CARNOT CYCLE

10–1C Why is excessive moisture in steam undesirable in steam turbines? What is the highest moisture content allowed?

10–2C Why is the Carnot cycle not a realistic model for steam power plants?

10-1C Because excessive moisture in steam causes erosion on the turbine blades. The highest moisture content allowed is about 10%.

10-2C The Carnot cycle is not a realistic model for steam power plants because (1) limiting the heat transfer processes to two-phase systems to maintain isothermal conditions severely limits the maximum temperature that can be used in the cycle, (2) the turbine will have to handle steam with a high moisture content which causes erosion, and (3) it is not practical to design a compressor that will handle two phases.

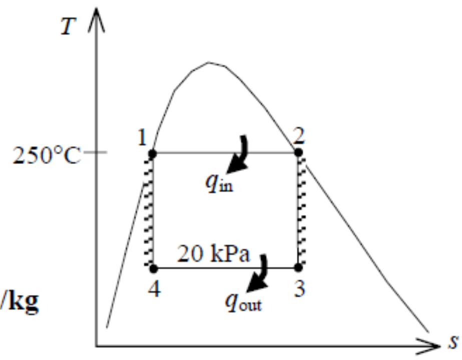
10–4 A steady-flow Carnot cycle uses water as the working fluid. Water changes from saturated liquid to saturated vapor as heat is transferred to it from a source at 250°C. Heat rejection takes place at a pressure of 20 kPa. Show the cycle on a *T-s* diagram relative to the saturation lines, and determine (*a*) the thermal efficiency, (*b*) the amount of heat rejected, in kJ/kg, and (*c*) the net work output.

10-4 A steady-flow Carnot engine with water as the working fluid operates at specified conditions. The thermal efficiency, the amount of heat rejected, and the net work output are to be determined.

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

Analysis (*a*) Noting that T_H = 250°C = 523 K and $T_L = T_{sat\ @\ 20\ kPa}$ = 60.06°C = 333.1 K, the thermal efficiency becomes

$$\eta_{th,C} = 1 - \frac{T_L}{T_H} = 1 - \frac{333.1\text{ K}}{523\text{ K}} = 0.3632 = \mathbf{36.3\%}$$



(*b*) The heat supplied during this cycle is simply the enthalpy of vaporization ,

$$q_{in} = h_{fg@\ 250°C} = 1715.3\text{ kJ/kg}$$

Thus,

$$q_{out} = q_L = \frac{T_L}{T_H} q_{in} = \left(\frac{333.1\text{ K}}{523\text{ K}}\right)(1715.3\text{ kJ/kg}) = \mathbf{1092.3\ kJ/kg}$$

(*c*) The net work output of this cycle is

$$w_{net} = \eta_{th} q_{in} = (0.3632)(1715.3\text{ kJ/kg}) = \mathbf{623.0\ kJ/kg}$$

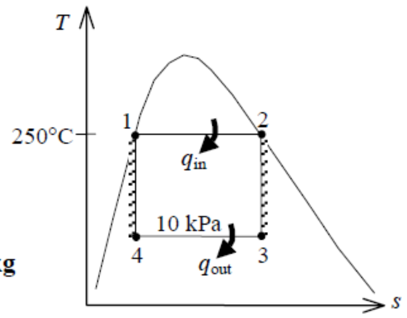
10–5 Repeat Prob. 10–4 for a heat rejection pressure of 10 kPa.

10-5 A steady-flow Carnot engine with water as the working fluid operates at specified conditions. The thermal efficiency, the amount of heat rejected, and the net work output are to be determined.

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

Analysis (*a*) Noting that T_H = 250°C = 523 K and $T_L = T_{sat\ @\ 10\ kPa}$ = 45.81°C = 318.8 K, the thermal efficiency becomes

$$\eta_{th,C} = 1 - \frac{T_L}{T_H} = 1 - \frac{318.8\text{ K}}{523\text{ K}} = \mathbf{39.04\%}$$



(*b*) The heat supplied during this cycle is simply the enthalpy of vaporization ,

$$q_{in} = h_{fg@\ 250°C} = 1715.3\text{ kJ/kg}$$

Thus,

$$q_{out} = q_L = \frac{T_L}{T_H} q_{in} = \left(\frac{318.8\text{ K}}{523\text{ K}}\right)(1715.3\text{ kJ/kg}) = \mathbf{1045.6\ kJ/kg}$$

(*c*) The net work output of this cycle is

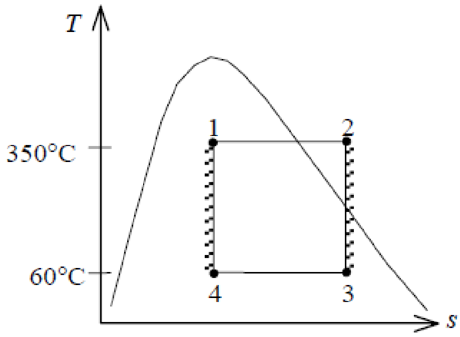
$$w_{net} = \eta_{th} q_{in} = (0.3904)(1715.3\text{ kJ/kg}) = \mathbf{669.7\ kJ/kg}$$

10-6 A steady-flow Carnot engine with water as the working fluid operates at specified conditions. The thermal efficiency, the pressure at the turbine inlet, and the net work output are to be determined.

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

Analysis (*a*) The thermal efficiency is determined from

$$\eta_{th,C} = 1 - \frac{T_L}{T_H} = 1 - \frac{60 + 273\text{ K}}{350 + 273\text{ K}} = \mathbf{46.5\%}$$



(*b*) Note that

$$s_2 = s_3 = s_f + x_3 s_{fg}$$
$$= 0.8313 + 0.891 \times 7.0769 = 7.1368\text{ kJ/kg·K}$$

Thus ,

$$\left.\begin{aligned} T_2 &= 350°C \\ s_2 &= 7.1368\text{ kJ/kg}\cdot\text{K} \end{aligned}\right\} P_2 \cong \mathbf{1.40\ MPa}\ \text{(Table A-6)}$$

(*c*) The net work can be determined by calculating the enclosed area on the *T*-*s* diagram,

$$s_4 = s_f + x_4 s_{fg} = 0.8313 + (0.1)(7.0769) = 1.5390\text{ kJ/kg}\cdot\text{K}$$

Thus,

$$w_{net} = \text{Area} = (T_H - T_L)(s_3 - s_4) = (350 - 60)(7.1368 - 1.5390) = \mathbf{1623\ kJ/kg}$$

SIMPLE RANKINE CYCLE

10–7C What four processes make up the simple ideal Rankine cycle?

10–8C Consider a simple ideal Rankine cycle with fixed turbine inlet conditions. What is the effect of lowering the condenser pressure on

Pump work input:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Turbine work output:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Heat supplied:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Heat rejected:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Cycle efficiency:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Moisture content at turbine exit:	(a) increases, (b) decreases, (c) remains the same

10–9C Consider a simple ideal Rankine cycle with fixed turbine inlet temperature and condenser pressure. What is the effect of increasing the boiler pressure on

Pump work input:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Turbine work output:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Heat supplied:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Heat rejected:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Cycle efficiency:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Moisture content at turbine exit:	(*a*) increases, (*b*) decreases, (*c*) remains the same

10–10C Consider a simple ideal Rankine cycle with fixed boiler and condenser pressures. What is the effect of superheating the steam to a higher temperature on

Pump work input:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Turbine work output:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Heat supplied:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Heat rejected:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Cycle efficiency:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Moisture content at turbine exit:	(*a*) increases, (*b*) decreases, (*c*) remains the same

10–11C How do actual vapor power cycles differ from idealized ones?

10–12C Compare the pressures at the inlet and the exit of the boiler for (*a*) actual and (*b*) ideal cycles.

10–13C The entropy of steam increases in actual steam turbines as a result of irreversibilities. In an effort to control entropy increase, it is proposed to cool the steam in the turbine by running cooling water around the turbine casing. It is argued that this will reduce the entropy and the enthalpy of the steam at the turbine exit and thus increase the work output. How would you evaluate this proposal?

10–14C Is it possible to maintain a pressure of 10 kPa in a condenser that is being cooled by river water entering at 20°C?

10-7C The four processes that make up the simple ideal cycle are (1) Isentropic compression in a pump, (2) P = constant heat addition in a boiler, (3) Isentropic expansion in a turbine, and (4) P = constant heat rejection in a condenser.

10-8C Heat rejected decreases; everything else increases.

10-9C Heat rejected decreases; everything else increases.

10-10C The pump work remains the same, the moisture content decreases, everything else increases.

10-11C The actual vapor power cycles differ from the idealized ones in that the actual cycles involve friction and pressure drops in various components and the piping, and heat loss to the surrounding medium from these components and piping.

10-12C The boiler exit pressure will be (a) lower than the boiler inlet pressure in actual cycles, and (b) the same as the boiler inlet pressure in ideal cycles.

10-13C We would reject this proposal because $w_{turb} = h_1 - h_2 - q_{out}$, and any heat loss from the steam will adversely affect the turbine work output.

10-14C Yes, because the saturation temperature of steam at 10 kPa is 45.81°C, which is much higher than the temperature of the cooling water.

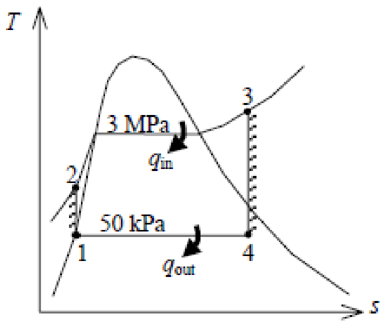
10–15 A steam power plant operates on a simple ideal Rankine cycle between the pressure limits of 3 MPa and 50 kPa. The temperature of the steam at the turbine inlet is 300°C, and the mass flow rate of steam through the cycle is 35 kg/s. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the thermal efficiency of the cycle and (*b*) the net power output of the power plant.

10-15 A steam power plant operates on a simple ideal Rankine cycle between the specified pressure limits. The thermal efficiency of the cycle and the net power output of the plant 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),

$$h_1 = h_{f@\,50\text{ kPa}} = 340.54\text{ kJ/kg}$$
$$v_1 = v_{f@\,50\text{ kPa}} = 0.001030\text{ m}^3\text{/kg}$$



$$w_{p,\text{in}} = v_1(P_2 - P_1) = (0.001030\text{ m}^3\text{/kg})(3000-50)\text{kPa}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 3.04\text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,\text{in}} = 340.54 + 3.04 = 343.58\text{ kJ/kg}$$

$$\left.\begin{aligned} P_3 &= 3\text{ MPa} \\ T_3 &= 300\,°\text{C} \end{aligned}\right\} \begin{aligned} h_3 &= 2994.3\text{ kJ/kg} \\ s_3 &= 6.5412\text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_4 &= 50\text{ kPa} \\ s_4 &= s_3 \end{aligned}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.5412 - 1.0912}{6.5019} = 0.8382$$

$$h_4 = h_f + x_4 h_{fg} = 340.54 + (0.8382)(2304.7) = 2272.3\text{ kJ/kg}$$

Thus,

$$q_{\text{in}} = h_3 - h_2 = 2994.3 - 343.58 = 2650.7\text{ kJ/kg}$$
$$q_{\text{out}} = h_4 - h_1 = 2272.3 - 340.54 = 1931.8\text{ kJ/kg}$$
$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 2650.7 - 1931.8 = 718.9\text{ kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1931.8}{2650.7} = \mathbf{27.1\%}$$

(*b*) $$\dot{W}_{\text{net}} = \dot{m} w_{\text{net}} = (35\text{ kg/s})(718.9\text{ kJ/kg}) = \mathbf{25.2\text{ MW}}$$

10–16 Consider a 210-MW steam power plant that operates on a simple ideal Rankine cycle. Steam enters the turbine at 10 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the quality of the steam at the turbine exit, (*b*) the thermal efficiency of the cycle, and (*c*) the mass flow rate of the steam. *Answers:* (*a*) 0.793, (*b*) 40.2 percent, (*c*) 165 kg/s

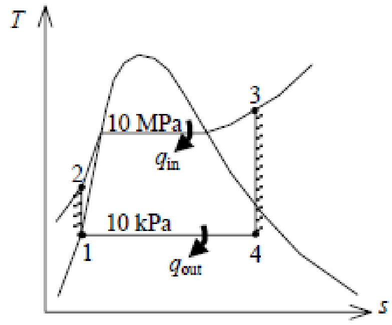
10-16 A steam power plant that operates on a simple ideal Rankine cycle is considered. The quality of the steam at the turbine exit, the thermal efficiency of the cycle, and the mass flow rate of the steam are to be determined.

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),

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

$$v_1 = v_{f\,@\,10\text{ kPa}} = 0.00101\text{ m}^3\text{/kg}$$



$$\begin{aligned} w_{p,\text{in}} &= v_1(P_2 - P_1) \\ &= \left(0.00101\text{ m}^3\text{/kg}\right)\left(10{,}000 - 10\text{ kPa}\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 10.09\text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{p,\text{in}} = 191.81 + 10.09 = 201.90\text{ kJ/kg}$$

$$\left.\begin{aligned} P_3 &= 10\text{ MPa} \\ T_3 &= 500\text{ °C} \end{aligned}\right\} \begin{aligned} h_3 &= 3375.1\text{ kJ/kg} \\ s_3 &= 6.5995\text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_4 &= 10\text{ kPa} \\ s_4 &= s_3 \end{aligned}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.5995 - 0.6492}{7.4996} = \mathbf{0.7934}$$

$$h_4 = h_f + x_4 h_{fg} = 191.81 + (0.7934)(2392.1) = 2089.7\text{ kJ/kg}$$

(*b*)

$$q_{\text{in}} = h_3 - h_2 = 3375.1 - 201.90 = 3173.2\text{ kJ/kg}$$

$$q_{\text{out}} = h_4 - h_1 = 2089.7 - 191.81 = 1897.9\text{ kJ/kg}$$

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 3173.2 - 1897.9 = 1275.4\text{ kJ/kg}$$

and

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1275.4\text{ kJ/kg}}{3173.2\text{ kJ/kg}} = \mathbf{40.2\%}$$

(*c*)

$$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{210{,}000\text{ kJ/s}}{1275.4\text{ kJ/kg}} = \mathbf{164.7\text{ kg/s}}$$

10–17 Repeat Prob. 10–16 assuming an isentropic efficiency of 85 percent for both the turbine and the pump. *Answers:* (*a*) 0.874, (*b*) 34.1 percent, (*c*) 194 kg/s

10-17 A steam power plant that operates on a simple nonideal Rankine cycle is considered. The quality of the steam at the turbine exit, the thermal efficiency of the cycle, and the mass flow rate of the steam are to be determined.

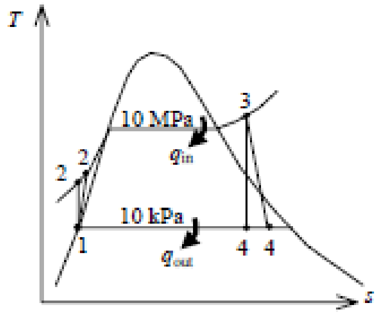
Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

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

$$h_1 = h_{f@10\text{ kPa}} = 191.81\text{ kJ/kg}$$
$$v_1 = v_{f@10\text{ kPa}} = 0.00101\text{ m}^3/\text{kg}$$

$$w_{p,\text{in}} = v_1(P_2 - P_1)/\eta_p = \left(0.00101\text{ m}^3/\text{kg}\right)\left(10{,}000 - 10\text{ kPa}\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)/(0.85) = 11.87\text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,\text{in}} = 191.81 + 11.87 = 203.68\text{ kJ/kg}$$



$$\left.\begin{array}{l} P_3 = 10\text{ MPa} \\ T_3 = 500\,^\circ\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3375.1\text{ kJ/kg} \\ s_3 = 6.5995\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_{4s} = 10\text{ kPa} \\ s_{4s} = s_3 \end{array}\right\} x_{4s} = \frac{s_{4s} - s_f}{s_{fg}} = \frac{6.5995 - 0.6492}{7.4996} = \mathbf{0.7934}$$

$$h_{4s} = h_f + x_4 h_{fg} = 191.81 + (0.7934)(2392.1) = 2089.7\text{ kJ/kg}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} \longrightarrow h_4 = h_3 - \eta_T(h_3 - h_{4s}) = 3375.1 - (0.85)(3375.1 - 2089.7) = 2282.5\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 10\text{ kPa} \\ h_4 = 2282.5\text{ kJ/kg} \end{array}\right\} x_4 = \frac{h_4 - h_f}{h_{fg}} = \frac{2282.5 - 191.81}{2392.1} = \mathbf{0.874}$$

(*b*)

$$q_{\text{in}} = h_3 - h_2 = 3375.1 - 203.68 = 3171.4\text{ kJ/kg}$$
$$q_{\text{out}} = h_4 - h_1 = 2282.5 - 191.81 = 2090.7\text{ kJ/kg}$$
$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 3171.4 - 2090.7 = 1080.7\text{ kJ/kg}$$

and

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1080.7\text{ kJ/kg}}{3171.5\text{ kJ/kg}} = \mathbf{34.1\%}$$

(*c*)

$$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{210{,}000\text{ kJ/s}}{1080.7\text{ kJ/kg}} = \mathbf{194.3\text{ kg/s}}$$

10–20 Consider a coal-fired steam power plant that produces 300 MW of electric power. The power plant operates on a simple ideal Rankine cycle with turbine inlet conditions of 5 MPa and 450°C and a condenser pressure of 25 kPa. The coal has a heating value (energy released when the fuel is burned) of 29,300 kJ/kg. Assuming that 75 percent of this energy is transferred to the steam in the boiler and that the electric generator has an efficiency of 96 percent, determine (*a*) the overall plant efficiency (the ratio of net electric power output to the energy input as fuel) and (*b*) the required rate of coal supply. *Answers:* (*a*) 24.5 percent, (*b*) 150 t/h

10-20 A 300-MW coal-fired steam power plant operates on a simple ideal Rankine cycle between the specified pressure limits. The overall plant efficiency and the required rate of the coal supply are to be determined.

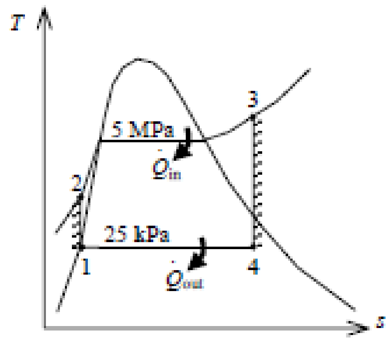
Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

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

$$h_1 = h_{f@25\text{ kPa}} = 271.96 \text{ kJ/kg}$$
$$v_1 = v_{f@25\text{ kPa}} = 0.001020 \text{ m}^3\text{/kg}$$

$$w_{p,\text{in}} = v_1(P_2 - P_1) = (0.00102 \text{ m}^3\text{/kg})(5000 - 25 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 5.07 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,\text{in}} = 271.96 + 5.07 = 277.03 \text{ kJ/kg}$$



$$\left.\begin{array}{l} P_3 = 5 \text{ MPa} \\ T_3 = 450°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3317.2 \text{ kJ/kg} \\ s_3 = 6.8210 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 25 \text{ kPa} \\ s_4 = s_3 \end{array}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.8210 - 0.8932}{6.9370} = 0.8545$$
$$h_4 = h_f + x_4 h_{fg} = 271.96 + (0.8545)(2345.5) = 2276.2 \text{ kJ/kg}$$

The thermal efficiency is determined from

$$q_{\text{in}} = h_3 - h_2 = 3317.2 - 277.03 = 3040.2 \text{ kJ/kg}$$
$$q_{\text{out}} = h_4 - h_1 = 2276.2 - 271.96 = 2004.2 \text{ kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{2004.2}{3040.2} = 0.3407$$

Thus,

$$\eta_{\text{overall}} = \eta_{\text{th}} \times \eta_{\text{comb}} \times \eta_{\text{gen}} = (0.3407)(0.75)(0.96) = \mathbf{24.5\%}$$

(*b*) Then the required rate of coal supply becomes

$$\dot{Q}_{\text{in}} = \frac{\dot{W}_{\text{net}}}{\eta_{\text{overall}}} = \frac{300{,}000 \text{ kJ/s}}{0.2453} = 1{,}222{,}992 \text{ kJ/s}$$

and

$$\dot{m}_{\text{coal}} = \frac{\dot{Q}_{\text{in}}}{C_{\text{coal}}} = \frac{1{,}222{,}992 \text{ kJ/s}}{29{,}300 \text{ kJ/kg}}\left(\frac{1 \text{ ton}}{1000 \text{ kg}}\right) = 0.04174 \text{ tons/s} = \mathbf{150.3 \text{ tons/h}}$$

10–21 Consider a solar-pond power plant that operates on a simple ideal Rankine cycle with refrigerant-134a as the working fluid. The refrigerant enters the turbine as a saturated vapor at 1.4 MPa and leaves at 0.7 MPa. The mass flow rate of the refrigerant is 3 kg/s. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the thermal efficiency of the cycle and (*b*) the power output of this plant.

10-21 A solar-pond power plant that operates on a simple ideal Rankine cycle with refrigerant-134a as the working fluid is considered. The thermal efficiency of the cycle and the power output of the plant are to be determined.

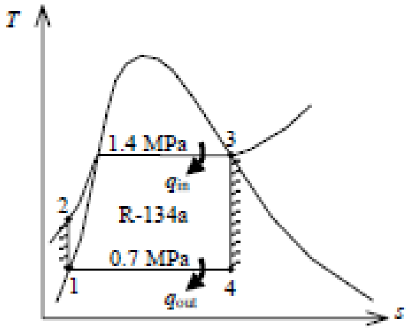
Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis (*a*) From the refrigerant tables (Tables A-11, A-12, and A-13),

$$h_1 = h_{f@\,0.7\text{ MPa}} = 88.82 \text{ kJ/kg}$$

$$v_1 = v_{f@\,0.7\text{ MPa}} = 0.0008331 \text{ m}^3\text{/kg}$$

$$w_{p,\text{in}} = v_1(P_2 - P_1) = (0.0008331 \text{ m}^3\text{/kg})(1400 - 700 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 0.58 \text{ kJ/kg}$$



$$h_2 = h_1 + w_{p,\text{in}} = 88.82 + 0.58 = 89.40 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 1.4 \text{ MPa} \\ \text{sat.vapor} \end{array}\right\} \begin{array}{l} h_3 = h_{g@\,1.4\text{ MPa}} = 276.12 \text{ kJ/kg} \\ s_3 = s_{g@\,1.4\text{ MPa}} = 0.9105 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 0.7 \text{ MPa} \\ s_4 = s_3 \end{array}\right\} \begin{array}{l} x_4 = \dfrac{s_4 - s_f}{s_{fg}} = \dfrac{0.9105 - 0.33230}{0.58763} = 0.9839 \\ h_4 = h_f + x_4 h_{fg} = 88.82 + (0.9839)(176.21) = 262.20 \text{ kJ/kg} \end{array}$$

Thus ,

$$q_{\text{in}} = h_3 - h_2 = 276.12 - 89.40 = 186.72 \text{ kJ/kg}$$

$$q_{\text{out}} = h_4 - h_1 = 262.20 - 88.82 = 173.38 \text{ kJ/kg}$$

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 186.72 - 173.38 = 13.34 \text{ kJ/kg}$$

and

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{13.34 \text{ kJ/kg}}{186.72 \text{ kJ/kg}} = \mathbf{7.1\%}$$

(*b*) $$\dot{W}_{\text{net}} = \dot{m} w_{\text{net}} = (3 \text{ kg/s})(13.34 \text{ kJ/kg}) = \mathbf{40.02 \text{ kW}}$$

10–22 Consider a steam power plant that operates on a simple ideal Rankine cycle and has a net power output of 45 MW. Steam enters the turbine at 7 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa by running cooling water from a lake through the tubes of the condenser at a rate of 2000 kg/s. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the thermal efficiency of the cycle, (*b*) the mass flow rate of the steam, and (*c*) the temperature rise of the cooling water. *Answers:* (*a*) 38.9 percent, (*b*) 36 kg/s, (*c*) 8.4°C

10-22 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),

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

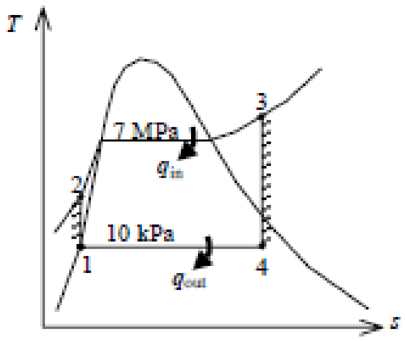
$$v_1 = v_{f@10\text{ kPa}} = 0.00101 \text{ m}^3\text{/kg}$$

$$w_{p,\text{in}} = v_1(P_2 - P_1)$$

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

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

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



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

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

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

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

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

(*b*)

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

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

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

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

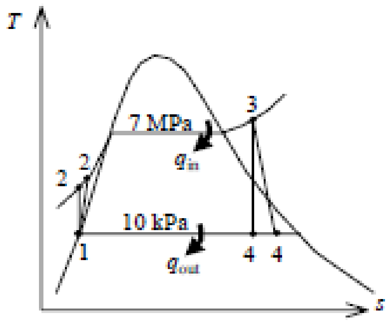
10–23 Repeat Prob. 10–22 assuming an isentropic efficiency of 87 percent for both the turbine and the pump. *Answers:* (*a*) 33.8 percent, (*b*) 41.4 kg/s, (*c*) 10.5°C

10-23 A steam power plant operates on a simple nonideal 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),

$$h_1 = h_{f @ 10\text{ kPa}} = 191.81\text{ kJ/kg}$$
$$v_1 = v_{f @ 10\text{ kPa}} = 0.00101\text{ m}^3\text{/kg}$$
$$w_{p,\text{in}} = v_1(P_2 - P_1)/\eta_p = \left(0.00101\text{ m}^3\text{/kg}\right)\left(7{,}000 - 10\text{ kPa}\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)/(0.87) = 8.11\text{ kJ/kg}$$
$$h_2 = h_1 + w_{p,\text{in}} = 191.81 + 8.11 = 199.92\text{ kJ/kg}$$



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

$$\left.\begin{array}{l} P_4 = 10\text{ kPa} \\ s_4 = s_3 \end{array}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.8000 - 0.6492}{7.4996} = 0.8201$$
$$h_{4s} = h_f + x_4 h_{fg} = 191.81 + (0.820)(2392.1) = 2153.6\text{ kJ/kg}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} \longrightarrow h_4 = h_3 - \eta_T(h_3 - h_{4s}) = 3411.4 - (0.87)(3411.4 - 2153.6) = 2317.1\text{ kJ/kg}$$

Thus,
$$q_{\text{in}} = h_3 - h_2 = 3411.4 - 199.92 = 3211.5\text{ kJ/kg}$$
$$q_{\text{out}} = h_4 - h_1 = 2317.1 - 191.81 = 2125.3\text{ kJ/kg}$$
$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 3211.5 - 2125.3 = 1086.2\text{ kJ/kg}$$

and
$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1086.2\text{ kJ/kg}}{3211.5\text{ kJ/kg}} = \mathbf{33.8\%}$$

(*b*)
$$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{45{,}000\text{ kJ/s}}{1086.2\text{ kJ/kg}} = \mathbf{41.43\text{ kg/s}}$$

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

$$\dot{Q}_{\text{out}} = \dot{m}q_{\text{out}} = (41.43\text{ kg/s})(2125.3\text{ kJ/kg}) = 88{,}051\text{ kJ/s}$$

$$\Delta T_{\text{coolingwater}} = \frac{\dot{Q}_{\text{out}}}{(\dot{m}c)_{\text{coolingwater}}} = \frac{88{,}051\text{ kJ/s}}{(2000\text{ kg/s})(4.18\text{ kJ/kg}\cdot°\text{C})} = \mathbf{10.5°C}$$

10–24 The net work output and the thermal efficiency for the Carnot and the simple ideal Rankine cycles with steam as the working fluid are to be calculated and compared. Steam enters the turbine in both cases at 10 MPa as a saturated vapor, and the condenser pressure is 20 kPa. In the Rankine cycle, the condenser exit state is saturated liquid and in the Carnot cycle, the boiler inlet state is saturated liquid. Draw the *T-s* diagrams for both cycles.

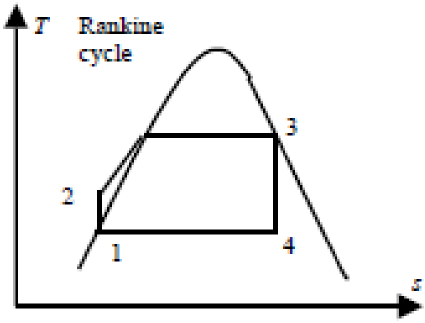
10-24 The net work outputs and the thermal efficiencies for a Carnot cycle and a simple ideal Rankine cycle are to be determined.

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

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

$$h_1 = h_{f @ 20\text{ kPa}} = 251.42\text{ kJ/kg}$$

$$v_1 = v_{f @ 20\text{ kPa}} = 0.001017\text{ m}^3\text{/kg}$$



$$\begin{aligned} w_{p,\text{in}} &= v_1(P_2 - P_1) \\ &= \left(0.001017\text{ m}^3\text{/kg}\right)\left(10{,}000 - 20\right)\text{kPa}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 10.15\text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{p,\text{in}} = 251.42 + 10.15 = 261.57\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 10\text{ MPa} \\ x_3 = 1 \end{array}\right\} \begin{array}{l} h_3 = 2725.5\text{ kJ/kg} \\ s_3 = 5.6159\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 20\text{ kPa} \\ s_4 = s_3 \end{array}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{5.6159 - 0.8320}{7.0752} = 0.6761$$

$$\begin{aligned} h_4 &= h_f + x_4 h_{fg} = 251.42 + (0.6761)(2357.5) \\ &= 1845.3\text{ kJ/kg} \end{aligned}$$

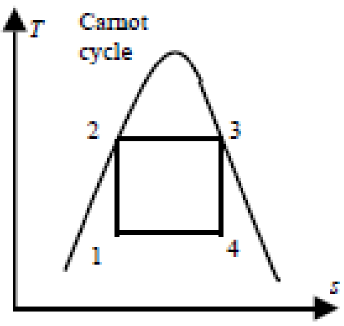
$$q_{\text{in}} = h_3 - h_2 = 2725.5 - 261.57 = 2463.9\text{ kJ/kg}$$

$$q_{\text{out}} = h_4 - h_1 = 1845.3 - 251.42 = 1594.0\text{ kJ/kg}$$

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 2463.9 - 1594.0 = \mathbf{869.9\text{ kJ/kg}}$$

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1594.0}{2463.9} = \mathbf{0.353}$$

(*b*) Carnot Cycle analysis:



$$\left.\begin{array}{l} P_3 = 10\text{ MPa} \\ x_3 = 1 \end{array}\right\} \begin{array}{l} h_3 = 2725.5\text{ kJ/kg} \\ T_3 = 311.0\,^\circ\text{C} \end{array}$$

$$\left.\begin{array}{l} T_2 = T_3 = 311.0\,^\circ\text{C} \\ x_2 = 0 \end{array}\right\} \begin{array}{l} h_2 = 1407.8\text{ kJ/kg} \\ s_2 = 3.3603\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_1 = 20\text{ kPa} \\ s_1 = s_2 \end{array}\right\} \begin{array}{l} x_1 = \dfrac{s_1 - s_f}{s_{fg}} = \dfrac{3.3603 - 0.8320}{7.0752} = 0.3574 \\ h_1 = h_f + x_1 h_{fg} \end{array}$$

$$= 251.42 + (0.3574)(2357.5) = 1093.9\text{ kJ/kg}$$

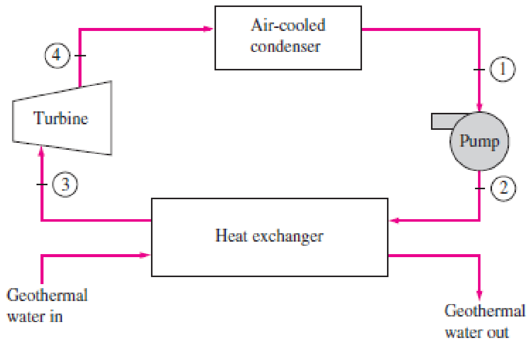
$$q_{\text{in}} = h_3 - h_2 = 2725.5 - 1407.8 = 1317.7\text{ kJ/kg}$$

$$q_{\text{out}} = h_4 - h_1 = 1845.3 - 1093.9 = 751.4\text{ kJ/kg}$$

$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 1317.7 - 752.3 = \mathbf{565.4\text{ kJ/kg}}$$

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{751.4}{1317.7} = \mathbf{0.430}$$

10–25 A binary geothermal power plant uses geothermal water at 160°C as the heat source. The cycle operates on the simple Rankine cycle with isobutane as the working fluid. Heat is transferred to the cycle by a heat exchanger in which geothermal liquid water enters at 160°C at a rate of 555.9 kg/s and leaves at 90°C. Isobutane enters the turbine at 3.25 MPa and 147°C at a rate of 305.6 kg/s, and leaves at 79.5°C and 410 kPa. Isobutane is condensed in an air-cooled condenser and pumped to the heat exchanger pressure. Assuming the pump to have an isentropic efficiency of 90 percent, determine (*a*) the isentropic efficiency of the turbine, (*b*) the net power output of the plant, and (*c*) the thermal efficiency of the cycle.

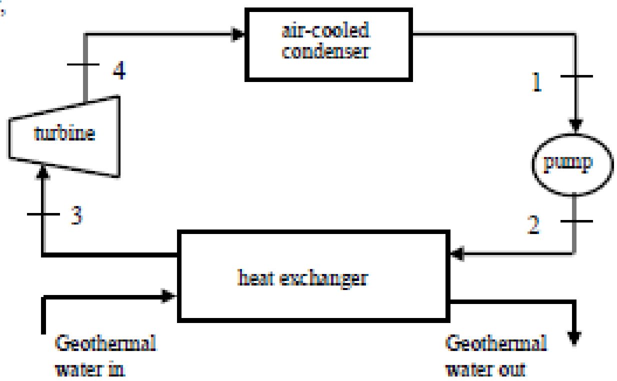


10-25 A binary geothermal power operates on the simple Rankine cycle with isobutane as the working fluid. The isentropic efficiency of the turbine, the net power output, and the thermal efficiency of the cycle are to be determined.

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

Properties The specific heat of geothermal water is taken to be 4.18 kJ/kg.°C.

Analysis (*a*) We need properties of isobutane, which are not available in the book. However, we can obtain the properties from EES.



Turbine:

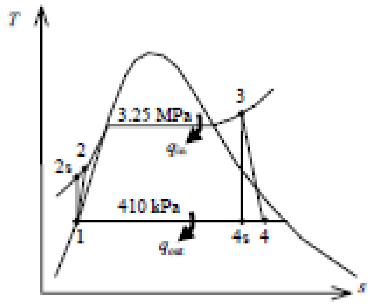
$$\left.\begin{array}{l} P_3 = 3250\text{ kPa} \\ T_3 = 147°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 761.54\text{ kJ/kg} \\ s_3 = 2.5457\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 410\text{ kPa} \\ s_4 = s_3 \end{array}\right\} h_{4s} = 670.40\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 410\text{ kPa} \\ T_4 = 179.5°\text{C} \end{array}\right\} h_4 = 689.74\text{ kJ/kg}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} = \frac{761.54 - 689.74}{761.54 - 670.40} = \mathbf{0.788}$$

(*b*) Pump:



$$h_1 = h_{f@\,410\text{ kPa}} = 273.01\text{ kJ/kg}$$

$$v_1 = v_{f@\,410\text{ kPa}} = 0.001842\text{ m}^3/\text{kg}$$

$$\begin{aligned} w_{p,\text{in}} &= v_1(P_2 - P_1)/\eta_P \\ &= (0.001842\text{ m}^3/\text{kg})(3250 - 410)\text{kPa}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)/0.90 \\ &= 5.81\text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{p,\text{in}} = 273.01 + 5.81 = 278.82\text{ kJ/kg}$$

$$\dot{W}_{\text{T,out}} = \dot{m}(h_3 - h_4) = (305.6\text{ kJ/kg})(761.54 - 689.74)\text{kJ/kg} = 21{,}941\text{ kW}$$

$$\dot{W}_{\text{P,in}} = \dot{m}(h_2 - h_1) = \dot{m}w_{\text{p,in}} = (305.6\text{ kJ/kg})(5.81\text{ kJ/kg}) = 1777\text{ kW}$$

$$\dot{W}_{\text{net}} = \dot{W}_{\text{T,out}} - \dot{W}_{\text{P,in}} = 21{,}941 - 1777 = \mathbf{20{,}165\text{ kW}}$$

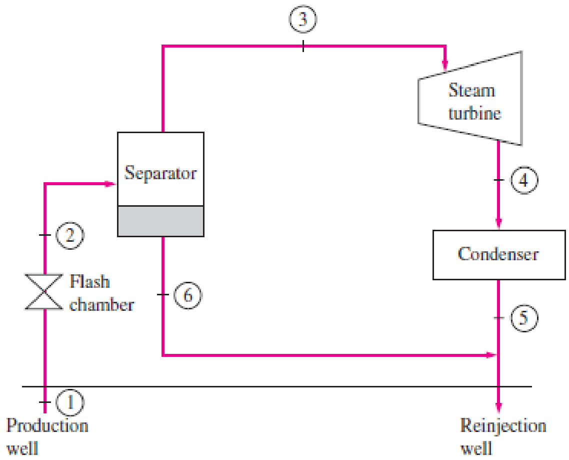
Heat Exchanger:

$$\dot{Q}_{\text{in}} = \dot{m}_{\text{geo}}c_{\text{geo}}(T_{\text{in}} - T_{\text{out}}) = (555.9\text{ kJ/kg})(4.18\text{ kJ/kg.°C})(160 - 90)°\text{C} = 162{,}656\text{ kW}$$

(*c*)

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{20{,}165}{162{,}656} = \mathbf{0.124 = 12.4\%}$$

10–26 The schematic of a single-flash geothermal power plant with state numbers is given in Fig. P10–26. Geothermal resource exists as saturated liquid at 230°C. The geothermal liquid is withdrawn from the production well at a rate of 230 kg/s, and is flashed to a pressure of 500 kPa by an essentially isenthalpic flashing process where the resulting vapor is separated from the liquid in a separator and directed to the turbine. The steam leaves the turbine at 10 kPa with a moisture content of 10 percent and enters the condenser where it is condensed and routed to a reinjection well along with the liquid coming off the separator. Determine (*a*) the mass flow rate of steam through the turbine, (*b*) the isentropic efficiency of the turbine, (*c*) the power output of the turbine, and (*d*) the thermal efficiency of the plant (the ratio of the turbine work output to the energy of the geothermal fluid relative to standard ambient conditions). *Answers:* (*a*) 38.2 kg/s, (*b*) 0.686, (*c*) 15.4 MW, (*d*) 7.6 percent



10-26 A single-flash geothermal power plant uses hot geothermal water at 230ºC as the heat source. The mass flow rate of steam through the turbine, the isentropic efficiency of the turbine, the power output from the turbine, and the thermal efficiency of the plant are to be determined.

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

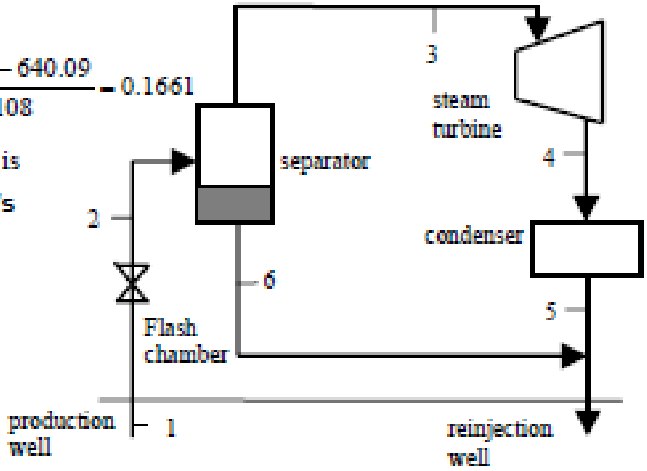
Analysis (*a*) We use properties of water for geothermal water (Tables A-4 through A-6)

$$\left.\begin{array}{l} T_1 = 230°\text{C} \\ x_1 = 0 \end{array}\right\} h_1 = 990.14 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 500 \text{ kPa} \\ h_2 = h_1 = 990.14 \text{ kJ/kg} \end{array}\right\} x_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{990.14 - 640.09}{2108} = 0.1661$$

The mass flow rate of steam through the turbine is

$$\dot{m}_3 = x_2 \dot{m}_1 = (0.1661)(230 \text{ kg/s}) = \mathbf{38.20 \text{ kg/s}}$$



(*b*) Turbine:

$$\left.\begin{array}{l} P_3 = 500 \text{ kPa} \\ x_3 = 1 \end{array}\right\} \begin{array}{l} h_3 = 2748.1 \text{ kJ/kg} \\ s_3 = 6.8207 \text{ kJ/kg·K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 10 \text{ kPa} \\ s_4 = s_3 \end{array}\right\} h_{4s} = 2160.3 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 10 \text{ kPa} \\ x_4 = 0.90 \end{array}\right\} h_4 = h_f + x_4 h_{fg} = 191.81 + (0.90)(2392.1) = 2344.7 \text{ kJ/kg}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} = \frac{2748.1 - 2344.7}{2748.1 - 2160.3} = \mathbf{0.686}$$

(*c*) The power output from the turbine is

$$\dot{W}_{\text{T,out}} = \dot{m}_3 (h_3 - h_4) = (38.20 \text{ kJ/kg})(2748.1 - 2344.7)\text{kJ/kg} = \mathbf{15{,}410 \text{ kW}}$$

(*d*) We use saturated liquid state at the standard temperature for dead state enthalpy

$$\left.\begin{array}{l} T_0 = 25°\text{C} \\ x_0 = 0 \end{array}\right\} h_0 = 104.83 \text{ kJ/kg}$$

$$\dot{E}_{\text{in}} = \dot{m}_1 (h_1 - h_0) = (230 \text{ kJ/kg})(990.14 - 104.83)\text{kJ/kg} = 203{,}622 \text{ kW}$$

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{T,out}}}{\dot{E}_{\text{in}}} = \frac{15{,}410}{203{,}622} = 0.0757 = \mathbf{7.6\%}$$

The Reheat Rankine Cycle

10–29C How do the following quantities change when a simple ideal Rankine cycle is modified with reheating? Assume the mass flow rate is maintained the same.

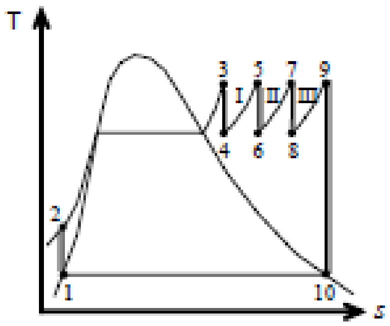
Pump work input:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Turbine work output:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Heat supplied:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Heat rejected:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Moisture content at turbine exit:	(*a*) increases, (*b*) decreases, (*c*) remains the same

10–30C Show the ideal Rankine cycle with three stages of reheating on a *T-s* diagram. Assume the turbine inlet temperature is the same for all stages. How does the cycle efficiency vary with the number of reheat stages?

10–31C Consider a simple Rankine cycle and an ideal Rankine cycle with three reheat stages. Both cycles operate between the same pressure limits. The maximum temperature is 700°C in the simple cycle and 450°C in the reheat cycle. Which cycle do you think will have a higher thermal efficiency?

10-29C The pump work remains the same, the moisture content decreases, everything else increases.

10-30C The *T-s* diagram of the ideal Rankine cycle with 3 stages of reheat is shown on the side. The cycle efficiency will increase as the number of reheating stages increases.



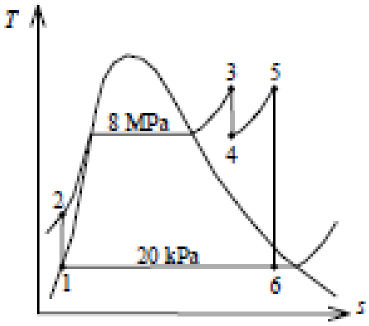
10-31C The thermal efficiency of the simple ideal Rankine cycle will probably be higher since the average temperature at which heat is added will be higher in this case.

10–32 A steam power plant operates on the ideal reheat Rankine cycle. Steam enters the high-pressure turbine at 8 MPa and 500°C and leaves at 3 MPa. Steam is then reheated at constant pressure to 500°C before it expands to 20 kPa in the low-pressure turbine. Determine the turbine work output, in kJ/kg, and the thermal efficiency of the cycle. Also, show the cycle on a *T-s* diagram with respect to saturation lines.

10-32 [*Also solved by EES on enclosed CD*] A steam power plant that operates on the ideal reheat Rankin cycle is considered. The turbine work output 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),



$$h_1 = h_{f\,@\,20\text{ kPa}} = 251.42\text{ kJ/kg}$$

$$v_1 = v_{f\,@\,20\text{ kPa}} = 0.001017\text{ m}^3\text{/kg}$$

$$w_{p,\text{in}} = v_1(P_2 - P_1) = (0.001017\text{ m}^3\text{/kg})(8000 - 20\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 8.12\text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,\text{in}} = 251.42 + 8.12 = 259.54\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 8\text{ MPa} \\ T_3 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3399.5\text{ kJ/kg} \\ s_3 = 6.7266\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 3\text{ MPa} \\ s_4 = s_3 \end{array}\right\} h_4 = 3105.1\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 3\text{ MPa} \\ T_5 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3457.2\text{ kJ/kg} \\ s_5 = 7.2359\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 20\text{ kPa} \\ s_6 = s_5 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{7.2359 - 0.8320}{7.0752} = 0.9051 \\ h_6 = h_f + x_6 h_{fg} = 251.42 + (0.9051)(2357.5) = 2385.2\text{ kJ/kg} \end{array}$$

The turbine work output and the thermal efficiency are determined from

$$w_{T,\text{out}} = (h_3 - h_4) + (h_5 - h_6) = 3399.5 - 3105.1 + 3457.2 - 2385.2 = \mathbf{1366.4\ kJ/kg}$$

and

$$q_{\text{in}} = (h_3 - h_2) + (h_5 - h_4) = 3399.5 - 259.54 + 3457.2 - 3105.1 = 3492.0\text{ kJ/kg}$$

$$w_{\text{net}} = w_{T,out} - w_{p,\text{in}} = 1366.4 - 8.12 = 1358.3\text{ kJ/kg}$$

Thus,

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1358.3\text{ kJ/kg}}{3492.5\text{ kJ/kg}} = \mathbf{38.9\%}$$

10–34 Consider a steam power plant that operates on a reheat Rankine cycle and has a net power output of 80 MW. Steam enters the high-pressure turbine at 10 MPa and 500°C and the low-pressure turbine at 1 MPa and 500°C. Steam leaves the condenser as a saturated liquid at a pressure of 10 kPa. The isentropic efficiency of the turbine is 80 percent, and that of the pump is 95 percent. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the quality (or temperature, if superheated) of the steam at the turbine exit, (*b*) the thermal efficiency of the cycle, and (*c*) the mass flow rate of the steam. *Answers:* (*a*) 88.1°C, (*b*) 34.1 percent, (*c*) 62.7 kg/s

10-34 A steam power plant that operates on a reheat Rankine cycle is considered. The quality (or temperature, if superheated) of the steam at the turbine exit, the thermal efficiency of the cycle, and the mass flow rate of the steam are to be determined.

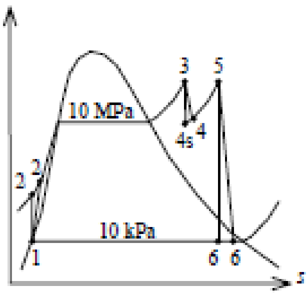
Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

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

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

$$v_1 = v_{f@10\text{ kPa}} = 0.001010\text{ m}^3\text{/kg}$$

$$w_{p,in} = v_1(P_2 - P_1)/\eta_p = (0.00101\text{ m}^3\text{/kg})(10{,}000 - 10\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)/(0.95) = 10.62\text{ kJ/kg}$$



$$h_2 = h_1 + w_{p,in} = 191.81 + 10.62 = 202.43\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 10\text{ MPa} \\ T_3 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3375.1\text{ kJ/kg} \\ s_3 = 6.5995\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_{4s} = 1\text{ MPa} \\ s_{4s} = s_3 \end{array}\right\} h_{4s} = 2783.8\text{ kJ/kg}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} \longrightarrow h_4 = h_3 - \eta_T(h_3 - h_{4s}) = 3375.1 - (0.80)(3375.1 - 2783.7) = 2902.0\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 1\text{ MPa} \\ T_5 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3479.1\text{ kJ/kg} \\ s_5 = 7.7642\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_{6s} = 10\text{ kPa} \\ s_{6s} = s_5 \end{array}\right\} \begin{array}{l} x_{6s} = \dfrac{s_{6s} - s_f}{s_{fg}} = \dfrac{7.7642 - 0.6492}{7.4996} = 0.9487\ \text{(at turbine exit)} \\ h_{6s} = h_f + x_{6s}h_{fg} = 191.81 + (0.9487)(2392.1) = 2461.2\text{ kJ/kg} \end{array}$$

$$\eta_T = \frac{h_5 - h_6}{h_5 - h_{6s}} \longrightarrow h_6 = h_5 - \eta_T(h_5 - h_{6s}) = 3479.1 - (0.80)(3479.1 - 2461.2) = 2664.8\text{ kJ/kg} > h_g\ \text{(superheated vapor)}$$

From steam tables at 10 kPa we read T_6 = **88.1°C**.

(*b*)

$$w_{T,out} = (h_3 - h_4) + (h_5 - h_6) = 3375.1 - 2902.0 + 3479.1 - 2664.8 = 1287.4\text{ kJ/kg}$$

$$q_{in} = (h_3 - h_2) + (h_5 - h_4) = 3375.1 - 202.43 + 3479.1 - 2902.0 = 3749.8\text{ kJ/kg}$$

$$w_{net} = w_{T,out} - w_{p,in} = 1287.4 - 10.62 = 1276.8\text{ kJ/kg}$$

Thus the thermal efficiency is

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{1276.8\text{ kJ/kg}}{3749.8\text{ kJ/kg}} = \mathbf{34.1\%}$$

(*c*) The mass flow rate of the steam is

$$\dot{m} = \frac{\dot{W}_{net}}{w_{net}} = \frac{80{,}000\text{ kJ/s}}{1276.9\text{ kJ/kg}} = \mathbf{62.7\ kg/s}$$

10–35 Repeat Prob. 10–34 assuming both the pump and the turbine are isentropic. *Answers:* (*a*) 0.949, (*b*) 41.3 percent, (*c*) 50.0 kg/s

10-35 A steam power plant that operates on the ideal reheat Rankine cycle is considered. The quality (temperature, if superheated) of the steam at the turbine exit, the thermal efficiency of the cycle, and t mass flow rate of the steam are to be determined.

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

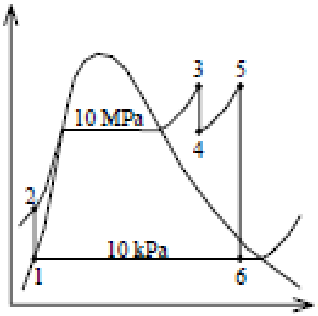
Analysis (*a*) From the steam tables (Tables A-4, A-5, and A-6),

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

$$v_1 = v_{f@\,10\text{ kPa}} = 0.00101\text{ m}^3\text{/kg}$$

$$w_{p,\text{in}} = v_1(P_2 - P_1) = (0.00101\text{ m}^3\text{/kg})(10{,}000 - 10\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 10.09\text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,\text{in}} = 191.81 + 10.09 = 201.90\text{ kJ/kg}$$



$$\left.\begin{array}{l} P_3 = 10\text{ MPa} \\ T_3 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3375.1\text{ kJ/kg} \\ s_3 = 6.5995\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 1\text{ MPa} \\ s_4 = s_3 \end{array}\right\} h_4 = 2783.8\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 1\text{ MPa} \\ T_5 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3479.1\text{ kJ/kg} \\ s_5 = 7.7642\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 10\text{ kPa} \\ s_6 = s_5 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{7.7642 - 0.6492}{7.4996} = \mathbf{0.9487}\ \ (\text{at turbine exit}) \\ h_6 = h_f + x_6 h_{fg} = 191.81 + (0.9487)(2392.1) = 2461.2\text{ kJ/kg} \end{array}$$

(*b*)

$$w_{\text{T,out}} = (h_3 - h_4) + (h_5 - h_6) = 3375.1 - 2783.7 + 3479.1 - 2461.2 = 1609.3\text{ kJ/kg}$$

$$q_{\text{in}} = (h_3 - h_2) + (h_5 - h_4) = 3375.1 - 201.90 + 3479.1 - 2783.7 = 3868.5\text{ kJ/kg}$$

$$w_{\text{net}} = w_{\text{T,out}} - w_{p,\text{in}} = 1609.4 - 10.09 = 1599.3\text{ kJ/kg}$$

Thus the thermal efficiency is

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1599.3\text{ kJ/kg}}{3868.5\text{ kJ/kg}} = \mathbf{41.3\%}$$

(*c*) The mass flow rate of the steam is

$$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{80{,}000\text{ kJ/s}}{1599.3\text{ kJ/kg}} = \mathbf{50.0\text{ kg/s}}$$

10–37 A steam power plant operates on an ideal reheat Rankine cycle between the pressure limits of 15 MPa and 10 kPa. The mass flow rate of steam through the cycle is 12 kg/s. Steam enters both stages of the turbine at 500°C. If the moisture content of the steam at the exit of the low-pressure turbine is not to exceed 10 percent, determine (*a*) the pressure at which reheating takes place, (*b*) the total rate of heat input in the boiler, and (*c*) the thermal efficiency of the cycle. Also, show the cycle on a *T-s* diagram with respect to saturation lines.

10-37 A steam power plant that operates on an ideal reheat Rankine cycle between the specified pressure limits is considered. The pressure at which reheating takes place, the total rate of heat input 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.

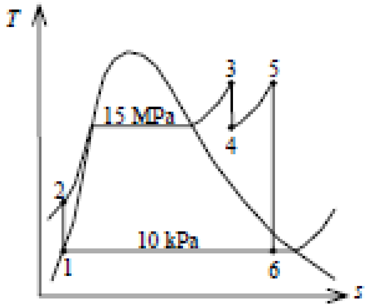
Analysis (*a*) From the steam tables (Tables A-4, A-5, and A-6),

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

$$v_1 = v_{sat @ 10\text{ kPa}} = 0.00101 \text{ m}^3\text{/kg}$$

$$w_{p,in} = v_1(P_2 - P_1) = (0.00101 \text{ m}^3\text{/kg})(15{,}000 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 15.14 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,in} = 191.81 + 15.14 = 206.95 \text{ kJ/kg}$$



$$\left.\begin{array}{l} P_3 = 15 \text{ MPa} \\ T_3 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3310.8 \text{ kJ/kg} \\ s_3 = 6.3480 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 10 \text{ kPa} \\ s_6 = s_5 \end{array}\right\} \begin{array}{l} h_6 = h_f + x_6 h_{fg} = 191.81 + (0.90)(2392.1) = 2344.7 \text{ kJ/kg} \\ s_6 = s_f + x_6 s_{fg} = 0.6492 + (0.90)(7.4996) = 7.3988 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_5 = 500°\text{C} \\ s_5 = s_6 \end{array}\right\} \begin{array}{l} P_5 = \mathbf{2161 \text{ kPa}} \text{ (the reheat pressure)} \\ h_5 = 3466.53 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_4 = 2.161 \text{ MPa} \\ s_4 = s_3 \end{array}\right\} h_4 = 2817.2 \text{ kJ/kg}$$

(*b*) The rate of heat supply is

$$\dot{Q}_{in} = \dot{m}[(h_3 - h_2) + (h_5 - h_4)] = (12 \text{ kg/s})(3310.8 - 206.95 + 3466.53 - 2817.2) \text{kJ/kg} = \mathbf{45{,}038 \text{ kW}}$$

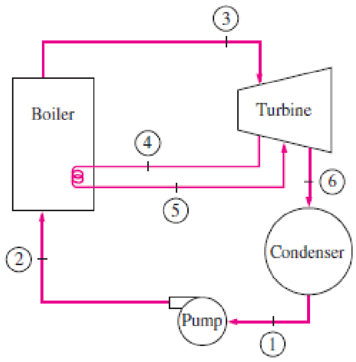
(*c*) The thermal efficiency is determined from

$$\dot{Q}_{out} = \dot{m}(h_6 - h_1) = (12 \text{ kJ/s})(2344.7 - 191.81) \text{kJ/kg} = 25{,}835 \text{ kJ/s}$$

Thus,

$$\eta_{th} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{25{,}834 \text{ kJ/s}}{45{,}039 \text{ kJ/s}} = \mathbf{42.6\%}$$

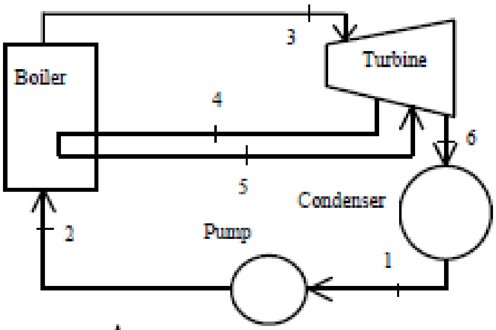
10–38 A steam power plant operates on the reheat Rankine cycle. Steam enters the high-pressure turbine at 12.5 MPa and 550°C at a rate of 7.7 kg/s and leaves at 2 MPa. Steam is then reheated at constant pressure to 450°C before it expands in the low-pressure turbine. The isentropic efficiencies of the turbine and the pump are 85 percent and 90 percent, respectively. Steam leaves the condenser as a saturated liquid. If the moisture content of the steam at the exit of the turbine is not to exceed 5 percent, determine (*a*) the condenser pressure, (*b*) the net power output, and (*c*) the thermal efficiency. *Answers: (a) 9.73 kPa, (b) 10.2 MW, (c) 36.9 percent*



10-38 A steam power plant that operates on a reheat Rankine cycle is considered. The condenser pressure, the net power output, and the thermal efficiency 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),

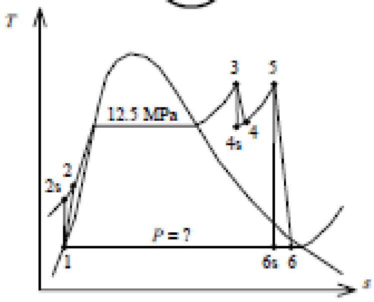


$$\left.\begin{array}{l} P_3 = 12.5 \text{ MPa} \\ T_3 = 550°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3476.5 \text{ kJ/kg} \\ s_3 = 6.6317 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 2 \text{ MPa} \\ s_{4s} = s_3 \end{array}\right\} h_{4s} = 2948.1 \text{ kJ/kg}$$

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

$$\rightarrow h_4 = h_3 - \eta_T(h_3 - h_{4s})$$
$$= 3476.5 - (0.85)(3476.5 - 2948.1)$$
$$= 3027.3 \text{ kJ/kg}$$



$$\left.\begin{array}{l} P_5 = 2 \text{ MPa} \\ T_5 = 450°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3358.2 \text{ kJ/kg} \\ s_5 = 7.2815 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = ? \\ x_6 = 0.95 \end{array}\right\} h_6 =$$

$$\left.\begin{array}{l} P_6 = ? \\ s_6 = s_5 \end{array}\right\} h_{6s} =$$

$$\eta_T = \frac{h_5 - h_6}{h_5 - h_{6s}} \longrightarrow h_6 = h_5 - \eta_T(h_5 - h_{6s})$$
$$= 3358.2 - (0.85)(3358.2 - 2948.1) = 3027.3 \text{ kJ/kg}$$

The pressure at state 6 may be determined by a trial-error approach from the steam tables or by using EES from the above equations:

P_6 = **9.73 kPa**, h_6 = 2463.3 kJ/kg,

(*b*) Then,

$$h_1 = h_{f @ 9.73 \text{ kPa}} = 189.57 \text{ kJ/kg}$$

$$v_1 = v_{f @ 10 \text{ kPa}} = 0.001010 \text{ m}^3/\text{kg}$$

$$w_{p,\text{in}} = v_1(P_2 - P_1)/\eta_p$$
$$= (0.00101 \text{ m}^3/\text{kg})(12{,}500 - 9.73 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)/(0.90)$$
$$= 14.02 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,\text{in}} = 189.57 + 14.02 = 203.59 \text{ kJ/kg}$$

Cycle analysis:

$$q_{\text{in}} = (h_3 - h_2) + (h_5 - h_4) = 3476.5 - 3027.3 + 3358.2 - 2463.3 = 3603.8 \text{ kJ/kg}$$

$$q_{\text{out}} = h_6 - h_1 = 3027.3 - 189.57 = 2273.7 \text{ kJ/kg}$$

$$\dot{W}_{\text{net}} = \dot{m}(q_{\text{in}} - q_{\text{out}}) = (7.7 \text{ kg/s})(3603.8 - 2273.7)\text{kJ/kg} = \mathbf{10{,}242 \text{ kW}}$$

(*c*) The thermal efficiency is

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{2273.7 \text{ kJ/kg}}{3603.8 \text{ kJ/kg}} = 0.369 = \mathbf{36.9\%}$$

Regenerative Rankine Cycle

10–39C How do the following quantities change when the simple ideal Rankine cycle is modified with regeneration? Assume the mass flow rate through the boiler is the same.

Turbine work output:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Heat supplied:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Heat rejected:	(*a*) increases, (*b*) decreases, (*c*) remains the same
Moisture content at turbine exit:	(*a*) increases, (*b*) decreases, (*c*) remains the same

10–40C During a regeneration process, some steam is extracted from the turbine and is used to heat the liquid water leaving the pump. This does not seem like a smart thing to do since the extracted steam could produce some more work in the turbine. How do you justify this action?

10–41C How do open feedwater heaters differ from closed feedwater heaters?

10–42C Consider a simple ideal Rankine cycle and an ideal regenerative Rankine cycle with one open feedwater heater. The two cycles are very much alike, except the feedwater in the regenerative cycle is heated by extracting some steam just before it enters the turbine. How would you compare the efficiencies of these two cycles?

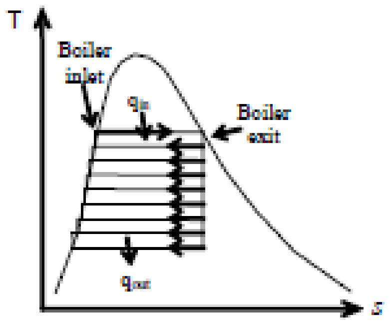
10-39C Moisture content remains the same, everything else decreases.

10-40C This is a smart idea because we waste little work potential but we save a lot from the heat input. The extracted steam has little work potential left, and most of its energy would be part of the heat rejected anyway. Therefore, by regeneration, we utilize a considerable amount of heat by sacrificing little work output.

10-41C In open feedwater heaters, the two fluids actually mix, but in closed feedwater heaters there is no mixing.

10-42C Both cycles would have the same efficiency.

10-43C To have the same thermal efficiency as the Carnot cycle, the cycle must receive and reject heat isothermally. Thus the liquid should be brought to the saturated liquid state at the boiler pressure isothermally, and the steam must be a saturated vapor at the turbine inlet. This will require an infinite number of heat exchangers (feedwater heaters), as shown on the *T-s* diagram.

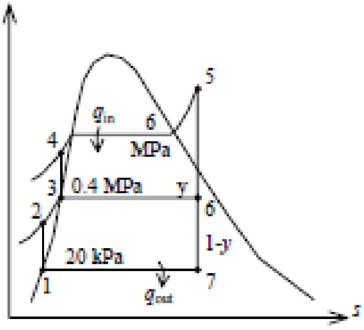


10–44 A steam power plant operates on an ideal regenerative Rankine cycle. Steam enters the turbine at 6 MPa and 450°C and is condensed in the condenser at 20 kPa. Steam is extracted from the turbine at 0.4 MPa to heat the feedwater in an open feedwater heater. Water leaves the feedwater heater as a saturated liquid. Show the cycle on a *T-s* diagram, and determine (*a*) the net work output per kilogram of steam flowing through the boiler and (*b*) the thermal efficiency of the cycle. *Answers:* (*a*) 1017 kJ/kg, (*b*) 37.8 percent

10-44 A steam power plant that operates on an ideal regenerative Rankine cycle with an open feedwater heater is considered. The net work output per kg of steam 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 (*a*) From the steam tables (Tables A-4, A-5, and A-6),



$$h_1 = h_{f@20\text{ kPa}} = 251.42 \text{ kJ/kg}$$

$$v_1 = v_{f@20\text{ kPa}} = 0.001017 \text{ m}^3\text{/kg}$$

$$w_{pI,in} = v_1(P_2 - P_1) = (0.001017 \text{ m}^3\text{/kg})(400 - 20 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 0.39 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{pI,in} = 251.42 + 0.39 = 251.81 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 0.4 \text{ MPa} \\ \text{sat.liquid} \end{array}\right\} \begin{array}{l} h_3 = h_{f@0.4\text{ MPa}} = 604.66 \text{ kJ/kg} \\ v_3 = v_{f@0.4\text{ MPa}} = 0.001084 \text{ m}^3\text{/kg} \end{array}$$

$$w_{pII,in} = v_3(P_4 - P_3) = (0.001084 \text{ m}^3\text{/kg})(6000 - 400 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 6.07 \text{ kJ/kg}$$

$$h_4 = h_3 + w_{pII,in} = 604.66 + 6.07 = 610.73 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 6 \text{ MPa} \\ T_5 = 450°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3302.9 \text{ kJ/kg} \\ s_5 = 6.7219 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 0.4 \text{ MPa} \\ s_6 = s_5 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{6.7219 - 1.7765}{5.1191} = 0.9661 \\ h_6 = h_f + x_6 h_{fg} = 604.66 + (0.9661)(2133.4) = 2665.7 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_7 = 20 \text{ kPa} \\ s_7 = s_5 \end{array}\right\} \begin{array}{l} x_7 = \dfrac{s_7 - s_f}{s_{fg}} = \dfrac{6.7219 - 0.8320}{7.0752} = 0.8325 \\ h_7 = h_f + x_7 h_{fg} = 251.42 + (0.8325)(2357.5) = 2214.0 \text{ kJ/kg} \end{array}$$

The fraction of steam extracted is determined from the steady-flow energy balance equation applied to the feedwater heater. Noting that $\dot{Q} \cong \dot{W} \cong \Delta ke \cong \Delta pe \cong 0$,

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}^{\,\nearrow 0\,(\text{steady})} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_6 h_6 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \longrightarrow y h_6 + (1-y) h_2 = 1(h_3)$$

where y is the fraction of steam extracted from the turbine ($= \dot{m}_6 / \dot{m}_3$). Solving for y,

$$y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{604.66 - 251.81}{2665.7 - 251.81} = 0.1462$$

Then,

$$q_{in} = h_5 - h_4 = 3302.9 - 610.73 = 2692.2 \text{ kJ/kg}$$

$$q_{out} = (1-y)(h_7 - h_1) = (1 - 0.1462)(2214.0 - 251.42) = 1675.7 \text{ kJ/kg}$$

And $w_{net} = q_{in} - q_{out} = 2692.2 - 1675.7 = \mathbf{1016.5 \text{ kJ/kg}}$

(b) The thermal efficiency is determined from

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1675.7 \text{ kJ/kg}}{2692.2 \text{ kJ/kg}} = \mathbf{37.8\%}$$

10–45 Repeat Prob. 10–44 by replacing the open feedwater heater with a closed feedwater heater. Assume that the feedwater leaves the heater at the condensation temperature of the extracted steam and that the extracted steam leaves the heater as a saturated liquid and is pumped to the line carrying the feedwater.

10-45 A steam power plant that operates on an ideal regenerative Rankine cycle with a closed feedwater heater is considered. The net work output per kg of steam 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.

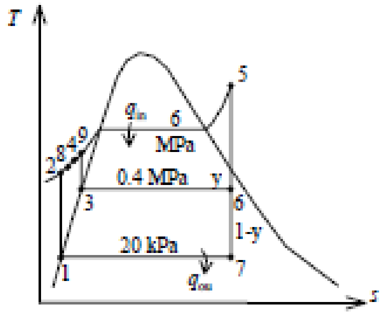
Analysis (*a*) From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f@\,20\text{ kPa}} = 251.42\text{ kJ/kg}$$

$$v_1 = v_{f@\,20\text{ kPa}} = 0.001017\text{ m}^3/\text{kg}$$

$$w_{pI,in} = v_1(P_2 - P_1) = \left(0.001017\text{ m}^3/\text{kg}\right)\left(6000 - 20\text{ kPa}\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 6.08\text{ kJ/kg}$$

$$h_2 = h_1 + w_{pI,in} = 251.42 + 6.08 = 257.50\text{ kJ/kg}$$



$$\left.\begin{array}{l} P_3 = 0.4\text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} h_3 = h_{f@\,0.4\text{ MPa}} = 604.66\text{ kJ/kg} \\ v_3 = v_{f@\,0.4\text{ MPa}} = 0.001084\text{ m}^3/\text{kg} \end{array}$$

$$w_{pII,in} = v_3(P_9 - P_3) = \left(0.001084\text{ m}^3/\text{kg}\right)\left(6000 - 400\text{ kPa}\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 6.07\text{ kJ/kg}$$

$$h_9 = h_3 + w_{pII,in} = 604.66 + 6.07 = 610.73\text{ kJ/kg}$$

$$h_8 = h_3 + v_3(P_8 - P_3) = h_9 = 610.73\text{ kJ/kg}$$

Also, $h_4 = h_9 = h_8 = 610.73$ kJ/kg since the two fluid streams which are being mixed have the same enthalpy.

$$\left.\begin{array}{l} P_5 = 6\text{ MPa} \\ T_5 = 450°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3302.9\text{ kJ/kg} \\ s_5 = 6.7219\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 0.4\text{ MPa} \\ s_6 = s_5 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{6.7219 - 1.7765}{5.1191} = 0.9661 \\ h_6 = h_f + x_6 h_{fg} = 604.66 + (0.9661)(2133.4) = 2665.7\text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_7 = 20\text{ kPa} \\ s_7 = s_5 \end{array}\right\} \begin{array}{l} x_7 = \dfrac{s_7 - s_f}{s_{fg}} = \dfrac{6.7219 - 0.8320}{7.0752} = 0.8325 \\ h_7 = h_f + x_7 h_{fg} = 251.42 + (0.8325)(2357.5) = 2214.0\text{ kJ/kg} \end{array}$$

The fraction of steam extracted is determined from the steady-flow energy balance equation applied to the feedwater heater. Noting that $\dot{Q} \cong \dot{W} \cong \Delta\text{ke} \cong \Delta\text{pe} \cong 0$,

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\nearrow 0\,(\text{steady})} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_2(h_8 - h_2) = \dot{m}_6(h_6 - h_3) \longrightarrow (1-y)(h_8 - h_2) = y(h_6 - h_3)$$

where y is the fraction of steam extracted from the turbine ($= \dot{m}_6/\dot{m}_5$). Solving for y,

$$y = \frac{h_8 - h_2}{(h_6 - h_3) + (h_8 - h_2)} = \frac{610.73 - 257.50}{2665.7 - 604.66 + 610.73 - 257.50} = 0.1463$$

Then,

$$q_{in} = h_5 - h_4 = 3302.9 - 610.73 = 2692.2\text{ kJ/kg}$$

$$q_{out} = (1-y)(h_7 - h_1) = (1 - 0.1463)(2214.0 - 251.42) = 1675.4\text{ kJ/kg}$$

And $\quad w_{net} = q_{in} - q_{out} = 2692.2 - 1675.4 = \mathbf{1016.8\text{ kJ/kg}}$

(*b*) The thermal efficiency is determined from

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1675.4\text{ kJ/kg}}{2692.2\text{ kJ/kg}} = \mathbf{37.8\%}$$

EXERGETIC ANALYSIS OF POWER CYCLES

10–54 Determine the exergy destruction associated with each of the processes of the Rankine cycle described in Prob. 10–15, assuming a source temperature of 1500 K and a sink temperature of 290 K.

10-54 The exergy destructions associated with each of the processes of the Rankine cycle described in Prob. 10-15 are to be determined for the specified source and sink temperatures.

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

Analysis From Problem 10-15,

$$s_1 = s_2 = s_{f@\,50\text{ kPa}} = 1.0912\text{ kJ/kg}\cdot\text{K}$$
$$s_3 = s_4 = 6.5412\text{ kJ/kg}\cdot\text{K}$$
$$q_{in} = 2650.72\text{ kJ/kg}$$
$$q_{out} = 1931.8\text{ kJ/kg}$$

Processes 1-2 and 3-4 are isentropic. Thus, $i_{12} = \mathbf{0}$ and $i_{34} = \mathbf{0}$. Also,

$$x_{\text{destroyed},23} = T_0\left(s_3 - s_2 + \frac{q_{R,23}}{T_R}\right) = (290\text{ K})\left(6.5412 - 1.0912 + \frac{-2650.8\text{ kJ/kg}}{1500\text{ K}}\right) = \mathbf{1068\ \ kJ/kg}$$

$$x_{\text{destroyed},41} = T_0\left(s_1 - s_4 + \frac{q_{R,41}}{T_R}\right) = (290\text{ K})\left(1.0912 - 6.5412 + \frac{1931.8\text{ kJ/kg}}{290\text{ K}}\right) = \mathbf{351.3\ \ kJ/kg}$$

10–55 Determine the exergy destruction associated with each of the processes of the Rankine cycle described in Prob. 10–16, assuming a source temperature of 1500 K and a sink temperature of 290 K. *Answers:* 0, 1112 kJ/kg, 0, 172.3 kJ/kg

10-55 The exergy destructions associated with each of the processes of the Rankine cycle described in Prob. 10-16 are to be determined for the specified source and sink temperatures.

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

Analysis From Problem 10-16,

$$s_1 = s_2 = s_{f@10\text{kPa}} = 0.6492\text{ kJ/kg}\cdot\text{K}$$
$$s_3 = s_4 = 6.5995\text{ kJ/kg}\cdot\text{K}$$
$$q_{\text{in}} = 3173.2\text{ kJ/kg}$$
$$q_{\text{out}} = 1897.9\text{ kJ/kg}$$

Processes 1-2 and 3-4 are isentropic. Thus, $i_{12} = \mathbf{0}$ and $i_{34} = \mathbf{0}$. Also,

$$x_{\text{destroyed},23} = T_0\left(s_3 - s_2 + \frac{q_{R,23}}{T_R}\right) = (290\text{ K})\left(6.5995 - 0.6492 + \frac{-3173.2\text{ kJ/kg}}{1500\text{ K}}\right) = \mathbf{1112.1\ \ kJ/kg}$$

$$x_{\text{destroyed},41} = T_0\left(s_1 - s_4 + \frac{q_{R,41}}{T_R}\right) = (290\text{ K})\left(0.6492 - 6.5995 + \frac{1897.9\text{ kJ/kg}}{290\text{ K}}\right) = \mathbf{172.3\ \ kJ/kg}$$

10–56 Determine the exergy destruction associated with the heat rejection process in Prob. 10–22. Assume a source temperature of 1500 K and a sink temperature of 290 K. Also, determine the exergy of the steam at the boiler exit. Take $P_0 = 100$ kPa.

10-56 The exergy destruction associated with the heat rejection process in Prob. 10-22 is to be determined for the specified source and sink temperatures. The exergy of the steam at the boiler exit is also to be determined.

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

Analysis From Problem 10-22,

$$s_1 = s_2 = s_{f@10\text{kPa}} = 0.6492 \text{ kJ/kg}\cdot\text{K}$$
$$s_3 = s_4 = 6.8000 \text{ kJ/kg}\cdot\text{K}$$
$$h_3 = 3411.4 \text{ kJ/kg}$$
$$q_{out} = 1961.8 \text{ kJ/kg}$$

The exergy destruction associated with the heat rejection process is

$$x_{destroyed,41} = T_0\left(s_1 - s_4 + \frac{q_{R,41}}{T_R}\right) = (290\text{ K})\left(0.6492 - 6.8000 + \frac{1961.8\text{ kJ/kg}}{290\text{ K}}\right) = \mathbf{178.0\ kJ/kg}$$

The exergy of the steam at the boiler exit is simply the flow exergy,

$$\psi_3 = (h_3 - h_0) - T_0(s_3 - s_0) + \frac{V_3^2}{2}^{\nearrow 0} + gz_3^{\nearrow 0} = (h_3 - h_0) - T_0(s_3 - s_0)$$

where
$$h_0 = h_{@(290\text{ K},\ 100\text{ kPa})} \cong h_{f\ @\ 290\text{ K}} = 71.95 \text{ kJ/kg}$$
$$s_0 = s_{@(290\text{ K},100\text{ kPa})} \cong s_{f\ @\ 290\text{ K}} = 0.2533 \text{ kJ/kg}\cdot\text{K}$$

Thus, $\psi_3 = (3411.4 - 71.95)\text{ kJ/kg} - (290\text{ K})(6.800 - 0.2532)\text{ kJ/kg}\cdot\text{K} = \mathbf{1440.9\ \ kJ/kg}$

10–57 Determine the exergy destruction associated with each of the processes of the reheat Rankine cycle described in Prob. 10–32. Assume a source temperature of 1800 K and a sink temperature of 300 K.

10-57 The exergy destructions associated with each of the processes of the reheat Rankine cycle described in Prob. 10-32 are to be determined for the specified source and sink temperatures.

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

Analysis From Problem 10-32,

$$s_1 = s_2 = s_{f@20\text{kPa}} = 0.8320 \text{ kJ/kg}\cdot\text{K}$$
$$s_3 = s_4 = 6.7266 \text{ kJ/kg}\cdot\text{K}$$
$$s_5 = s_6 = 7.2359 \text{ kJ/kg}\cdot\text{K}$$
$$q_{23,in} = 3399.5 - 259.54 = 3140.0 \text{ kJ/kg}$$
$$q_{45,in} = 3457.2 - 3105.1 = 352.1 \text{ kJ/kg}$$
$$q_{out} = h_6 - h_1 = 2385.2 - 251.42 = 2133.8 \text{ kJ/kg}$$

Processes 1-2, 3-4, and 5-6 are isentropic. Thus, $i_{12} = i_{34} = i_{56} = \mathbf{0}$. Also,

$$x_{destroyed,23} = T_0\left(s_3 - s_2 + \frac{q_{R,23}}{T_R}\right) = (300\text{ K})\left(6.7266 - 0.8320 + \frac{-3140.0\text{ kJ/kg}}{1800\text{ K}}\right) = \mathbf{1245.0\ kJ/kg}$$

$$x_{destroyed,45} = T_0\left(s_5 - s_4 + \frac{q_{R,45}}{T_R}\right) = (300\text{ K})\left(7.2359 - 6.7266 + \frac{-352.5\text{ kJ/kg}}{1800\text{ K}}\right) = \mathbf{94.1\ kJ/kg}$$

$$x_{destroyed,61} = T_0\left(s_1 - s_6 + \frac{q_{R,61}}{T_R}\right) = (300\text{ K})\left(0.8320 - 7.2359 + \frac{2133.8\text{ kJ/kg}}{300\text{ K}}\right) = \mathbf{212.6\ kJ/kg}$$

10–59 Determine the exergy destruction associated with the heat addition process and the expansion process in Prob. 10–34. Assume a source temperature of 1600 K and a sink temperature of 285 K. Also, determine the exergy of the steam at the boiler exit. Take P_0 = 100 kPa. *Answers:* 1289 kJ/kg, 247.9 kJ/kg, 1495 kJ/kg

10-59 The exergy destruction associated with the heat addition process and the expansion process in Prob. 10-34 are to be determined for the specified source and sink temperatures. The exergy of the steam at the boiler exit is also to be determined.

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

Analysis From Problem 10-34,

$$s_1 = s_2 = s_{f\,@\,10\text{ kPa}} = 0.6492 \text{ kJ/kg}\cdot\text{K}$$
$$s_3 = 6.5995 \text{ kJ/kg}\cdot\text{K}$$
$$s_4 = 6.8464 \text{ kJ/kg}\cdot\text{K} \quad (P_4 = 1 \text{ MPa},\ h_4 = 2902.0 \text{ kJ/kg})$$
$$s_5 = 7.7642 \text{ kJ/kg}\cdot\text{K}$$
$$s_6 = 8.3870 \text{ kJ/kg}\cdot\text{K} \quad (P_6 = 10 \text{ kPa},\ h_6 = 2664.8 \text{ kJ/kg})$$
$$h_3 = 3375.1 \text{ kJ/kg}$$
$$q_{in} = 3749.8 \text{ kJ/kg}$$

The exergy destruction associated with the combined pumping and the heat addition processes is

$$x_{\text{destroyed}} = T_0\left(s_3 - s_1 + s_5 - s_4 + \frac{q_{R,15}}{T_R}\right)$$
$$= (285 \text{ K})\left(6.5995 - 0.6492 + 7.7642 - 6.8464 + \frac{-3749.8 \text{ kJ/kg}}{1600 \text{ K}}\right) = 1289.5 \text{ kJ/kg}$$

The exergy destruction associated with the pumping process is

$$x_{\text{destroyed},12} \cong w_{p,a} - w_{p,s} = w_{p,a} - v\Delta P = 10.62 - 10.09 = 0.53 \text{kJ/kg}$$

Thus,

$$x_{\text{destroyed, heating}} = x_{\text{destroyed}} - x_{\text{destroyed},12} = 1289.5 - 0.5 = \mathbf{1289\ kJ/kg}$$

The exergy destruction associated with the expansion process is

$$x_{\text{destroyed},34} = T_0\left((s_4 - s_3) + (s_6 - s_5) + \frac{q_{R,36}^{\ \nearrow 0}}{T_R}\right)$$
$$= (285 \text{ K})(6.8464 - 6.5995 + 8.3870 - 7.7642) \text{kJ/kg}\cdot\text{K} = \mathbf{247.9\ kJ/kg}$$

The exergy of the steam at the boiler exit is determined from

$$\psi_3 = (h_3 - h_0) - T_0(s_3 - s_0) + \frac{V_3^2}{2}^{\nearrow 0} + gz_3^{\nearrow 0}$$
$$= (h_3 - h_0) - T_0(s_3 - s_0)$$

where

$$h_0 = h_{@\,(285\text{ K},\,100\text{ kPa})} \cong h_{f\,@\,285\text{ K}} = 50.51 \text{ kJ/kg}$$
$$s_0 = s_{@\,(285\text{ K},\,100\text{ kPa})} \cong s_{f\,@\,285\text{ K}} = 0.1806 \text{ kJ/kg}\cdot\text{K}$$

Thus,

$$\psi_3 = (3375.1 - 50.51) \text{kJ/kg} - (285 \text{ K})(6.5995 - 0.1806) \text{kJ/kg}\cdot\text{K} = \mathbf{1495\ kJ/kg}$$

10–60 Determine the exergy destruction associated with the regenerative cycle described in Prob. 10–44. Assume a source temperature of 1500 K and a sink temperature of 290 K. *Answer:* 1155 kJ/kg

10-60 The exergy destruction associated with the regenerative cycle described in Prob. 10-44 is to be determined for the specified source and sink temperatures.

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

Analysis From Problem 10-44, q_{in} = 2692.2 kJ/kg and q_{out} = 1675.7 kJ/kg. Then the exergy destruction associated with this regenerative cycle is

$$x_{destroyed,cycle} = T_0\left(\frac{q_{out}}{T_L} - \frac{q_{in}}{T_H}\right) = (290\text{ K})\left(\frac{1675.7\text{ kJ/kg}}{290\text{ K}} - \frac{2692.2\text{ kJ/kg}}{1500\text{ K}}\right) = \mathbf{1155\ \ kJ/kg}$$

10-61 The exergy destruction associated with the reheating and regeneration processes described in Prob. 10-49 are to be determined for the specified source and sink temperatures.

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

Analysis From Problem 10-49 and the steam tables,

$$y = 0.2016$$
$$s_3 = s_{f@0.8\text{MPa}} = 2.0457\text{ kJ/kg}\cdot\text{K}$$
$$s_5 = s_6 = 6.7585\text{ kJ/kg}\cdot\text{K}$$
$$s_7 = 7.8692\text{ kJ/kg}\cdot\text{K}$$
$$s_1 = s_2 = s_{f@10\text{kPa}} = 0.6492\text{ kJ/kg}\cdot\text{K}$$
$$q_{reheat} = h_7 - h_6 = 3481.3 - 2812.7 = 668.6\text{ kJ/kg}$$

Then the exergy destruction associated with reheat and regeneration processes are

$$x_{destroyed,reheat} = T_0\left(s_7 - s_6 + \frac{q_{R,67}}{T_R}\right)$$
$$= (290\text{ K})\left(7.8692 - 6.7585 + \frac{-668.6\text{ kJ/kg}}{1800\text{ K}}\right) = \mathbf{214.3\ \ kJ/kg}$$

$$x_{destroyed,regen} = T_0 s_{gen} = T_0\left(\sum m_e s_e - \sum m_i s_i + \frac{q_{surr}}{T_0}^{\nearrow 0}\right) = T_0\left(s_3 - y s_6 - (1-y)s_2\right)$$
$$= (290\text{ K})[2.0457 - (0.2016)(6.7585) - (1-0.2016)(0.6492)] = \mathbf{47.8\ kJ/kg}$$

COGENERATION

10–63C How is the utilization factor ϵ_u for cogeneration plants defined? Could ϵ_u be unity for a cogeneration plant that does not produce any power?

10–64C Consider a cogeneration plant for which the utilization factor is 1. Is the irreversibility associated with this cycle necessarily zero? Explain.

10–65C Consider a cogeneration plant for which the utilization factor is 0.5. Can the exergy destruction associated with this plant be zero? If yes, under what conditions?

10–66C What is the difference between cogeneration and regeneration?

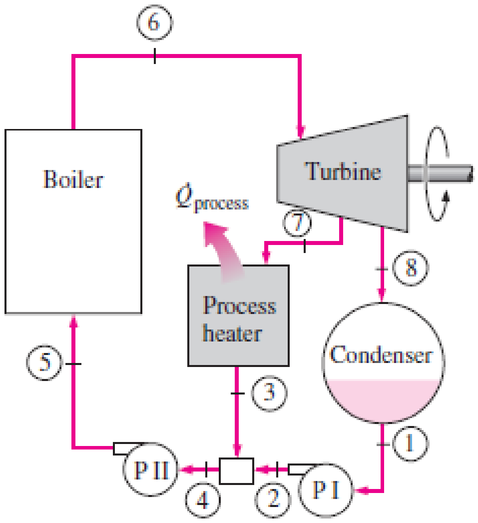
10-63C The utilization factor of a cogeneration plant is the ratio of the energy utilized for a useful purpose to the total energy supplied. It could be unity for a plant that does not produce any power.

10-64C No. A cogeneration plant may involve throttling, friction, and heat transfer through a finite temperature difference, and still have a utilization factor of unity.

10-65C Yes, if the cycle involves no irreversibilities such as throttling, friction, and heat transfer through a finite temperature difference.

10-66C Cogeneration is the production of more than one useful form of energy from the same energy source. Regeneration is the transfer of heat from the working fluid at some stage to the working fluid at some other stage.

10–67 Steam enters the turbine of a cogeneration plant 7 MPa and 500°C. One-fourth of the steam is extracted fr the turbine at 600-kPa pressure for process heating. T remaining steam continues to expand to 10 kPa. T extracted steam is then condensed and mixed with feedwa at constant pressure and the mixture is pumped to the boi pressure of 7 MPa. The mass flow rate of steam through t boiler is 30 kg/s. Disregarding any pressure drops and h losses in the piping, and assuming the turbine and the pu to be isentropic, determine the net power produced and t utilization factor of the plant.



10-67 A cogeneration plant is to generate power and process heat. Part of the steam extracted from the turbine at a relatively high pressure is used for process heating. The net power produced and the utilization factor of the plant 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),

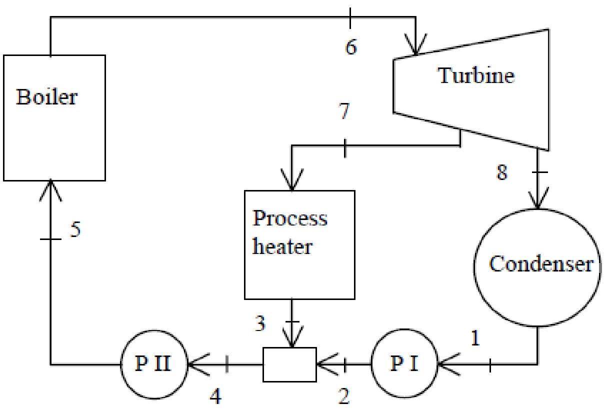
$$h_1 = h_{f\,@\,10\text{ kPa}} = 191.81\text{ kJ/kg}$$

$$v_1 = v_{f\,@\,10\text{ kPa}} = 0.00101\text{ m}^3\text{/kg}$$

$$\begin{aligned} w_{\text{pI,in}} &= v_1(P_2 - P_1) \\ &= (0.00101\text{ m}^3\text{/kg})(600-10\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 0.60\text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 191.81 + 0.60 = 192.41\text{ kJ/kg}$$

$$h_3 = h_{f\,@\,0.6\text{ MPa}} = 670.38\text{ kJ/kg}$$



Mixing chamber:

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta\dot{E}_{\text{system}}^{\nearrow 0\text{ (steady)}} = 0 \longrightarrow \dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

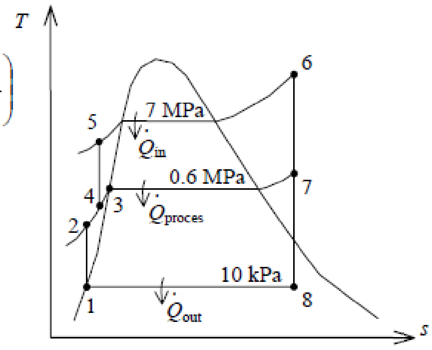
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_4 h_4 = \dot{m}_2 h_2 + \dot{m}_3 h_3$$

or, $$h_4 = \frac{\dot{m}_2 h_2 + \dot{m}_3 h_3}{\dot{m}_4} = \frac{(22.50)(192.41) + (7.50)(670.38)}{30} = 311.90\text{ kJ/kg}$$

$$v_4 \cong v_{f\,@\,h_f = 311.90\text{ kJ/kg}} = 0.001026\text{ m}^3\text{/kg}$$

$$w_{pII,in} = v_4(P_5 - P_4) = (0.001026 \text{ m}^3/\text{kg})(7000 - 600 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 6.57 \text{ kJ/kg}$$

$$h_5 = h_4 + w_{pII,in} = 311.90 + 6.57 = 318.47 \text{ kJ/kg}$$



$$\left.\begin{array}{l} P_6 = 7 \text{ MPa} \\ T_6 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_6 = 3411.4 \text{ kJ/kg} \\ s_6 = 6.8000 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_7 = 0.6 \text{ MPa} \\ s_7 = s_6 \end{array}\right\} h_7 = 2774.6 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_8 = 10 \text{ kPa} \\ s_8 = s_6 \end{array}\right\} \begin{array}{l} x_8 = \dfrac{s_8 - s_f}{s_{fg}} = \dfrac{6.8000 - 0.6492}{7.4996} = 0.8201 \\ h_8 = h_f + x_8 h_{fg} = 191.81 + (0.8201)(2392.1) = 2153.6 \text{ kJ/kg} \end{array}$$

Then,

$$\dot{W}_{T,out} = \dot{m}_6(h_6 - h_7) + \dot{m}_8(h_7 - h_8) = (30 \text{ kg/s})(3411.4 - 2774.6)\text{kJ/kg} + (22.5 \text{ kg/s})(2774.6 - 2153.6)\text{kJ/kg} = 33{,}077 \text{ kW}$$

$$\dot{W}_{p,in} = \dot{m}_1 w_{pI,in} + \dot{m}_4 w_{pII,in} = (22.5 \text{ kg/s})(0.60 \text{ kJ/kg}) + (30 \text{ kg/s})(6.57 \text{ kJ/kg}) = 210.6 \text{ kW}$$

$$\dot{W}_{net} = \dot{W}_{T,out} - \dot{W}_{p,in} = 33{,}077 - 210.6 = \mathbf{32{,}866 \text{ kW}}$$

Also,

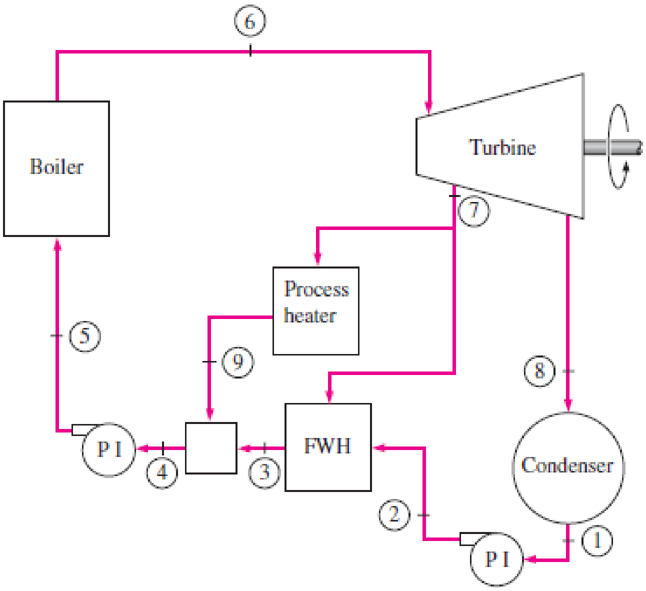
$$\dot{Q}_{process} = \dot{m}_7(h_7 - h_3) = (7.5 \text{ kg/s})(2774.6 - 670.38) \text{ kJ/kg} = 15{,}782 \text{ kW}$$

$$\dot{Q}_{in} = \dot{m}_5(h_6 - h_5) = (30 \text{ kg/s})(3411.4 - 318.47) = 92{,}788 \text{ kW}$$

and

$$\varepsilon_u = \frac{\dot{W}_{net} + \dot{Q}_{process}}{\dot{Q}_{in}} = \frac{32{,}866 + 15{,}782}{92{,}788} = \mathbf{52.4\%}$$

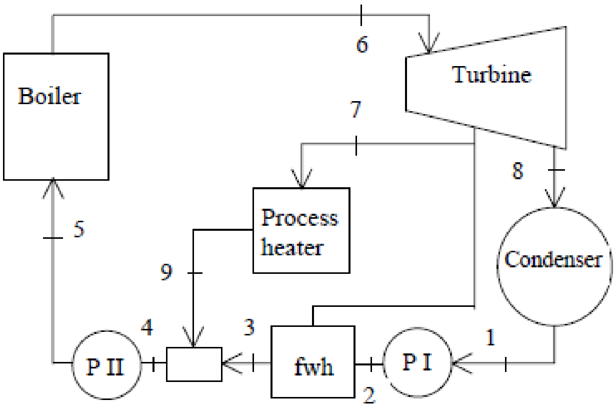
10-70 Consider a cogeneration power plant modified with regeneration. Steam enters the turbine at 6 MPa and 450°C and expands to a pressure of 0.4 MPa. At this pressure, 60 percent of the steam is extracted from the turbine, and the remainder expands to 10 kPa. Part of the extracted steam is used to heat the feedwater in an open feedwater heater. The rest of the extracted steam is used for process heating and leaves the process heater as a saturated liquid at 0.4 MPa. It is subsequently mixed with the feedwater leaving the feedwater heater, and the mixture is pumped to the boiler pressure.



10-70 A cogeneration plant modified with regeneration is to generate power and process heat. The mass flow rate of steam through the boiler for a net power output of 15 MW is 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),

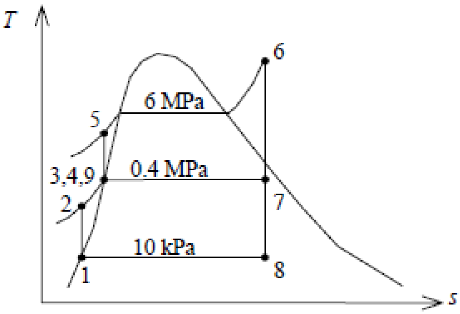
$$h_1 = h_{f\ @\ 10\ \text{kPa}} = 191.81\ \text{kJ/kg}$$
$$v_1 = v_{f\ @\ 10\ \text{kPa}} = 0.00101\ \text{m}^3/\text{kg}$$

$$w_{\text{pI,in}} = v_1(P_2 - P_1) = (0.00101\ \text{m}^3/\text{kg})(400 - 10\ \text{kPa})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = 0.39\ \text{kJ/kg}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 191.81 + 0.39 = 192.20\ \text{kJ/kg}$$
$$h_3 = h_4 = h_9 = h_{f\ @\ 0.4\ \text{MPa}} = 604.66\ \text{kJ/kg}$$
$$v_4 = v_{f\ @\ 0.4\ \text{MPa}} = 0.001084\ \text{m}^3/\text{kg}$$

$$w_{\text{pII,in}} = v_4(P_5 - P_4) = (0.001084\ \text{m}^3/\text{kg})(6000 - 400\ \text{kPa})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) = 6.07\ \text{kJ/kg}$$

$$h_5 = h_4 + w_{\text{pII,in}} = 604.66 + 6.07 = 610.73\ \text{kJ/kg}$$



$$\left.\begin{array}{l} P_6 = 6\ \text{MPa} \\ T_6 = 450°\text{C} \end{array}\right\} \begin{array}{l} h_6 = 3302.9\ \text{kJ/kg} \\ s_6 = 6.7219\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_7 = 0.4\ \text{MPa} \\ s_7 = s_6 \end{array}\right\} \begin{array}{l} x_7 = \dfrac{s_7 - s_f}{s_{fg}} = \dfrac{6.7219 - 1.7765}{5.1191} = 0.9661 \\ h_7 = h_f + x_7 h_{fg} = 604.66 + (0.9661)(2133.4) = 2665.7\ \text{kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_8 = 10\ \text{kPa} \\ s_8 = s_6 \end{array}\right\} \begin{array}{l} x_8 = \dfrac{s_8 - s_f}{s_{fg}} = \dfrac{6.7219 - 0.6492}{7.4996} = 0.8097 \\ h_8 = h_f + x_8 h_{fg} = 191.81 + (0.8097)(2392.1) = 2128.7\ \text{kJ/kg} \end{array}$$

Then, per kg of steam flowing through the boiler, we have

$$w_{\text{T,out}} = (h_6 - h_7) + 0.4(h_7 - h_8) = (3302.9 - 2665.7)\ \text{kJ/kg} + (0.4)(2665.7 - 2128.7)\ \text{kJ/kg} = 852.0\ \text{kJ/kg}$$

$$w_{\text{p,in}} = 0.4w_{\text{pI,in}} + w_{\text{pII,in}} = (0.4)(0.39\ \text{kJ/kg}) + (6.07\ \text{kJ/kg}) = 6.23\ \text{kJ/kg}$$

$$w_{\text{net}} = w_{\text{T,out}} - w_{\text{p,in}} = 852.0 - 6.23 = 845.8\ \text{kJ/kg}$$

Thus,

$$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{15{,}000\ \text{kJ/s}}{845.8\ \text{kJ/kg}} = \mathbf{17.73\ kg/s}$$