{\text{th}} = \frac{474.3}{736.7};$$
$$\Rightarrow \eta_{\text{th}} = 64\%$$

(c) $\text{MEP} = \frac{W_{\text{net}}}{\cancel{V}_d};$

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$$\Rightarrow \text{MEP} = \frac{W_{\text{net}}}{m(v_1 - v_2)};$$

$$\Rightarrow \text{MEP} = \frac{W_{\text{net}}}{mv_2(r-1)};$$

$$\Rightarrow \text{MEP} = \frac{(474.3)}{(0.5)(0.05548)(14)};$$

$$\Rightarrow \text{MEP} = 1221.3 \text{ kPa}$$

TEST Solution and What-if Scenario:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution and perform the what-if study. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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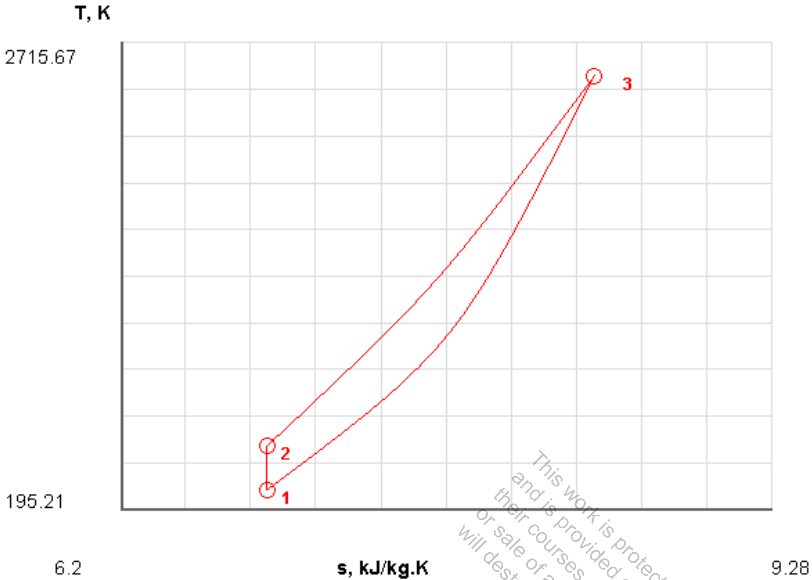
7-5-5 [OGH] A 3-stroke cycle is executed in a closed system with 1 kg of air, and it consists of the following three processes: (1) Isentropic compression from 100 kPa, 300 K to 800 kPa, (2) p = constant during heat addition in amount of 2000 kJ, (3) $p = cv$ during heat rejection to initial state. Calculate (a) the maximum temperature and (b) efficiency. Show the cycle on T-s and p-v diagrams. Use the PG model for air. (c) What-if Scenario: What would the efficiency be if the constant pressure heat addition amounted to 1000 kJ?

SOLUTION



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Given:

$$c_v = 0.717 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1, m_1):

$$v_1 = \frac{RT_1}{p_1} = 0.861 \ \frac{\text{m}^3}{\text{kg}};$$

State-2 (given $p_2, s_2 = s_1$):

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (300)(8)^{\frac{1.4-1}{1.4}} = 543.4 \text{ K};$$

State-3 (given $p_3 = p_2, Q_{\text{in}}$):

$$T_3 = T_2 + \frac{Q_{\text{in}}}{mc_p} = 543.4 + \frac{2000}{(1)(1.005)} = 2533.4 \text{ K};$$

An energy analysis for the heat rejection process yields:

Process 3-1:

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$$Q_{\text{out}} = -Q_{31};$$

$$\Rightarrow Q_{\text{out}} = m\left(u_3 - u_1\right);$$

$$\Rightarrow Q_{\text{out}} = mc_v\left(T_3 - T_1\right);$$

$$\Rightarrow Q_{\text{out}} = (1)(0.717)(2533.4 - 300);$$

$$\Rightarrow Q_{\text{out}} = 1601.3 \text{ kJ};$$

(a) $T = 2533.4 \text{ K}$

(b) Therefore efficiency can be calculated as:

$$\eta_{\text{th}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}};$$

$$\Rightarrow \eta_{\text{th}} = 1 - \frac{1601.3}{2000};$$

$$\Rightarrow \eta_{\text{th}} = 19.9\%$$

TEST Solution and What-if Scenario:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution and perform the what-if study. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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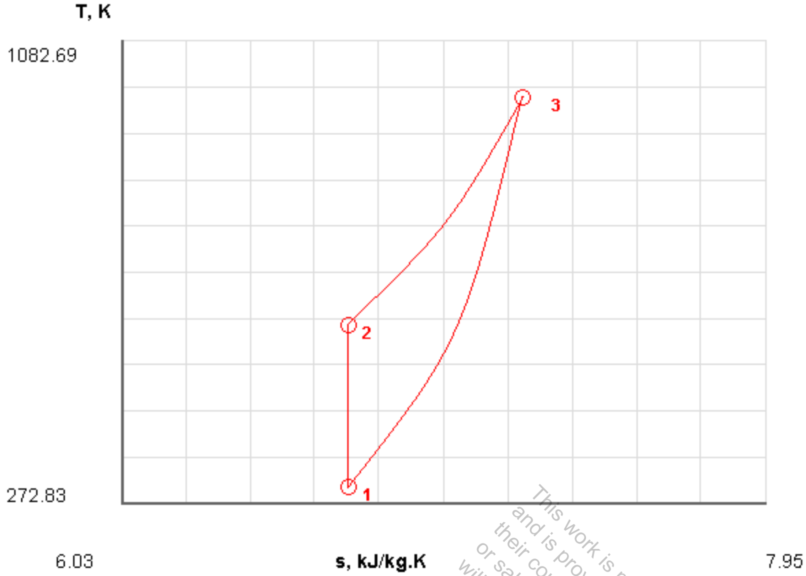
7-5-6 [OGE] An air standard cycle is executed in a closed system with 0.005 kg of air, and it consists of the following three processes: (1) Isentropic compression from 200 kPa, 30°C to 2 MPa, (2) p = constant during heat addition in the amount of 2 kJ, (3) $p = c_1 v + c_2$ heat rejection to initial state. Calculate (a) the heat rejected, and (b) the thermal efficiency (η_{th}). Assume constant specific heats at room temperature.

SOLUTION



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Given:

$$c_v = 0.717 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1, m_1):

$$\cancel{V}_1 = \frac{m_1 R T_1}{p_1} = \frac{(0.005)(0.287)(303)}{200} = 0.002174 \text{ m}^3;$$

State-2 (given $p_2, s_2 = s_1$):

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (300)\left(\frac{2000}{200}\right)^{\frac{1.4-1}{1.4}} = 585 \text{ K};$$

$$\cancel{V}_2 = \frac{m R T_2}{p_2} = \frac{(0.005)(0.287)(585)}{2000} = 0.0004197 \text{ m}^3;$$

State-3 (given $p_3 = p_2, Q_{\text{in}}$):

$$T_3 = T_2 + \frac{Q_{\text{in}}}{m c_p} = 585 + \frac{2}{(0.005)(1.005)} = 983 \text{ K};$$

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The boundary work for the compression process:

$W_{12} = W_B;$

$$\Rightarrow W_{12} = \int_{\cancel{V}_1}^{\cancel{V}_2} p\,d\cancel{V};$$

$$\Rightarrow W_{12} = p\left(\cancel{V}_2 - \cancel{V}_1\right);$$

$$\Rightarrow W_{12} = (2000)(0.0004179 - 0.002174);$$

$$\Rightarrow W_{12} = -3.512 \text{ kJ};$$

(a) From the energy balance equation

$W_B = Q_{\text{in}} + Q_{\text{out}};$

$$\Rightarrow Q_{\text{out}} = W_B - Q_{\text{in}};$$

$$\Rightarrow Q_{\text{out}} = 3.508 - 2;$$

$$\Rightarrow Q_{\text{out}} = 1.508 \text{ kJ}$$

Therefore, the net work and efficiency can be calculated as

$W_{\text{net}} = Q_{\text{in}} - Q_{\text{out}};$

$$\Rightarrow W_{\text{net}} = 2 - 1.508;$$

$$\Rightarrow W_{\text{net}} = 0.492 \text{ kJ};$$

(b) $\eta_{\text{th}} = \dfrac{W_{\text{net}}}{Q_{in}};$

$$\Rightarrow \eta_{\text{th}} = \frac{0.492}{2};$$

$$\Rightarrow \eta_{\text{th}} = 24.6\%$$

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TEST Solution:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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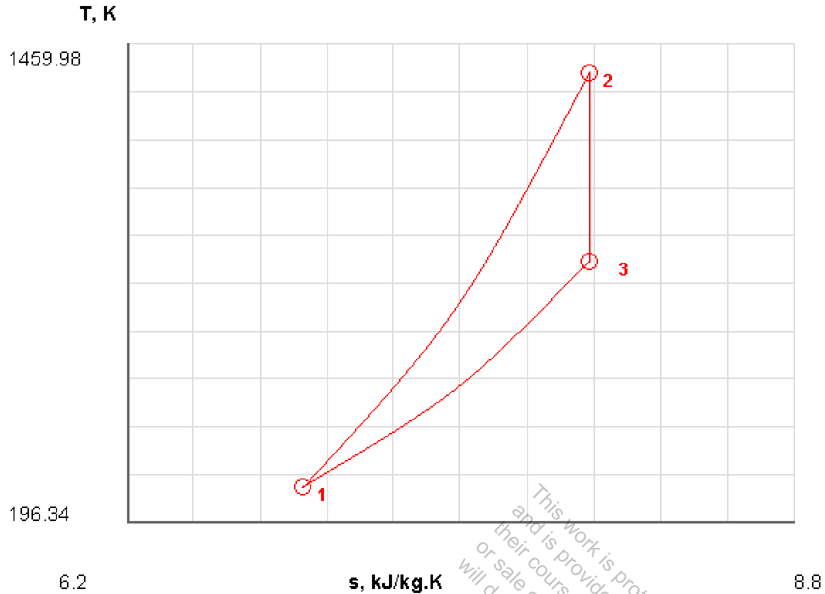
7-5-7 [OGI] An air standard cycle is executed in a closed system with 0.001 kg of air, and it consists of the following three processes: (1) v = constant during heat addition from 95 kPa 20°C to 450 kPa, (2) isentropic expansion to 95 kPa, (3) p = constant heat rejection to initial state. Using PG model calculate (a) the net work (W_{net}) per cycle in kJ, and (b) the thermal efficiency (η_{th}).

SOLUTION



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Given:

$$c_v = 0.717 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1, m_1)

State-2 (given $p_2, v_2 = v_1$):

$$T_2 = T_1 \frac{p_2}{p_1} = (293)\left(\frac{450}{95}\right) = 1387.9 \text{ K};$$

State-3 (given $p_3 = p_1, s_2 = s_1$):

$$T_3 = T_2 \left(\frac{p_3}{p_2}\right)^{\frac{k-1}{k}} = (1387.9)\left(\frac{95}{450}\right)^{\frac{1.4-1}{1.4}} = 889.9 \text{ K};$$

An energy analysis for the heat addition and rejection processes yields:
Process 1-2:

$$Q_{\text{in}} = m(u_2 - u_1);$$

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$$\Rightarrow Q_{\text{in}} = mc_v\left(T_2 - T_1\right);$$
$$\Rightarrow Q_{\text{in}} = (0.001)(0.717)(1387.9 - 293);$$
$$\Rightarrow Q_{\text{in}} = 0.785 \text{ kJ};$$

Process 3-1:

$$Q_{\text{out}} = m\left(u_3 - u_1\right);$$
$$\Rightarrow Q_{\text{out}} = mc_p\left(T_3 - T_1\right);$$
$$\Rightarrow Q_{\text{out}} = (0.001)(1.005)(889.9 - 293);$$
$$\Rightarrow Q_{\text{out}} = 0.60 \text{ kJ};$$

Therefore, the net work and efficiency are calculated as:

(a) $W_{\text{net}} = Q_{\text{in}} - Q_{\text{out}};$

$$\Rightarrow W_{\text{net}} = 0.785 - 0.60;$$
$$\Rightarrow W_{\text{net}} = 0.185 \text{ kJ}$$

(b) $\eta_{\text{th}} = \dfrac{W_{\text{net}}}{Q_{in}};$

$$\Rightarrow \eta_{\text{th}} = \frac{0.185}{0.785};$$
$$\Rightarrow \eta_{\text{th}} = 23.5\%$$

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TEST Solution:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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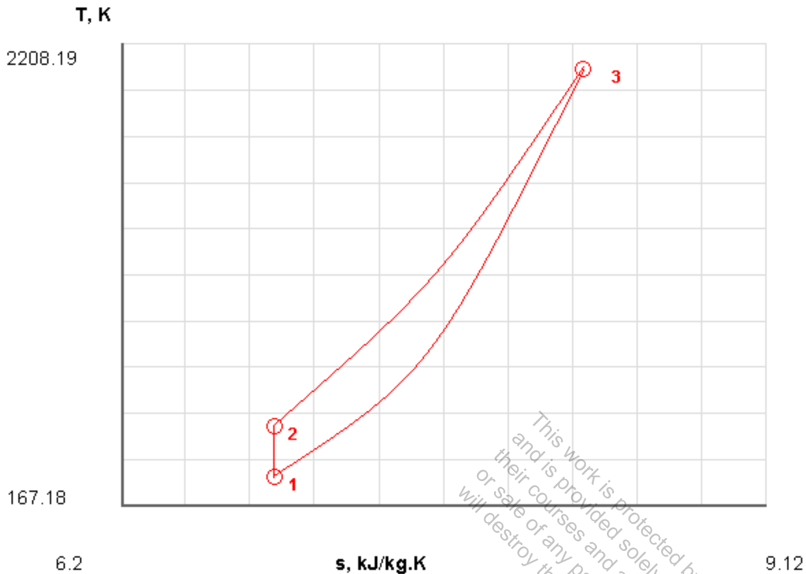
7-5-8 [OGL] An air standard cycle is executed in a closed system with 1 kg of air, and it consists of the following three processes: (1) Isentropic compression from 100 kPa, 27°C to 700 kPa, (2) *p* = constant during heat addition to initial specific volume, (3) *v* = constant during heat rejection to initial state. Calculate (a) the maximum temperature and (b) efficiency. Show the cycle on *T*-*s* and *p*-*v* diagrams. Use the PG model. (c) What-if Scenario: What would the maximum temperature be if isentropic compression took place from 100 kPa, 27°C to 500 kPa?

SOLUTION



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Given:

$$c_v = 0.717\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1, m_1):

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287)(300)}{100} = 0.861\ \frac{\text{m}^3}{\text{kg}};$$

State-2 (given $p_2, s_2 = s_1$):

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (300)(7)^{\frac{1.4-1}{1.4}} = 523.1\ \text{K};$$

State-3 (given $p_3 = p_2, v_3 = v_1$):

(a) $$T_3 = \frac{p_3 v_3}{R} = \frac{(700)(0.861)}{(0.287)} = 2100\ \text{K} = 1827°\text{C}$$

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An energy analysis for the heat addition and rejection processes yields:
Process 2-3:

$$Q_{\text{in}} = Q_{23};$$

$$\Rightarrow Q_{\text{in}} = mc_p\left(T_3 - T_2\right);$$

$$\Rightarrow Q_{\text{in}} = (1)(1.005)(2100 - 523.1);$$

$$\Rightarrow Q_{\text{in}} = 1584.8 \text{ kJ};$$

Process 3-1:

$$Q_{\text{out}} = -Q_{31};$$

$$\Rightarrow Q_{\text{out}} = m\left(u_3 - u_1\right);$$

$$\Rightarrow Q_{\text{out}} = mc_v\left(T_3 - T_1\right);$$

$$\Rightarrow Q_{\text{out}} = (1)(0.717)(2100 - 300);$$

$$\Rightarrow Q_{\text{out}} = 1290.6 \text{ kJ};$$

(b) Therefore, the efficiency can be calculated as:

$$\eta_{\text{th}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}};$$

$$\Rightarrow \eta_{\text{th}} = 1 - \frac{1290.6}{1584.8};$$

$$\Rightarrow \eta_{\text{th}} = 18.6\%$$

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TEST Solution and What-if Scenario:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution and perform the what-if study. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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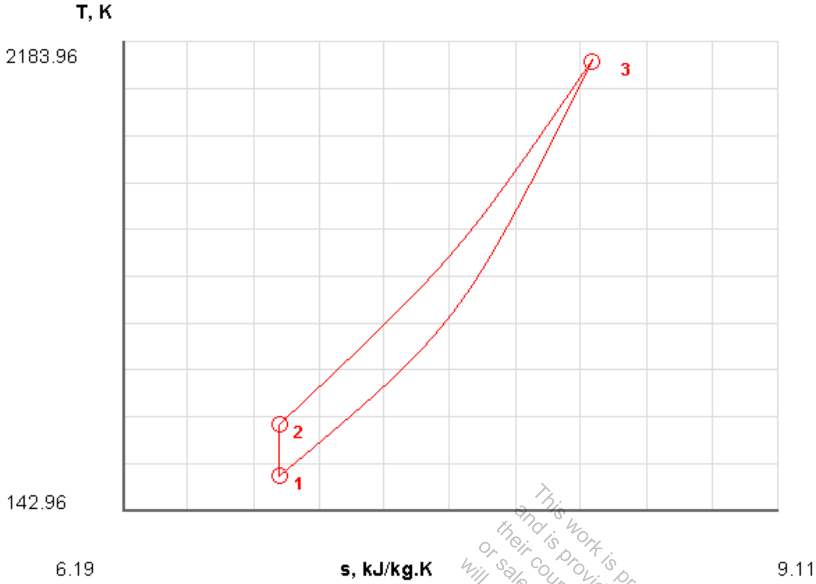
7-5-9 [OGZ] An air standard cycle is executed in a closed system with 1 kg of air, and it consists of the following three processes: (1) Isentropic compression from 100 kPa, 27°C to 700 kPa, (2) p = constant during heat addition to initial specific volume, (3) v = constant during heat rejection to initial state. Calculate (a) the maximum temperature and (b) efficiency. Show the cycle on T-s and p-v diagrams. Use the IG model.

SOLUTION



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Given:

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

State-1 (given p_1, T_1, m_1):

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287)(300)}{100} = 0.861 \ \frac{\text{m}^3}{\text{kg}};$$

$$u_1 = -84.12 \ \frac{\text{kJ}}{\text{kg}};$$

$$s_1 = 6.8934 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

State-2 (given $p_2, s_2 = s_1$):

$$v_2 = 0.213 \ \frac{\text{m}^3}{\text{kg}};$$

$$u_2 = 76.62 \ \frac{\text{kJ}}{\text{kg}};$$

State-3 (given $p_3 = p_2, v_3 = v_1$):

$$u_3 = 1475.53 \ \frac{\text{kJ}}{\text{kg}};$$

(a) $$T_3 = \frac{p_3 v_3}{R} = \frac{(700)(0.861)}{(0.287)} = 2100 \text{ K} = 1827°\text{C}$$

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An energy analysis for the heat addition and rejection processes yields:
Process 2-3:

$$\Delta E_{23} = Q_{23} - W_{\text{ext},23};$$

$$\Rightarrow Q_{23} = \Delta U_{23} + W_{B,23};$$

$$Q_{\text{in}} = Q_{23};$$

$$\Rightarrow Q_{\text{in}} = m(u_3 - u_2) + mp_2(v_3 - v_2);$$

$$\Rightarrow Q_{\text{in}} = (1)(1475.53 - 76.62) + (1)(700)(0.861 - 0.213);$$

$$\Rightarrow Q_{\text{in}} = 1852.51 \text{ kJ};$$

Process 3-1:

$$Q_{\text{out}} = -Q_{31};$$

$$\Rightarrow Q_{\text{out}} = m(u_3 - u_1);$$

$$\Rightarrow Q_{\text{out}} = (1)(1475.53 + 84.12);$$

$$\Rightarrow Q_{\text{out}} = 1559.65 \text{ kJ};$$

(b) Therefore, the efficiency can be calculated as:

$$\eta_{\text{th}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}};$$

$$\Rightarrow \eta_{\text{th}} = 1 - \frac{1559.65}{1852.51};$$

$$\Rightarrow \eta_{\text{th}} = 15.8\%$$

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TEST Solution:
Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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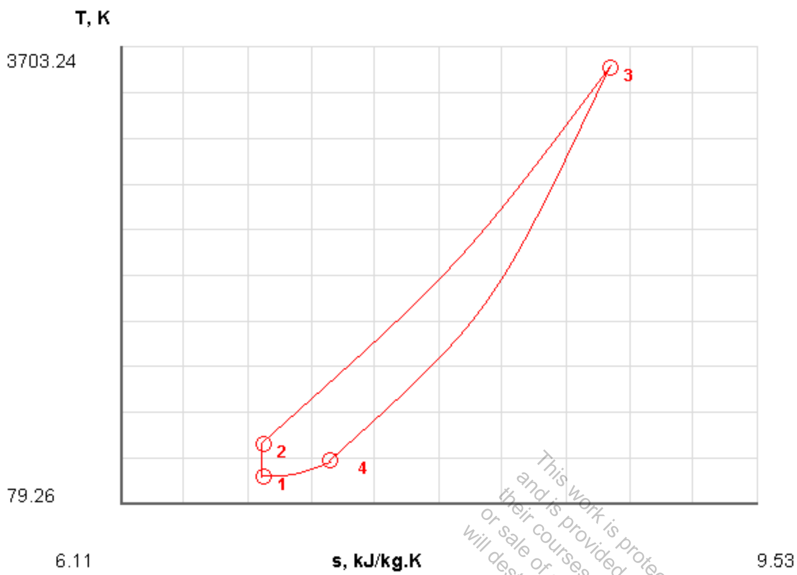
7-5-10 [OGG] An air standard cycle is executed in a closed system and is composed of the following four processes: (1) 1-2: Isentropic compression from 110 kPa and 30°C to 900 kPa, (2) 2-3: p = constant during heat addition in the amount of 3000 kJ/kg, (3) 3-4: v = constant during heat rejection to 110 kPa, (4) 4-1: p = constant during heat rejection to initial state. (a) Calculate the maximum temperature in the cycle and (b) determine the thermal efficiency (η_{th}). Use the PG model.

SOLUTION



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Given:

$$c_v = 0.717 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1):

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287)(303)}{110} = 0.79055 \ \frac{\text{m}^3}{\text{kg}};$$

State-2 (given $p_2, s_2 = s_1$):

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (303)\left(\frac{900}{110}\right)^{\frac{1.4-1}{1.4}} = 552.4 \text{ K};$$

State-3 (given $p_3 = p_2, q_{\text{in}}$):

(a) $$T_3 = T_2 + \frac{q_{\text{in}}}{c_p} = 552.4 + \frac{3000}{1.005} = 3537.5 \text{ K}$$

$$v_3 = \frac{RT_3}{p_3} = \frac{(0.287)(3537.5)}{900} = 1.128 \ \frac{\text{m}^3}{\text{kg}};$$

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State-4 (given $p_4 = p_1, v_4 = v_1$):

$$T_4 = \frac{p_4 v_4}{R} = \frac{(110)(1.128)}{(0.287)} = 432.3\text{ K};$$

An energy analysis for the heat rejection process yields:
Process 3-1:

$$q_{\text{out}} = -(q_{34} + q_{41});$$
$$\Rightarrow q_{\text{out}} = c_v(T_3 - T_4) + c_p(T_4 - T_1);$$
$$\Rightarrow q_{\text{out}} = (0.717)(3537.5 - 432.3) + (1.005)(432.3 - 303);$$
$$\Rightarrow q_{\text{out}} = 2356.4\ \frac{\text{kJ}}{\text{kg}};$$

Therefore, the net work and efficiency can be calculated as:

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}};$$
$$\Rightarrow w_{\text{net}} = 3000 - 2356.4;$$
$$\Rightarrow w_{\text{net}} = 643.6\ \frac{\text{kJ}}{\text{kg}};$$

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(b) $\eta_{\text{th}} = \dfrac{w_{\text{net}}}{q_{\text{in}}};$

$$\Rightarrow \eta_{\text{th}} = \frac{643.6}{3000};$$
$$\Rightarrow \eta_{\text{th}} = 21.4\%$$

TEST Solution:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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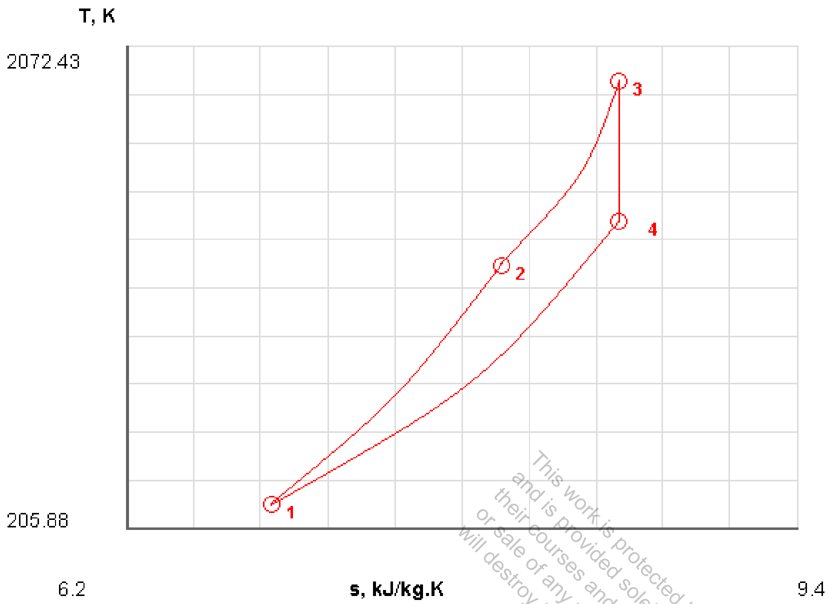
7-5-11 [OGK] An air standard cycle is executed in a closed system and is composed of the following four processes: (1) 1-2: v = constant during heat addition from 15 psia and 85°F in the amount of 320 Btu/lbm, (2) 2-3: p = constant during heat addition to 3500°R, (3) 3-4: Isentropic expansion to 15 psia, (4) 4-1: p = constant during heat rejection to initial state. (a) Calculate the amount of heat addition in the cycle and (b) determine the thermal efficiency (η_{th}). Use the IG model.

SOLUTION



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State-1 (given p_1, T_1):

$$v_1 = 13.45\ \frac{\text{ft}^3}{\text{lbm}};$$

$$u_2 = -35.41\ \frac{\text{Btu}}{\text{lbm}};$$

State-2 (given $v_2 = v_1, q_{\text{in}}$):

$$T_2 = 1753.7\text{°F};$$

$$p_2 = 60.96\ \text{psia};$$

$$u_2 = 284.59\ \frac{\text{Btu}}{\text{lbm}};$$

State-3 (given $p_3 = p_2, T_3$):

$$v_3 = 21.26\ \frac{\text{ft}^3}{\text{lbm}};$$

$$u_3 = 570.66\ \frac{\text{Btu}}{\text{lbm}};$$

State-4 (given $p_4 = p_1, s_4 = s_3$):

$$v_4 = 62.23\ \frac{\text{ft}^3}{\text{lbm}};$$

$$u_4 = 350.89\ \frac{\text{Btu}}{\text{lbm}};$$

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An energy analysis for the heat addition and heat rejection processes yield:
Process 1-3: (Note factor of 0.185 to convert $\text{psia} \times \text{ft}^3$ to Btu)

$$\Delta e_{23} = q_{23} - w_{\text{ext},23};$$
$$\Rightarrow q_{23} = \Delta u_{23} + w_{B,23};$$

(a) $q_{\text{in}} = q_{13};$

$$\Rightarrow q_{\text{in}} = q_{12} + q_{23};$$
$$\Rightarrow q_{\text{in}} = q_{12} + (u_3 - u_2) + p_2(v_3 - v_2)(0.185);$$
$$\Rightarrow q_{\text{in}} = 320 + (570.66 - 284.59) + (60.96)(21.26 - 13.45)(0.185);$$
$$\Rightarrow q_{\text{in}} = 694.14 \frac{\text{Btu}}{\text{lbm}}$$

Process 4-1: (Note factor of 0.185 to convert $\text{psia} \times \text{ft}^3$ to Btu)

$$\Delta e_{41} = q_{41} - w_{\text{ext},41};$$
$$\Rightarrow q_{41} = \Delta u_{41} + w_{B,41};$$

$$q_{\text{out}} = -q_{41};$$
$$\Rightarrow q_{\text{out}} = (u_4 - u_1) + p_4(v_4 - v_1)(0.185);$$
$$\Rightarrow q_{\text{out}} = (350.89 + 35.41) + (15)(62.23 - 13.45)(0.185);$$
$$\Rightarrow q_{\text{out}} = 521.66 \frac{\text{Btu}}{\text{lbm}};$$

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Therefore, the net work and efficiency can be calculated as:

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}};$$
$$\Rightarrow w_{\text{net}} = 694.14 - 521.66;$$
$$\Rightarrow w_{\text{net}} = 172.48 \frac{\text{Btu}}{\text{lbm}};$$

(b) $\eta_{\text{th}} = \dfrac{w_{\text{net}}}{q_{\text{in}}};$

$$\Rightarrow \eta_{\text{th}} = \frac{172.48}{694.14};$$
$$\Rightarrow \eta_{\text{th}} = 24.8\%$$

TEST Solution:
Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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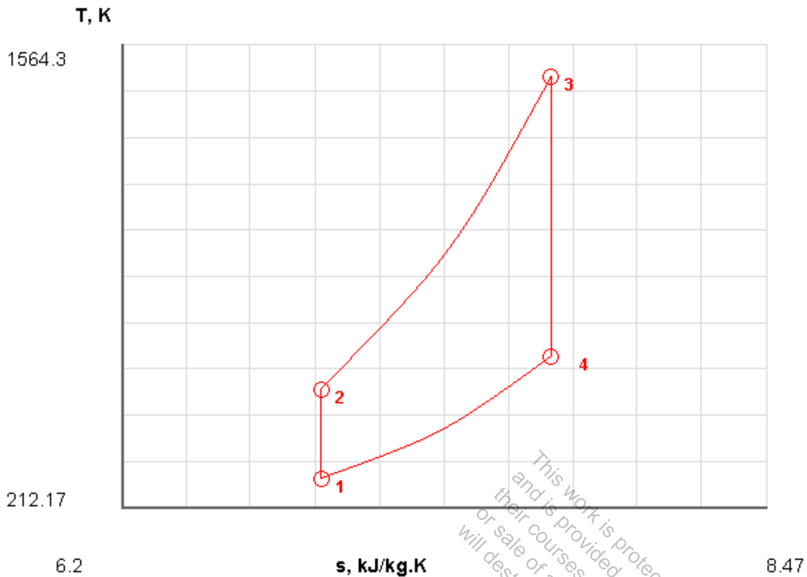
7-5-12 [OGU] An air standard cycle with a variable specific heats is executed in a closed system and is composed of the following four processes: (1) 1-2: Isentropic compression from 95 kPa and 25°C to 900 kPa, (2) 2-3: *v* = constant during heat addition to 1200°C, (3) 3-4: Isentropic expansions to 95 kPa, (4) 4-1: *p* = constant during heat rejection to initial state. (a) Calculate the net work (w_{net}) output per unit mass and (b) determine the thermal efficiency (η_{th}). Use the IG model for air.

SOLUTION



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State-1 (given p_1, T_1):

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287)(298)}{95} = 0.900 \ \frac{\text{m}^3}{\text{kg}};$$

$$u_1 = -85.55 \ \frac{\text{kJ}}{\text{kg}};$$

State-2 (given $p_2, s_2 = s_1$):

$$T_2 = 560.34 \text{ K};$$

$$v_2 = \frac{RT_2}{p_2} = \frac{(0.287)(560.34)}{900} = 0.179 \ \frac{\text{m}^3}{\text{kg}};$$

$$u_2 = 107.97 \ \frac{\text{kJ}}{\text{kg}};$$

State-3 (given $T_3, v_3 = v_2$):

$$p_3 = \frac{RT_3}{v_3} = \frac{(0.287)(1473)}{0.179} = 2361.7 \text{ kPa};$$

$$u_3 = 883.43 \ \frac{\text{kJ}}{\text{kg}};$$

State-4 (given $p_4 = p_1, s_4 = s_3$):

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$T_4 = 653.56 \text{ K};$

$$v_4 = \frac{RT_1}{p_1} = \frac{(0.287)(653.56)}{95} = 1.974 \ \frac{\text{m}^3}{\text{kg}};$$

$$u_4 = 179.80 \ \frac{\text{kJ}}{\text{kg}};$$

An energy analysis for the heat addition and rejection processes yields:
Process 2-3:

$$q_{\text{in}} = q_{23};$$
$$\Rightarrow q_{\text{in}} = u_3 - u_2;$$
$$\Rightarrow q_{\text{in}} = 883.43 - 107.97;$$
$$\Rightarrow q_{\text{in}} = 775.46 \ \frac{\text{kJ}}{\text{kg}};$$

Process 4-1:

$$\Delta e_{41} = q_{41} - w_{\text{ext},41};$$
$$\Rightarrow q_{41} = \Delta u_{41} + w_{B,41};$$

$$q_{\text{out}} = -q_{41};$$
$$\Rightarrow q_{\text{out}} = (u_4 - u_1) + p_4(v_4 - v_1);$$
$$\Rightarrow q_{\text{out}} = (179.80 + 85.55) + (95)(1.974 - 0.900);$$
$$\Rightarrow q_{\text{out}} = 367.38 \ \frac{\text{kJ}}{\text{kg}};$$

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Therefore, the net work and efficiency can be calculated as:

(a) $w_{\text{net}} = q_{\text{in}} - q_{\text{out}};$
$$\Rightarrow w_{\text{net}} = 775.46 - 367.38;$$
$$\Rightarrow w_{\text{net}} = 408.08 \ \frac{\text{kJ}}{\text{kg}}$$

(b) $\eta_{\text{th}} = \dfrac{w_{\text{net}}}{q_{\text{in}}};$
$$\Rightarrow \eta_{\text{th}} = \frac{408.08}{775.46};$$
$$\Rightarrow \eta_{\text{th}} = 52.6\%$$

TEST Solution:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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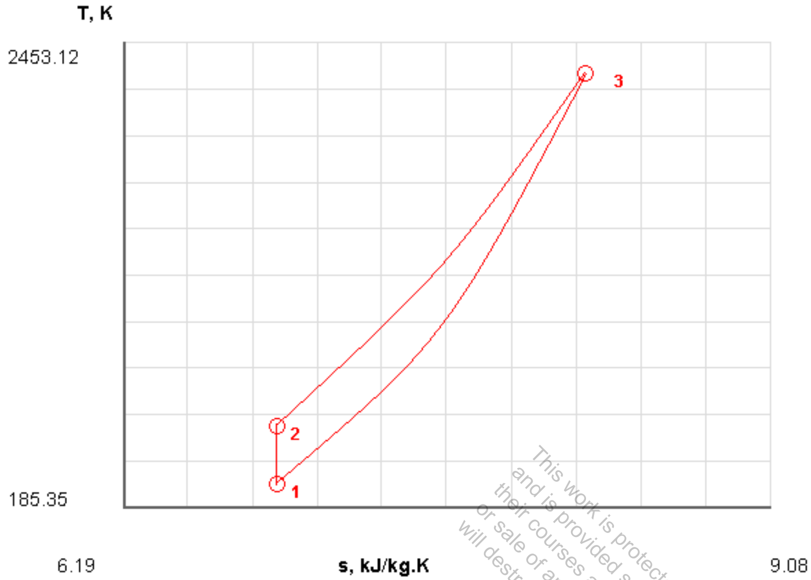
7-5-13 [OGC] An air standard cycle is executed in a closed system with 0.001 kg of air and is composed of the following three processes: (1) 1-2: Isentropic compression from 110 kPa and 30ºC to 1.1 MPa (2) 2-3: p = constant during heat addition in the amount of 1.73 kJ (3) 3-1: $p = c_1 v + c_2$ during heat rejection to initial state (c_1 and c_2 are constant) (a) Calculate the heat rejected and (b) determine the thermal efficiency (η_{th}). Use the PG model.

SOLUTION



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Given:

$$c_v = 0.717 \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1, m_1)

State-2 (given $p_2, s_2 = s_1$):

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (303)\left(\frac{1100}{110}\right)^{\frac{1.4-1}{1.4}} = 585 \text{ K};$$

State-3 (given $p_3 = p_2, Q_{\text{in}}$):

$$T_3 = T_2 + \frac{Q_{\text{in}}}{mc_p} = 585 + \frac{1.73}{(0.001)(1.005)} = 2306.4 \text{ K};$$

An energy analysis for the heat rejection process yields:

(a) $Q_{\text{out}} = -Q_{31};$

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$$\Rightarrow Q_{\text{out}} = m\left(u_3 - u_1\right);$$
$$\Rightarrow Q_{\text{out}} = mc_v\left(T_3 - T_1\right);$$
$$\Rightarrow Q_{\text{out}} = (0.001)(0.717)(2306.4 - 303);$$
$$\Rightarrow Q_{\text{out}} = 1.44 \text{ kJ}$$

(b) Therefore, the efficiency can be calculated as:

$$\eta_{\text{th}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}};$$
$$\Rightarrow \eta_{\text{th}} = 1 - \frac{1.44}{1.73};$$
$$\Rightarrow \eta_{\text{th}} = 16.8\%$$

TEST Solution:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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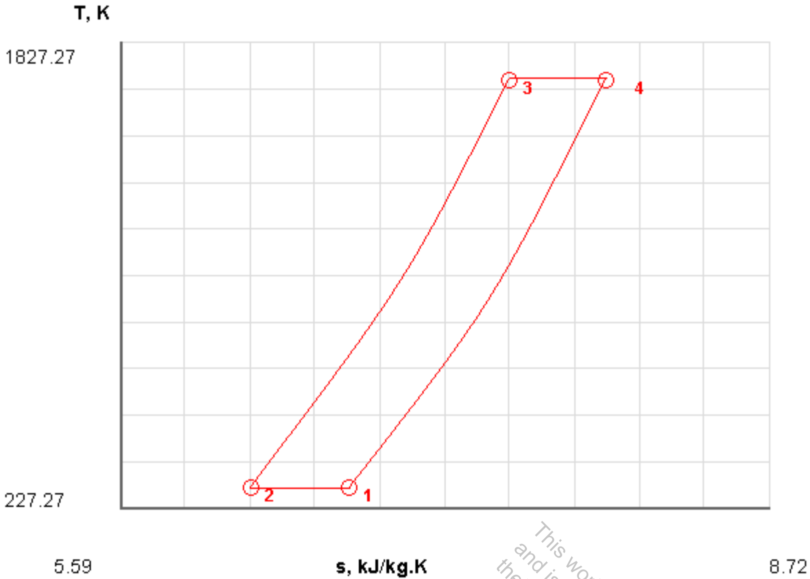
7-5-14 [OGP] An ideal Stirling cycle running on a closed system has air at 200 kPa, 300 K at the beginning of the isothermal compression process. Heat supplied from a source of 1700 K is 800 kJ/kg. Determine (a) the efficiency and (b) the net work (w_{net}) output per kg of air. Use the PG model.

SOLUTION



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Given:

$$c_v = 0.717 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1):

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287)(300)}{200} = 0.4305 \ \frac{\text{m}^3}{\text{kg}};$$

State-2 (given $T_2 = T_1, v_2 = v_3$):

$$p_2 = \frac{RT_2}{v_2} = \frac{(0.287)(300)}{0.0835} = 1031.1 \text{ kPa};$$

State-3 (given $T_3 = T_4, q_{\text{in}}$):

$$q_{34} = w_{B,34};$$

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$$\Rightarrow 800 = RT_4 \ln\frac{v_4}{v_3};$$

$$\Rightarrow v_3 = v_4 \exp\left(\frac{-w_{B,34}}{RT_4}\right);$$

$$\Rightarrow v_3 = v_4 \exp\left(\frac{-w_{B,34}}{RT_4}\right);$$

$$\Rightarrow v_3 = (0.4305)\exp\left(\frac{-800}{(0.287)(1700)}\right);$$

$$\Rightarrow v_3 = 0.0835\ \frac{\text{m}^3}{\text{kg}};$$

State-4 (given $T_4, v_4 = v_1$):

$$p_4 = \frac{RT_4}{v_4} = \frac{(0.287)(1700)}{0.4305} = 1133.33\ \text{kPa};$$

w_{12} in process 1-2 can be calculated:

$$w_{12} = q_{12} - \cancel{(e_2 - e_1)}^{0};$$

$$\Rightarrow w_{12} = w_{B,12};$$

$$\Rightarrow w_{12} = -RT_1 \ln\frac{p_2}{p_1};$$

$$\Rightarrow w_{12} = -(0.287)(300)\ln\left(\frac{200}{1031.1}\right);$$

$$\Rightarrow w_{12} = -141.2\ \frac{\text{kJ}}{\text{kg}};$$

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The net work and thermal efficiency can now be calculated:

$$w_{\text{net}} = w_{12} + w_{34};$$

$$\Rightarrow w_{\text{net}} = -141.2 + 800.0;$$

$$\Rightarrow w_{\text{net}} = 658.8\ \frac{\text{kJ}}{\text{kg}}$$

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}};$$

$$\Rightarrow \eta_{\text{th}} = \frac{658.8}{800};$$

$$\Rightarrow \eta_{\text{th}} = 82.3\%$$

TEST Solution:

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Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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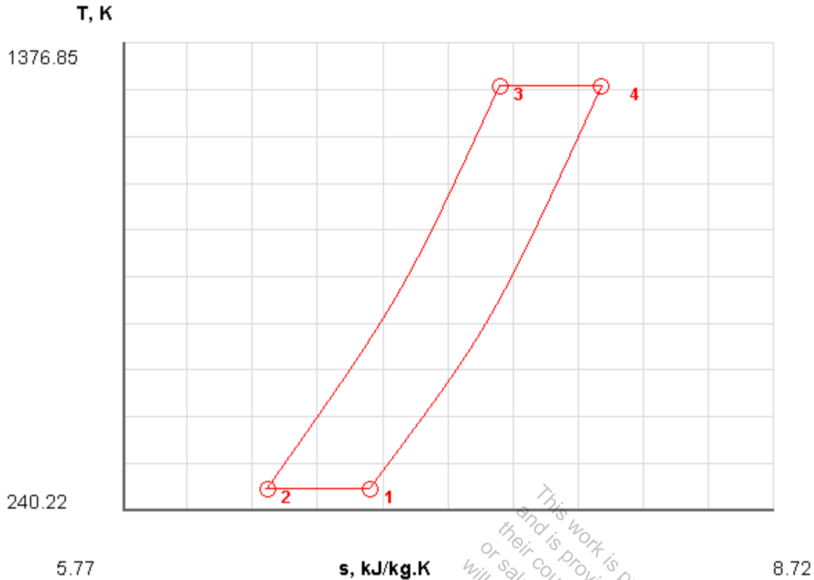
7-5-15 [OGX] Consider an ideal Stirling cycle engine in which the pressure and temperature at the beginning of the isothermal compression process are 95 kPa, 20°C, the compression ratio is 5, and the maximum temperature in the cycle is 1000°C. Determine (a) maximum pressure and (b) the thermal efficiency (η_{th}) of the cycle. Use the PG model.

SOLUTION



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Given:

$$c_v = 0.717 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1):

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287)(293)}{95} = 0.885 \ \frac{\text{m}^3}{\text{kg}};$$

State-2 (given $T_2 = T_1, r$):

$$p_2 = 5p_1 = (5)(95) = 475 \text{ kPa};$$

$$v_2 = \frac{v_1}{5} = \frac{0.885}{5} = 0.177 \ \frac{\text{m}^3}{\text{kg}};$$

State-3 (given $T_3, v_3 = v_2$):

$$p_3 = \frac{RT_3}{v_3} = \frac{(0.287)(1273)}{0.177} = 2064.1 \text{ kPa};$$

State-4 (given $T_4 = T_3, v_4 = v_1$):

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$$p_4 = \frac{RT_4}{v_4} = \frac{(0.287)(1273)}{0.885} = 412.8 \text{ kPa};$$

(a) $p = 2064.1 \text{ kPa}$

w_{12} in process 1-2 can be calculated as:

$$w_{12} = q_{12} - \cancel{(e_2 - e_1)}^{0};$$

$$w_{12} = w_{B,12};$$

$$\Rightarrow w_{12} = -RT_1 \ln \frac{p_2}{p_1};$$

$$\Rightarrow w_{12} = -(0.287)(293) \ln \left(\frac{475}{95} \right);$$

$$\Rightarrow w_{12} = -135.3 \ \frac{\text{kJ}}{\text{kg}};$$

Therefore, $q_{12} = w_{12} = -135.3 \ \frac{\text{kJ}}{\text{kg}};$

The energy equation for process 3-4 yields:

$$w_{34} = q_{34} - \cancel{(e_4 - e_3)}^{0};$$

$$w_{34} = w_{B,34} = -RT_4 \ln \frac{p_4}{p_3};$$

$$\Rightarrow w_{B,34} = -(0.287)(1273) \ln \left(\frac{412.8}{2064.1} \right);$$

$$\Rightarrow w_{B,34} = 588 \ \frac{\text{kJ}}{\text{kg}};$$

Therefore, heat added to the cycle is: $q_{34} = w_{34} = 588 \ \frac{\text{kJ}}{\text{kg}};$

The net work and thermal efficiency can now be calculated:

$$w_{\text{net}} = w_{12} + w_{34};$$

$$\Rightarrow w_{\text{net}} = -135.3 + 588;$$

$$\Rightarrow w_{\text{net}} = 452.7 \ \frac{\text{kJ}}{\text{kg}};$$

(b) $\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}};$

$$\Rightarrow \eta_{\text{th}} = \frac{452.7}{588};$$

$$\Rightarrow \eta_{\text{th}} = 77\%$$

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TEST Solution:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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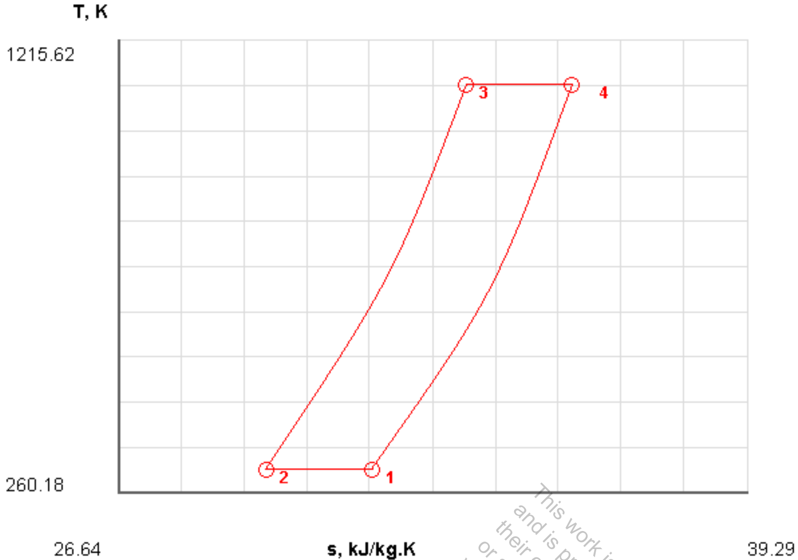
7-5-16 [OGT] An ideal Stirling engine using helium as the working fluid operates between the temperature limits of 38°C and 850°C and pressure limits of 102 kPa and 1020 kPa. Assuming the mass used in the cycle is 1 kg, determine (a) the thermal efficiency (η_{th}) of the cycle and (b) the net work (w_{net}).(c) What-if Scenario: What would the efficiency and net work be if argon were used as the working fluid?

SOLUTION



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Given:

$$c_v = 3.116 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 5.193 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 2.077 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.667;$$

State-1 (given p_1, T_1):

$$v_1 = \frac{RT_1}{p_1} = \frac{(2.077)(311)}{102} = 6.333 \ \frac{\text{m}^3}{\text{kg}};$$

State-2 (given $T_2 = T_1, v_2 = v_3$):

$$p_2 = \frac{RT_2}{v_2} = \frac{(2.077)(311)}{2.287} = 282.4 \text{ kPa};$$

State-3 (given p_3, T_3):

$$v_3 = \frac{RT_3}{p_3} = \frac{(2.077)(1123)}{1020} = 2.287 \ \frac{\text{m}^3}{\text{kg}};$$

State-4 (given $T_4 = T_3, v_4 = v_1$):

$$p_4 = \frac{RT_4}{v_4} = \frac{(2.077)(1123)}{(6.333)} = 368.3 \text{ kPa};$$

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w_{12} in process 1-2 can be calculated as:

$$w_{12} = q_{12} - m\left(\cancel{e_2 - e_1}\right)^0;$$

$$\Rightarrow w_{12} = w_{B,12};$$

$$\Rightarrow w_{12} = -RT_1 \ln \frac{p_2}{p_1};$$

$$\Rightarrow w_{12} = -(2.077)(311)\ln\left(\frac{282.4}{102}\right);$$

$$\Rightarrow w_{12} = -657.8 \ \frac{\text{kJ}}{\text{kg}};$$

The energy equation for process 3-4 yields:

$$w_{B,34} = -RT_4 \ln \frac{p_4}{p_3};$$

$$\Rightarrow w_{B,34} = -(2.077)(1123)\ln\left(\frac{368.3}{1020}\right);$$

$$\Rightarrow w_{B,34} = 2376 \ \frac{\text{kJ}}{\text{kg}};$$

Heat added to the cycle can be calculated as:

$$q_{\text{in}} = q_{23} + q_{34};$$

$$\Rightarrow q_{\text{in}} = c_v\left(T_H - T_C\right) + w_{B,34};$$

$$\Rightarrow q_{\text{in}} = (3.116)(1123 - 311) + 2376;$$

$$\Rightarrow q_{\text{in}} = 4906.2 \ \frac{\text{kJ}}{\text{kg}};$$

The net work and thermal efficiency can now be calculated:

$$w_{\text{net}} = w_{12} + w_{34};$$

$$\Rightarrow w_{\text{net}} = -657.8 + 2376;$$

$$\Rightarrow w_{\text{net}} = 1718.2 \ \frac{\text{kJ}}{\text{kg}}$$

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}};$$

$$\Rightarrow \eta_{\text{th}} = \frac{1718.2}{4906.2};$$

$$\Rightarrow \eta_{\text{th}} = 35\%$$

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TEST Solution and What-if Scenario:

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Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution and perform the what-if study. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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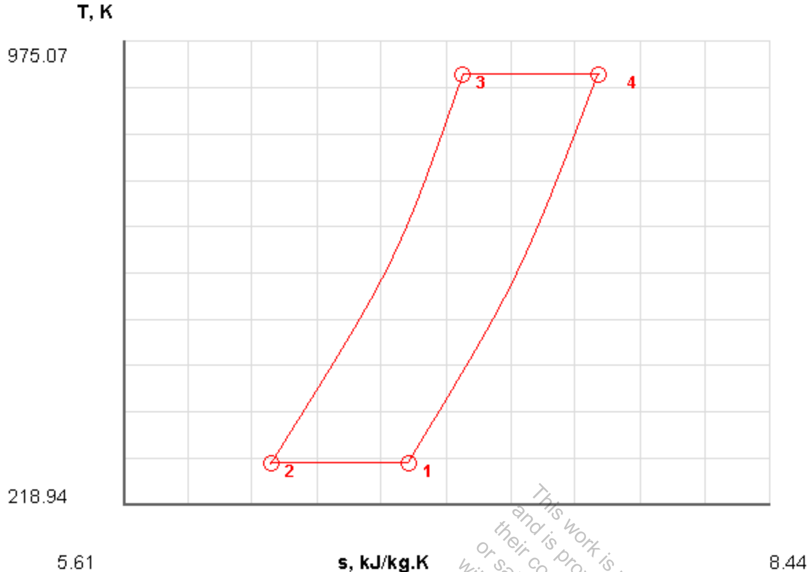
7-5-17 [OGV] Consider an ideal Stirling cycle engine in which the pressure, temperature and volume at the beginning of the isothermal compression process are 100 kPa, 15°C and 0.03 m^3, the compression ratio is 8, and the maximum temperature in the cycle is 650°C. Determine (a) the net work (W_{net}), (b) the thermal efficiency (η_{th}) and (c) the mean effective pressure. Use the PG model.

SOLUTION



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Given:

$$c_v = 0.717 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given $p_1, T_1, \cancel{V}_1$):

$$m_1 = \frac{\cancel{V}_1 p_1}{RT_1} = \frac{(0.03)(100)}{(0.287)(288)} = 0.0363 \text{ kg};$$

State-2 (given $T_2 = T_1, r$):

$$p_2 = 8p_1 = (8)(100) = 800 \text{ kPa};$$

$$\cancel{V}_2 = \frac{\cancel{V}_1}{8} = \frac{0.03}{8} = 0.00375 \text{ m}^3;$$

State-3 (given $T_3, \cancel{V}_3 = \cancel{V}_2$):

$$p_3 = \frac{mRT_3}{\cancel{V}_3} = \frac{(0.0363)(0.287)(923)}{(0.00375)} = 2564.2 \text{ kPa};$$

State-4 (given $T_4 = T_3, \cancel{V}_4 = \cancel{V}_1$):

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$$p_4 = \frac{mRT_4}{\cancel{V}_4} = \frac{(0.0363)(0.287)(923)}{(0.03)} = 320.5 \text{ kPa;}$$

W_{12} in process 1-2 can be calculated as:

$$W_{12} = Q_{12} - m\cancel{(e_2 - e_1)}^{0};$$

$$\Rightarrow W_{12} = W_{B,12};$$

$$\Rightarrow W_{12} = -mRT_1 \ln\frac{p_2}{p_1};$$

$$\Rightarrow W_{12} = -(0.0363)(0.287)(288)\ln\left(\frac{800}{100}\right);$$

$$\Rightarrow W_{12} = -6.24 \text{ kJ;}$$

The energy equation for process 3-4 yields:

$$W_{B,34} = -mRT_4 \ln\frac{p_4}{p_3};$$

$$\Rightarrow W_{B,34} = -(0.0363)(0.287)(923)\ln\left(\frac{320.5}{2564.2}\right);$$

$$\Rightarrow W_{B,34} = 20 \text{ kJ;}$$

Heat added to the cycle can be calculated as:

$$Q_{\text{in}} = Q_{23} + Q_{34};$$

$$\Rightarrow Q_{\text{in}} = mc_v(T_H - T_C) + W_{B,34};$$

$$\Rightarrow Q_{\text{in}} = (0.0363)(0.717)(923 - 288) + 20;$$

$$\Rightarrow Q_{\text{in}} = 36.53 \text{ kJ;}$$

The net work and thermal efficiency can now be calculated:

(a) $W_{\text{net}} = W_{12} + W_{34};$

$$\Rightarrow W_{\text{net}} = -6.24 + 20;$$

$$\Rightarrow W_{\text{net}} = 13.76 \text{ kJ}$$

(b) $\eta_{\text{th}} = \dfrac{W_{\text{net}}}{Q_{\text{in}}};$

$$\Rightarrow \eta_{\text{th}} = \frac{13.76}{36.53};$$

$$\Rightarrow \eta_{\text{th}} = 37.7\%$$

(c) $\text{MEP} = \dfrac{W_{\text{net}}}{\cancel{V}_d};$

$$\Rightarrow \text{MEP} = \frac{13.76}{0.03 - 0.00375};$$

$$\Rightarrow \text{MEP} = 524 \text{ kPa}$$

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TEST Solution:

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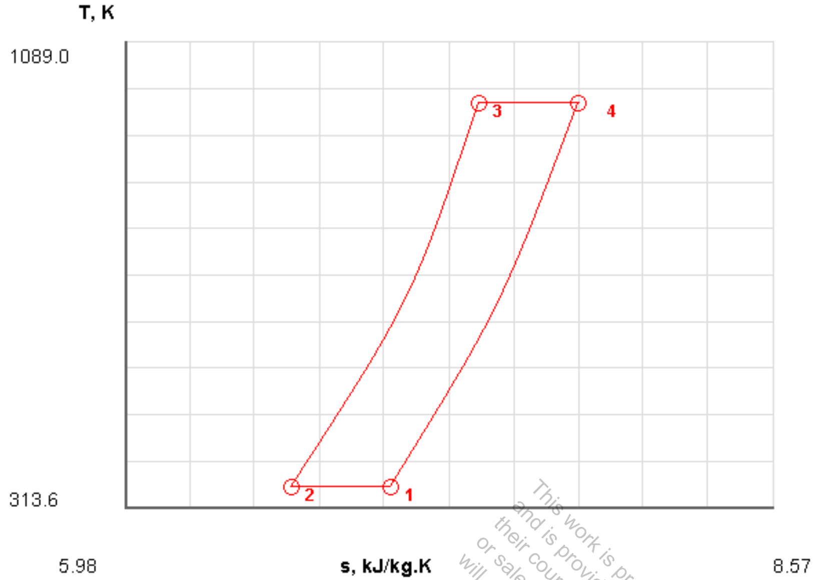
7-5-18 [OGQ] Fifty grams of air undergoes a Stirling cycle with a compression ratio of 4. At the beginning of the isothermal process, the pressure and volume are 100 kPa and 0.05 m^3, respectively. The temperature during the isothermal expansion is 990 K. Determine (a) the net work (W_{net}) output per kg and (b) the mean effective pressure. Use the PG model.

SOLUTION



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Given:

$c_v = 0.717 \dfrac{\text{kJ}}{\text{kg}\cdot\text{K}}$;

$c_p = 1.005 \dfrac{\text{kJ}}{\text{kg}\cdot\text{K}}$;

$R = 0.287 \dfrac{\text{kJ}}{\text{kg}\cdot\text{K}}$;

$k = 1.4$;

State-1 (given $p_1, \mathcal{V}_1\ m$):

$$T_1 = \frac{\mathcal{V}_1 p_1}{mR} = \frac{(0.05)(100)}{(0.05)(0.287)} = 348.4 \text{ K};$$

State-2 (given $T_2 = T_1, r$):

$$p_2 = 4p_1 = (4)(100) = 400 \text{ kPa};$$

$$\mathcal{V}_2 = \frac{\mathcal{V}_1}{4} = \frac{0.05}{4} = 0.0125 \text{ m}^3;$$

State-3 (given $T_3, \mathcal{V}_3 = \mathcal{V}_2$):

$$p_3 = \frac{mRT_3}{\mathcal{V}_3} = \frac{(0.05)(0.287)(990)}{(0.0125)} = 1136.5 \text{ kPa};$$

State-4 (given $T_4 = T_3, \mathcal{V}_4 = \mathcal{V}_1$):

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$$p_4 = \frac{mRT_4}{V_4} = \frac{(0.05)(0.287)(990)}{(0.05)} = 284.1 \text{ kPa};$$

W_{12} in process 1-2 can be calculated as:

$$W_{12} = Q_{12} - m\cancel{(e_2 - e_1)}^0;$$

$$\Rightarrow W_{12} = W_{B,12};$$

$$\Rightarrow W_{12} = -mRT_1 \ln\frac{p_2}{p_1};$$

$$\Rightarrow W_{12} = -(0.05)(0.287)(348.4)\ln\left(\frac{400}{100}\right);$$

$$\Rightarrow W_{12} = -6.93 \text{ kJ};$$

The energy equation for process 3-4 yields:

$$W_{B,34} = -mRT_4 \ln\frac{p_4}{p_3};$$

$$\Rightarrow W_{B,34} = -(0.05)(0.287)(990)\ln\left(\frac{284.1}{1136.5}\right);$$

$$\Rightarrow W_{B,34} = 19.7 \text{ kJ};$$

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The net work per unit mass and MEP can now be calculated:

(a) $$w_{\text{net}} = \frac{W_{12} + W_{34}}{m};$$

$$\Rightarrow W_{\text{net}} = \frac{-6.93 + 19.7}{0.05};$$

$$\Rightarrow W_{\text{net}} = 255.4 \ \frac{\text{kJ}}{\text{kg}}$$

(b) $$\text{MEP} = \frac{W_{\text{net}}}{V_d};$$

$$\Rightarrow \text{MEP} = \frac{12.77}{0.05 - 0.0125};$$

$$\Rightarrow \text{MEP} = 340.5 \text{ kPa} = 3.4 \text{ bar}$$

TEST Solution:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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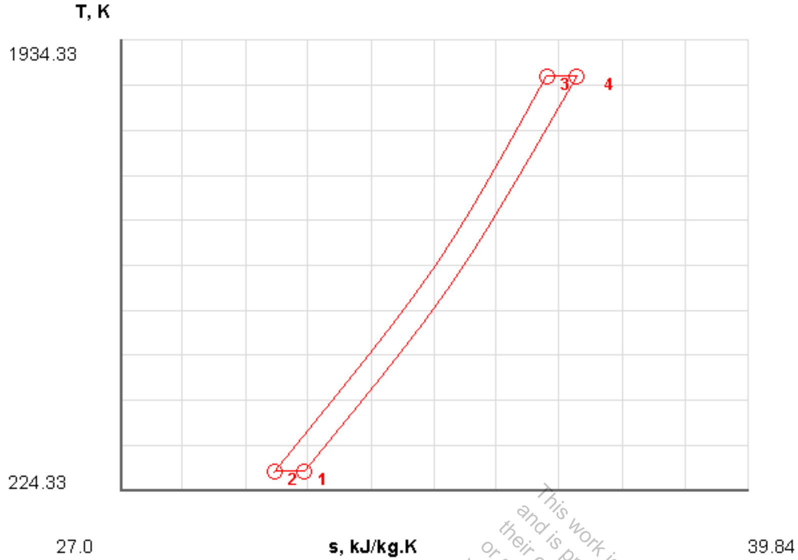
7-5-19 [OGY] An ideal Stirling engine using helium as the working fluid operates between the temperature limits of 300 K and 1800 K and pressure limits of 150 kPa and 1200 kPa. Assuming the mass used in the cycle is 1.5 kg, determine (a) the thermal efficiency (η_{th}) of the cycle, (b) the amount of heat transfer in the regenerator, and (c) the work output per cycle.

SOLUTION



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Given:

$$c_v = 3.116\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 5.193\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 2.077\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.667;$$

State-1 (given p_1, T_1, m_1):

$$\cancel{V}_1 = \frac{mRT_1}{p_1} = \frac{(1.5)(2.077)(300)}{150} = 6.23\ \text{m}^3;$$

State-2 (given $T_2 = T_1, \cancel{V}_2 = \cancel{V}_3$):

$$p_2 = \frac{mRT_2}{\cancel{V}_2} = \frac{(1.5)(2.077)(300)}{4.67} = 200.1\ \text{kPa};$$

State-3 (given p_3, T_3):

$$\cancel{V}_3 = \frac{mRT_3}{p_3} = \frac{(1.5)(2.077)(1800)}{1200} = 4.67\ \text{m}^3;$$

State-4 (given $T_4 = T_3, \cancel{V}_4 = \cancel{V}_1$):

$$p_4 = \frac{mRT_4}{\cancel{V}_4} = \frac{(1.5)(2.077)(1800)}{6.23} = 900.1\ \text{kPa};$$

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W_{12} in process 1-2 can be calculated as:

$$W_{12} = Q_{12} - m\cancel{(e_2 - e_1)}^{0};$$

$$\Rightarrow W_{12} = W_{B,12};$$

$$\Rightarrow W_{12} = -mRT_1 \ln \frac{p_2}{p_1};$$

$$\Rightarrow W_{12} = -(1.5)(2.077)(300)\ln\left(\frac{200.1}{150}\right);$$

$$\Rightarrow W_{12} = -269.3 \text{ kJ};$$

The energy equation for process 3-4 yields:

$$W_{B,34} = -mRT_4 \ln \frac{p_4}{p_3};$$

$$\Rightarrow W_{B,34} = -(1.5)(2.077)(1800)\ln\left(\frac{900.1}{1200}\right);$$

$$\Rightarrow W_{B,34} = 1612.7 \text{ kJ};$$

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Heat added to the cycle from the regenerator can be calculated as:

$$Q_{\text{reg}} = mc_v(T_H - T_C);$$

$$\Rightarrow Q_{\text{reg}} = (1.5)(3.116)(1800 - 300);$$

$$\Rightarrow Q_{\text{reg}} = 7011 \text{ kJ}$$

The work output and thermal efficiency can now be calculated:

$$W_{\text{out}} = W_{34} = 1612.7 \text{ kJ}$$

$$W_{\text{net}} = W_{12} + W_{34};$$

$$\Rightarrow W_{\text{net}} = -269.3 + 1612.7;$$

$$\Rightarrow W_{\text{net}} = 1343.4 \text{ kJ};$$

$$Q_{\text{in}} = Q_{\text{reg}} + W_{34};$$

$$\Rightarrow Q_{\text{in}} = 7011 + 1612.7;$$

$$\Rightarrow Q_{\text{in}} = 8623.7 \text{ kJ};$$

$$\eta_{\text{th}} = \frac{W_{\text{net}}}{Q_{\text{in}}};$$

$$\Rightarrow \eta_{\text{th}} = \frac{1343.4}{8623.7} = 15.6\%$$

TEST Solution:

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Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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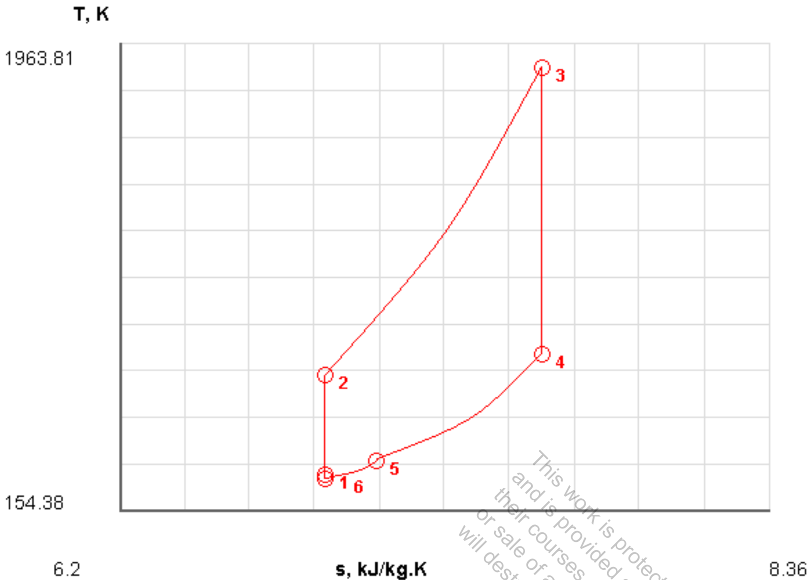
7-5-20 [OGF] At the beginning of the compression process of a Miller cycle with a compression ratio of 8 air is at 25ºC, 101 kPa. The maximum temperature during the cycle is 1600ºC. The minimum pressure during the cycle is 80 kPa. Determine (a) the net work (w_{net}) output per unit mass, (b) the thermal efficiency (η_{th}), and (c) the mean effective pressure. Use the PG model for air. (d) What-if Scenario: What would the answers be for an Otto cycle operating under the same conditions?

SOLUTION



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Given:

$$c_v = 0.717 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_p = 1.005 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$R = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$k = 1.4;$$

State-1 (given p_1, T_1):

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287)(298)}{101} = 0.847 \ \frac{\text{m}^3}{\text{kg}};$$

State-2 (given $s_2 = s_1, r$):

$$T_2 = T_1 r^{k-1} = (298)(8)^{1.4-1} = 684.6 \text{ K};$$

State-3 (given $T_3, v_3 = v_2$):

$$p_3 = \frac{RT_3}{v_3} = \frac{(0.287)(1873)}{0.106} = 5071.2 \text{ kPa};$$

State-4 (given $s_4 = s_3, v_4 = v_6$):

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$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{k-1} = (1873)\left(\frac{0.106}{1}\right)^{1.4-1} = 763.2\text{ K};$$

$$p_4 = p_3\left(\frac{v_3}{v_4}\right)^{k} = (5071.2)\left(\frac{0.106}{1}\right)^{1.4} = 219\text{ kPa};$$

State-5 (given $p_5 = p_1, v_5 = v_4$):

$$T_5 = \frac{p_5 v_5}{R} = \frac{(101)(1)}{(0.287)} = 351.9\text{ K};$$

State-6 (given $p_6, s_6 = s_1$):

$$v_6 = v_1\left(\frac{p_1}{p_6}\right)^{\frac{1}{k}} = (0.847)\left(\frac{101}{80}\right)^{\frac{1}{1.4}} = 1\ \frac{\text{m}^3}{\text{kg}};$$

An energy analysis for the heat addition and rejection processes yields:
Process 2-3:

$$q_{\text{in}} = q_{23};$$
$$\Rightarrow q_{\text{in}} = c_v\left(T_3 - T_2\right);$$
$$\Rightarrow q_{\text{in}} = (0.717)(1873 - 684.6);$$
$$\Rightarrow q_{\text{in}} = 852.1\ \frac{\text{kJ}}{\text{kg}};$$

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Process 4-1:

$$q_{\text{out}} = -\left(q_{45} + q_{51}\right);$$
$$\Rightarrow q_{\text{out}} = c_v\left(T_4 - T_5\right) + c_p\left(T_5 - T_1\right);$$
$$\Rightarrow q_{\text{out}} = (0.717)(763.2 - 351.9) + (1.005)(351.9 - 298);$$
$$\Rightarrow q_{\text{out}} = 349.1\ \frac{\text{kJ}}{\text{kg}};$$

Therefore, the net work per unit mass, efficiency and MEP are calculated as:

(a) $w_{\text{net}} = q_{\text{in}} - q_{\text{out}};$

$$\Rightarrow w_{\text{net}} = 852.1 - 349.1;$$
$$\Rightarrow w_{\text{net}} = 503\ \frac{\text{kJ}}{\text{kg}}$$

(b) $\eta_{\text{th}} = \dfrac{w_{\text{net}}}{q_{\text{in}}};$

$$\Rightarrow \eta_{\text{th}} = \frac{503}{852.1};$$
$$\Rightarrow \eta_{\text{th}} = 59\%$$

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(c) $\text{MEP} = \dfrac{w_{\text{net}}}{v_6 - v_2};$

$$\Rightarrow \text{MEP} = \frac{503}{1 - 0.106};$$

$$\Rightarrow \text{MEP} = 562.6 \text{ kPa}$$

TEST Solution and What-if Scenario:

Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution and perform the what-if study. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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