ENGR 251: Thermodynamics

Tutorial 8: Chapter 9

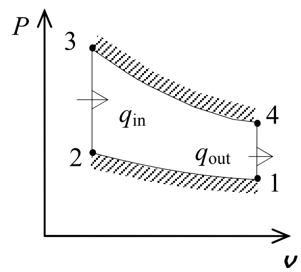
9-33C The thermal efficiency will be the highest for argon because it has the highest specific heat ratio, $k = 1.667$.

9-35 An ideal Otto cycle is considered. The thermal efficiency and the rate of heat input 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-2a).

Analysis The definition of cycle thermal efficiency reduces to



$$\eta_{th} = 1 - \frac{1}{r^{k-1}} = 1 - \frac{1}{12^{1.4-1}} = \mathbf{0.630}$$

The rate of heat addition is then

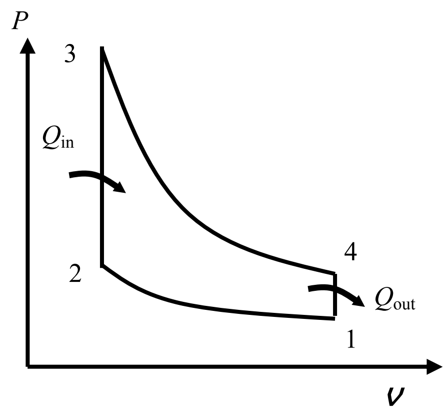
$$\dot{Q}_{in} = \frac{\dot{W}_{net}}{\eta_{th}} = \frac{200 \text{ kW}}{0.630} = \mathbf{318\ kW}$$

9-42 A gasoline engine operates on an Otto cycle. The compression and expansion processes are modeled as polytropic. The temperature at the end of expansion process, the net work output, the thermal efficiency, the mean effective pressure, the engine speed for a given net power, and the specific fuel consumption 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 850 K are $c_p = 1.110$ kJ/kg·K, $c_v = 0.823$ kJ/kg·K, $R = 0.287$ kJ/kg·K, and $k = 1.349$ (Table A-2b).

Analysis (*a*) Process 1-2: polytropic compression



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{n-1} = (333\text{ K})(10)^{1.3\text{-}1} = 664.4\text{ K}$$

$$P_2 = P_1\left(\frac{v_1}{v_2}\right)^{n} = (100\text{ kPa})(10)^{1.3} = 1995\text{ kPa}$$

Process 2-3: constant volume heat addition

$$T_3 = T_2\left(\frac{P_3}{P_2}\right) = (664.4\text{ K})\left(\frac{8000\text{ kPa}}{1995\text{ kPa}}\right) = 2664\text{ K}$$

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$$
$$= (0.823\text{ kJ/kg}\cdot\text{K})(2664 - 664.4)\text{K} = 1646\text{ kJ/kg}$$

Process 3-4: polytropic expansion.

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{n-1} = (2664\text{ K})\left(\frac{1}{10}\right)^{1.3\text{-}1} = \mathbf{1335\text{ K}}$$

$$P_4 = P_3\left(\frac{v_2}{v_1}\right)^{n} = (8000\text{ kPa})\left(\frac{1}{10}\right)^{1.3} = 400.9\text{ kPa}$$

Process 4-1: constant voume heat rejection.

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1) = (0.823\text{ kJ/kg}\cdot\text{K})(1335 - 333)\text{K} = 824.8\text{ kJ/kg}$$

(*b*) The net work output and the thermal efficiency are

$$w_{net,out} = q_{in} - q_{out} = 1646 - 824.8 = \mathbf{820.9\text{ kJ/kg}}$$

$$\eta_{th} = \frac{w_{net,out}}{q_{in}} = \frac{820.9\text{ kJ/kg}}{1646\text{ kJ/kg}} = \mathbf{0.499}$$

(*c*) The mean effective pressure is determined as follows

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(333\text{ K})}{100\text{ kPa}} = 0.9557\text{ m}^3/\text{kg} = v_{max}$$

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

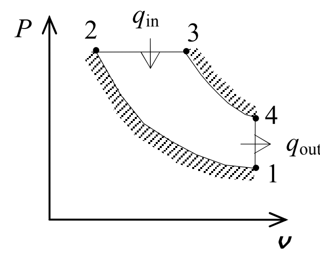
$$\text{MEP} = \frac{w_{net,out}}{v_1 - v_2} = \frac{w_{net,out}}{v_1(1 - 1/r)} = \frac{820.9\text{ kJ/kg}}{(0.9557\text{ m}^3/\text{kg})(1 - 1/10)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{954.3\text{ kPa}}$$

9-57 An ideal diesel cycle has a a cutoff ratio of 1.2. The power produced is 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-2a).

Analysis The specific volume of the air at the start of the compression is



$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(288\ \text{K})}{95\ \text{kPa}} = 0.8701\ \text{m}^3/\text{kg}$$

The total air mass taken by all 8 cylinders when they are charged is

$$m = N_{\text{cyl}}\frac{\Delta V}{v_1} = N_{\text{cyl}}\frac{\pi B^2 S/4}{v_1} = (8)\frac{\pi(0.10\ \text{m})^2(0.12\ \text{m})/4}{0.8701\ \text{m}^3/\text{kg}} = 0.008665\ \text{kg}$$

The rate at which air is processed by the engine is determined from

$$\dot{m} = \frac{m\dot{n}}{N_{\text{rev}}} = \frac{(0.008665\ \text{kg/cycle})(1600/60\ \text{rev/s})}{2\ \text{rev/cycle}} = 0.1155\ \text{kg/s}$$

since there are two revolutions per cycle in a four-stroke engine. The compression ratio is

$$r = \frac{1}{0.05} = 20$$

At the end of the compression, the air temperature is

$$T_2 = T_1 r^{k-1} = (288\ \text{K})(20)^{1.4-1} = 954.6\ \text{K}$$

Application of the first law and work integral to the constant pressure heat addition gives

$$q_{\text{in}} = c_p(T_3 - T_2) = (1.005\ \text{kJ/kg}\cdot\text{K})(2273 - 954.6)\text{K} = 1325\ \text{kJ/kg}$$

while the thermal efficiency is

$$\eta_{\text{th}} = 1 - \frac{1}{r^{k-1}}\frac{r_c^k - 1}{k(r_c - 1)} = 1 - \frac{1}{20^{1.4-1}}\frac{1.2^{1.4} - 1}{1.4(1.2 - 1)} = 0.6867$$

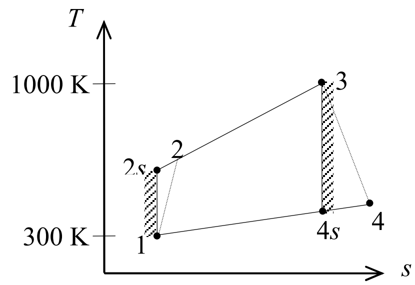
The power produced by this engine is then

$$\begin{aligned}\dot{W}_{\text{net}} &= \dot{m}w_{\text{net}} = \dot{m}\eta_{\text{th}}q_{\text{in}} \\ &= (0.1155\ \text{kg/s})(0.6867)(1325\ \text{kJ/kg}) \\ &= \mathbf{105.1\ kW}\end{aligned}$$

9-98 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,

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

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

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

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

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

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

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

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

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

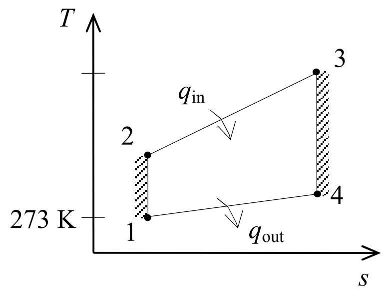
9-103 An aircraft engine operates as a simple ideal Brayton cycle with air as the working fluid. The pressure ratio and the rate of heat input are given. The net power and the thermal efficiency are to be determined.

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

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

Analysis For the isentropic compression process,

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



The heat addition is

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

Applying the first law to the heat addition process,

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

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

The temperature at the exit of the turbine is

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

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

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

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

The net power produced by the engine is then

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

Finally the thermal efficiency is

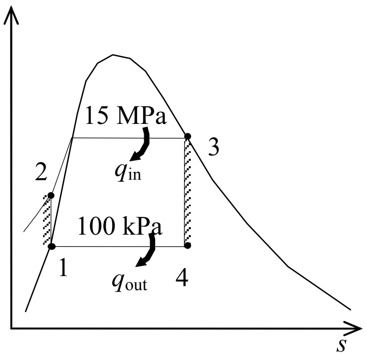
$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{241.2\text{ kW}}{500\text{ kW}} = \mathbf{0.482}$$

10-19 A simple ideal Rankine cycle with water as the working fluid operates between the specified pressure limits. The power produced by the turbine, the heat added in the boiler, and the thermal efficiency of the cycle are to be determined.

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

Analysis From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f@\,100\,\text{kPa}} = 417.51\ \text{kJ/kg}$$
$$\boldsymbol{v}_1 = \boldsymbol{v}_{f@\,100\,\text{kPa}} = 0.001043\ \text{m}^3/\text{kg}$$



$$\begin{aligned} w_{\text{p,in}} &= \boldsymbol{v}_1(P_2 - P_1) \\ &= (0.001043\ \text{m}^3/\text{kg})(15{,}000 - 100)\text{kPa}\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= 15.54\ \text{kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{\text{p,in}} = 417.51 + 15.54 = 433.05\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 15{,}000\ \text{kPa} \\ x_3 = 1 \end{array}\right\} \begin{array}{l} h_3 = 2610.8\ \text{kJ/kg} \\ s_3 = 5.3108\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 100\ \text{kPa} \\ s_4 = s_3 \end{array}\right\} \begin{array}{l} x_4 = \dfrac{s_4 - s_f}{s_{fg}} = \dfrac{5.3108 - 1.3028}{6.0562} = 0.6618 \\ h_4 = h_f + x_4 h_{fg} = 417.51 + (0.6618)(2257.5) = 1911.5\ \text{kJ/kg} \end{array}$$

Thus,

$$w_{\text{T,out}} = h_3 - h_4 = 2610.8 - 1911.5 = \mathbf{699.3\ kJ/kg}$$
$$q_{\text{in}} = h_3 - h_2 = 2610.8 - 433.05 = \mathbf{2177.8\ kJ/kg}$$
$$q_{\text{out}} = h_4 - h_1 = 1911.5 - 417.51 = 1494.0\ \text{kJ/kg}$$

The thermal efficiency of the cycle is

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1494.0}{2177.8} = \mathbf{0.314}$$

10-25 A steam power plant operates on a simple ideal Rankine cycle between the specified pressure limits. The thermal efficiency of the cycle, the mass flow rate of the steam, and the temperature rise of the cooling water are to be determined.

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

Analysis (*a*) From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f@\,10\text{ kPa}} = 191.81\text{ kJ/kg}$$

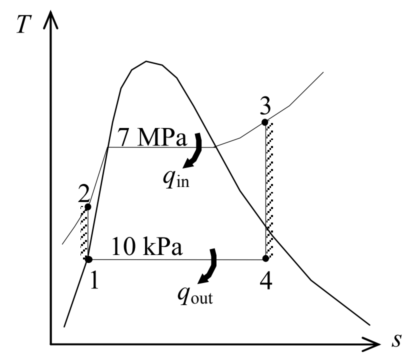
$$\boldsymbol{v}_1 = \boldsymbol{v}_{f@\,10\text{ kPa}} = 0.00101\text{ m}^3\text{/kg}$$

$$w_{p,\text{in}} = \boldsymbol{v}_1(P_2 - P_1)$$

$$= (0.00101\text{ m}^3\text{/kg})(7{,}000 - 10\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$

$$= 7.06\text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,\text{in}} = 191.81 + 7.06 = 198.87\text{ kJ/kg}$$



$$\left.\begin{array}{l} P_3 = 7\text{ MPa} \\ T_3 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3411.4\text{ kJ/kg} \\ s_3 = 6.8000\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 10\text{ kPa} \\ s_4 = s_3 \end{array}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.8000 - 0.6492}{7.4996} = 0.8201$$

$$h_4 = h_f + x_4 h_{fg} = 191.81 + (0.8201)(2392.1) = 2153.6\text{ kJ/kg}$$

Thus,

$$q_{\text{in}} = h_3 - h_2 = 3411.4 - 198.87 = 3212.5\text{ kJ/kg}$$

$$q_{\text{out}} = h_4 - h_1 = 2153.6 - 191.81 = 1961.8\text{ kJ/kg}$$

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 3212.5 - 1961.8 = 1250.7\text{ kJ/kg}$$

and

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1250.7\text{ kJ/kg}}{3212.5\text{ kJ/kg}} = \mathbf{38.9\%}$$

(*b*) $$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{45{,}000\text{ kJ/s}}{1250.7\text{ kJ/kg}} = \mathbf{36.0\text{ kg/s}}$$

(*c*) The rate of heat rejection to the cooling water and its temperature rise are

$$\dot{Q}_{\text{out}} = \dot{m}q_{\text{out}} = (35.98\text{ kg/s})(1961.8\text{ kJ/kg}) = 70{,}586\text{ kJ/s}$$

$$\Delta T_{\text{cooling water}} = \frac{\dot{Q}_{\text{out}}}{(\dot{m}c)_{\text{cooling water}}} = \frac{70{,}586\text{ kJ/s}}{(2000\text{ kg/s})(4.18\text{ kJ/kg}\cdot°\text{C})} = \mathbf{8.4°C}$$