while isobutane enters the turbine at 3.25 MPa and 145°C and leaves at 80°C and 400 kPa. Isobutane is condensed in an air-cooled condenser and then pumped to the heat exchanger pressure. Assuming an isentropic efficiency of 90 percent for the pump, determine (*a*) the mass flow rate of isobutane in the binary cycle, (*b*) the net power outputs of both the flashing and the binary sections of the plant, and (*c*) the thermal efficiencies of the binary cycle and the combined plant. The properties of isobutane may be obtained from EES. *Answers:* (*a*) 105.5 kg/s, (*b*) 15.4 MW, 6.14 MW, (*c*) 12.2 percent, 10.6 percent

The Reheat Rankine Cycle

10–28C 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

10–29C Is there an optimal pressure for reheating the steam of a Rankine cycle? Explain.

10–30C Consider a simple ideal 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?

10–31 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 Reconsider Prob. 10–31. Using EES (or other) software, solve this problem by the diagram window data entry feature of EES. Include the effects of the turbine and pump efficiencies and also show the effects of reheat on the steam quality at the low-pressure turbine exit. Plot the cycle on a *T-s* diagram with respect to the saturation lines. Discuss the results of your parametric studies.

10–33 Consider a steam power plant that operates on the ideal reheat Rankine cycle. The plant maintains the inlet of the high-pressure turbine at 4 MPa and 300°C, the inlet of the low-pressure turbine at 1.4 MPa and 300°C, and the condenser at 75 kPa. The net power produced by this plant is 5000 kW. Determine the rate of heat addition and rejection and the thermal efficiency of the cycle.

10–34 In Prob. 10–33, is there any advantage to operating the reheat section of the boiler at 0.8 MPa rather than 1.4 MPa while maintaining the same low-pressure turbine inlet temperature?

10–35 Consider a steam power plant that operates on the ideal reheat Rankine cycle. The plant maintains the boiler at 4000 kPa, the reheat section at 500 kPa, and the condenser at 10 kPa. The mixture quality at the exit of both turbines is 90 percent. Determine the temperature at the inlet of each turbine and the cycle's thermal efficiency. *Answers:* 292°C, 283°C, 33.5 percent

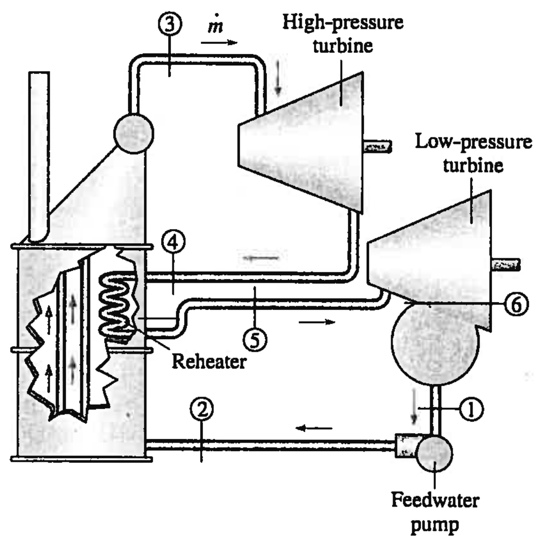

FIGURE P10–35

10–36 Consider a steam power plant that operates on the ideal reheat Rankine cycle. The plant maintains the boiler at 17.5 MPa, the reheater at 2 MPa, and the condenser at 50 kPa. The temperature is 550°C at the entrance of the high-pressure turbine, and 300°C at the entrance of the low-pressure turbine. Determine the thermal efficiency of this system.

10–37 How much does the thermal efficiency of the cycle in Prob. 10–36 change when the temperature at the entrance to the low-pressure turbine is increased to 550°C?

10–38 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.

10–39 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

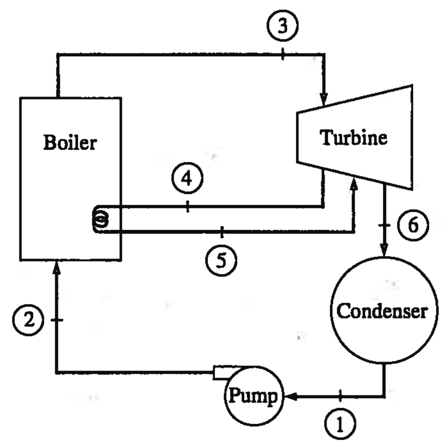

FIGURE P10–39

Regenerative Rankine Cycle

10–40C 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

10–41C 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?

10–42C How do open feedwater heaters differ from closed feedwater heaters?

10–43C 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?

10–44C Devise an ideal regenerative Rankine cycle that has the same thermal efficiency as the Carnot cycle. Show the cycle on a *T-s* diagram.

10–45 Ten kilograms per second of cold feedwater enter a 200-kPa open feedwater heater of a regenerative Rankine cycle at 70°C. Bleed steam is available from the turbine at 200 kPa and 160°C. At what rate must bleed steam be supplied to the open feedwater heater so the feedwater leaves this unit as a saturated liquid?

10–46 In a regenerative Rankine cycle, the closed feedwater heater with a pump as shown in the figure is arranged so that the water at state 5 is mixed with the water at state 2 to form a feedwater which is a saturated liquid at 1.4 MPa. Feedwater enters this heater at 175°C and 1.4 MPa with a flow rate of 1 kg/s. Bleed steam is taken from the turbine at 1 MPa and 200°C, and enters the pump as a saturated liquid at 1 MPa. Determine the mass flow rate of bleed steam required to operate this unit. *Answer:* 0.0445 kg/s

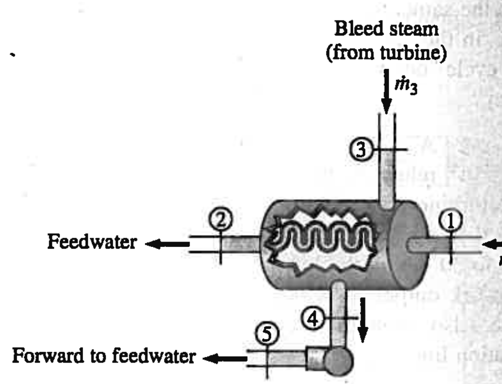

FIGURE P10–46

10–47 Feedwater at 4000 kPa is heated at a rate of 6 kg/s from 200°C to 245°C in a closed feedwater heater of a regenerative Rankine cycle. Bleed steam enters this unit at 3000 kPa with a quality of 90 percent, and leaves as a saturated liquid. Calculate the rate at which bleed steam is required.

10–48 A steam power plant operates on an ideal regenerative Rankine cycle with two open feedwater heaters. Steam enters the turbine at 10 MPa and 600°C and exhausts to the condenser at 5 kPa. Steam is extracted from the turbine at 0.6 and 0.2 MPa. Water leaves both feedwater heaters as a saturated liquid. The mass flow rate of steam through the boiler is 22 kg/s. Show the cycle on a *T-s* diagram, and determine (*a*) the net power output of the power plant and (*b*) the thermal efficiency of the cycle. *Answers:* (*a*) 30.5 MW, (*b*) 47.1 percent

10–49 Consider an ideal steam regenerative Rankine cycle with two feedwater heaters, one closed and one open. Steam enters the turbine at 12.5 MPa and 550°C and exhausts to the condenser at 10 kPa. Steam is extracted from the turbine at 0.8 MPa for the closed feedwater heater and at 0.3 MPa for the open one. The feedwater is heated to the condensation temperature of the extracted steam in the closed feedwater heater. The extracted steam leaves the closed feedwater heater as a saturated liquid, which is subsequently throttled to the open feedwater heater. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the mass flow rate of steam through the boiler for a net power output of 250 MW and (*b*) the thermal efficiency of the cycle.

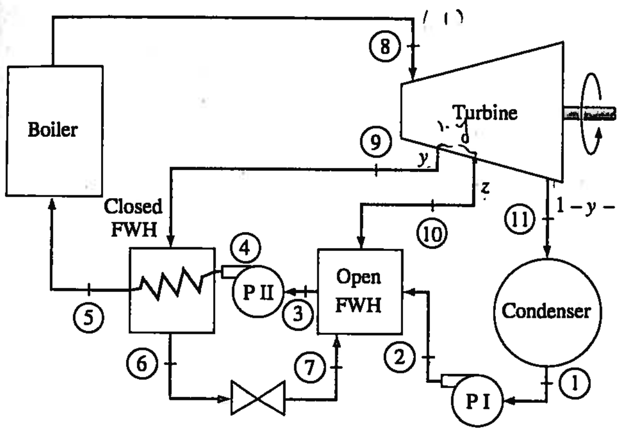

FIGURE P10–49

10–50 Reconsider Prob. 10–49. Using EES (or other) software, investigate the effects of turbine and pump efficiencies as they are varied from 70 percent to 100 percent on the mass flow rate and thermal efficiency. Plot the mass flow rate and the thermal efficiency as a function of turbine efficiency for pump efficiencies of 70, 85, and 100 percent, and discuss the results. Also plot the *T-s* diagram for turbine and pump efficiencies of 85 percent.

10–51 Consider a steam power plant that operates on the ideal regenerative Rankine cycle with a closed feedwater heater as shown in the figure. The plant maintains the turbine inlet at 3000 kPa and 350°C; and operates the condenser at 20 kPa. Steam is extracted at 1000 kPa to serve the closed feedwater heater, which discharges into the condenser after being throttled to condenser pressure. Calculate the work produced by the turbine, the work consumed by the pump, and the heat supply in the boiler for this cycle per unit of boiler flow rate. *Answers:* 741 kJ/kg, 3.0 kJ/kg, 2353 kJ/kg

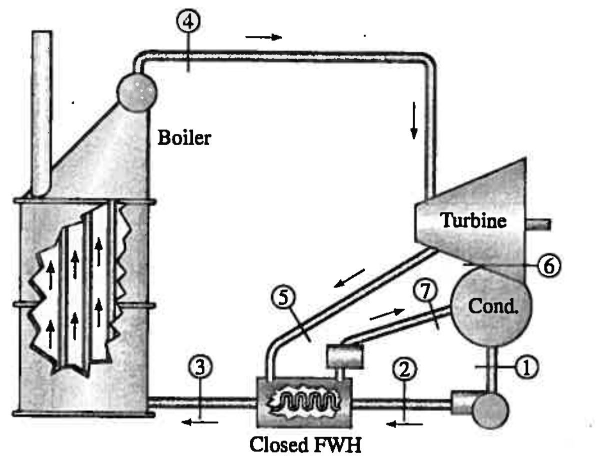

FIGURE P10–51

10–52 How much does the thermal efficiency of the cycle of Prob. 10–51 change when the steam serving the closed feedwater heater is extracted at 600 kPa rather than 1000 kPa?

10–53 Reconsider Prob. 10–51. Using EES (or other) software, determine the optimum bleed pressure for the closed feedwater heater that maximizes the thermal efficiency of the cycle. *Answer:* 220 kPa

10–54 Determine the thermal efficiency of the regenerative Rankine cycle of Prob. 10–51 when the isentropic efficiency of the turbine is 90 percent before and after steam extraction point.

10–55 Determine the thermal efficiency of the regenerative Rankine cycle of Prob. 10–51 when the isentropic efficiency of the turbine before and after steam extraction point is 90 percent and the condenser condensate is subcooled by 10°C.

10–56 Reconsider Prob. 10–51. Using EES (or other) software, determine how much additional heat must be supplied to the boiler when the turbine isentropic efficiency before and after the extraction point is 90 percent and there is a 10 kPa pressure drop across the boiler?

10–57 A steam power plant operates on an ideal reheat–regenerative Rankine cycle with one reheater and two open feedwater heaters. Steam enters the high-pressure turbine at 10 MPa and 600°C and leaves the low-pressure turbine at 7.5 kPa. Steam is extracted from the turbine at 1.8 and 0.3 MPa, and it is reheated to 550°C at a pressure of 1 MPa. Water leaves both feedwater heaters as a saturated liquid. Heat is transferred to the steam in the boiler at a rate of 400 MW. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the mass flow rate of steam through the boiler, (*b*) the net power output of the plant, and (*c*) the thermal efficiency of the cycle.

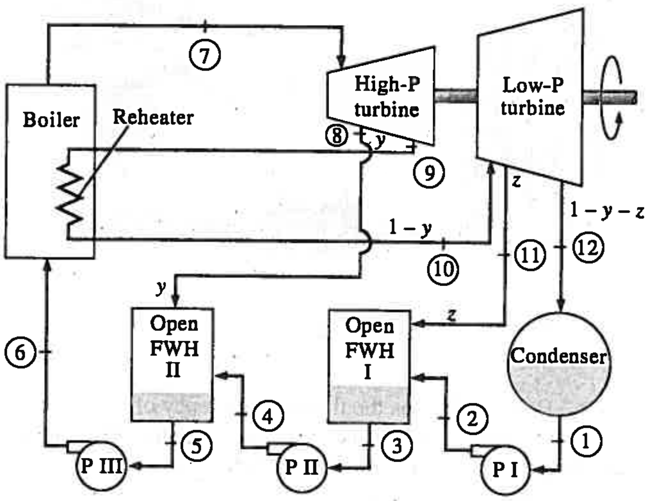

FIGURE P10–57

10–58 A steam power plant operates on the reheat-regenerative Rankine cycle with a closed feedwater heater. Steam enters the turbine at 12.5 MPa and 550°C at a rate of 24 kg/s and is condensed in the condenser at a pressure of 20 kPa. Steam is reheated at 5 MPa to 550°C. Some steam is extracted from the low-pressure turbine at 1.0 MPa, is completely condensed in the closed feedwater heater, and pumped to 12.5 MPa before it mixes with the feedwater at the same pressure. Assuming an isentropic efficiency of 88 percent for both the turbine and the pump, determine (*a*) the temperature of the steam at the inlet of the closed feedwater heater,

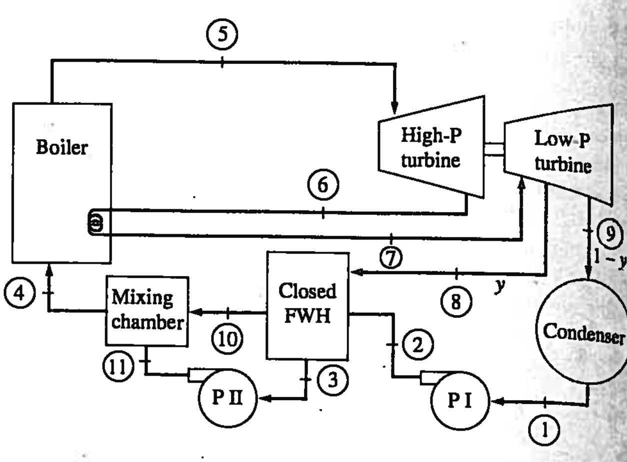

FIGURE P10–58

(*b*) the mass flow rate of the steam extracted from the turbine for the closed feedwater heater, (*c*) the net power output, and (*d*) the thermal efficiency. *Answers:* (*a*) 328°C, (*b*) 4.29 kg/s, (*c*) 28.6 MW, (*d*) 39.3 percent

Second-Law Analysis of Vapor Power Cycles

10–59C How can the second-law efficiency of a simple ideal Rankine cycle be improved?

10–60 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.

10–61 Calculate the exergy destruction in each of the components of the simple ideal Rankine cycle of Prob. 10–14 when heat is being rejected to a lake at 4°C, and heat is being supplied by a 800°C energy reservoir.

10–62 Calculate the exergy destruction in each of the components of the simple ideal Rankine cycle of Prob. 10–16 when heat is being rejected to the atmospheric air at 15°C, and heat is supplied from an energy reservoir at 750°C. *Answer:* 928 kJ/kg (boiler), 307 kJ/kg (condenser)

10–63 Determine the exergy destruction associated with each of the processes of the reheat Rankine cycle described in Prob. 10–31. Assume a source temperature of 1800 K and a sink temperature of 300 K.

10–64 Reconsider Prob. 10–63. Using EES (or other) software, solve this problem by the diagram window data entry feature of EES. Include the effects of the turbine and pump efficiencies to evaluate the irreversibilities associated with each of the processes. Plot the cycle on a *T-s* diagram with respect to the saturation lines. Discuss the results of your parametric studies.

10–65 The schematic of a single-flash geothermal power plant with state numbers is given in Fig. P10–65. 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 is directed to the turbine. The steam leaves the turbine at 10 kPa with a moisture content of 5 percent and enters the condenser where it is condensed; it is routed to a reinjection well along with the liquid coming off the separator. Determine (*a*) the power output of the turbine and the thermal efficiency of the plant, (*b*) the exergy of the geothermal liquid at the exit of the flash chamber, and the exergy destructions and the second-law (exergetic) efficiencies for (*c*) the flash chamber, (*d*) the turbine, and (*e*) the entire plant. *Answers:* (*a*) 10.8 MW, 0.053, (*b*) 17.3 MW, (*c*) 5.1 MW, 0.898, (*d*) 10.9 MW, 0.500, (*e*) 39.0 MW, 0.218

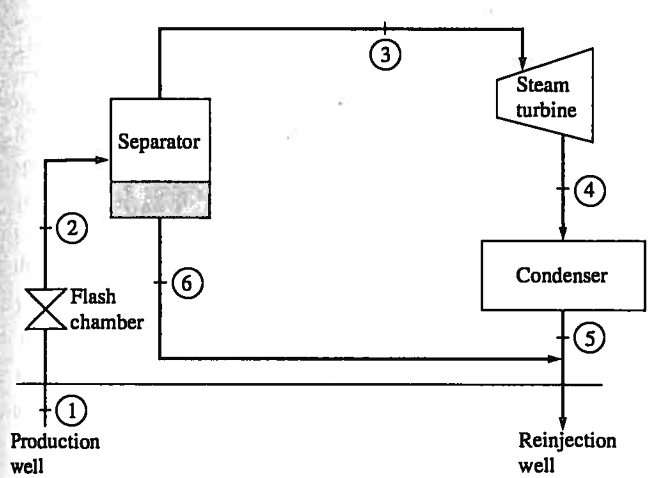

FIGURE P10–65

Cogeneration

10–66C 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?

10–67C Consider a cogeneration plant for which the utilization factor is 1. Is the irreversibility associated with this cycle necessarily zero? Explain.

10–68C 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?

10–69C What is the difference between cogeneration and regeneration?

10–70 Steam enters the turbine of a cogeneration plant at 7 MPa and 500°C. One-fourth of the steam is extracted from the turbine at 600-kPa pressure for process heating. The remaining steam continues to expand to 10 kPa. The extracted steam is then condensed and mixed with feedwater at constant pressure and the mixture is pumped to the boiler pressure of 7 MPa. The mass flow rate of steam through the boiler is 30 kg/s. Disregarding any pressure drops and heat losses in the piping, and assuming the turbine and the pump to be isentropic, determine the net power produced and the utilization factor of the plant.

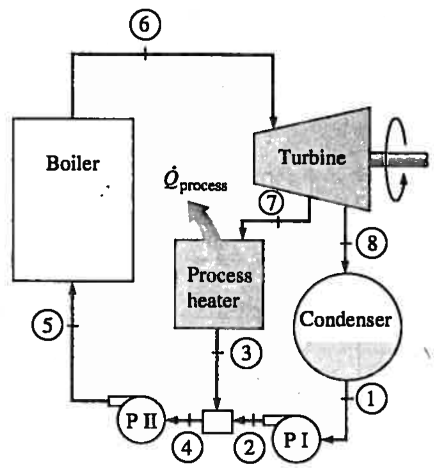

FIGURE P10–70

10–71 Steam is generated in the boiler of a cogeneration plant at 10 MPa and 450°C at a steady rate of 5 kg/s. In normal operation, steam expands in a turbine to a pressure of 0.5 MPa and is then routed to the process heater, where it supplies the process heat. Steam leaves the process heater as a saturated liquid and is pumped to the boiler pressure. In this mode, no steam passes through the condenser, which operates at 20 kPa.

(*a*) Determine the power produced and the rate at which process heat is supplied in this mode.

(*b*) Determine the power produced and the rate of process heat supplied if only 60 percent of the steam is routed to the process heater and the remainder is expanded to the condenser pressure.

10–72 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. Assuming the turbines and the pumps to be isentropic, show the cycle on a *T-s* diagram with respect to saturation lines,

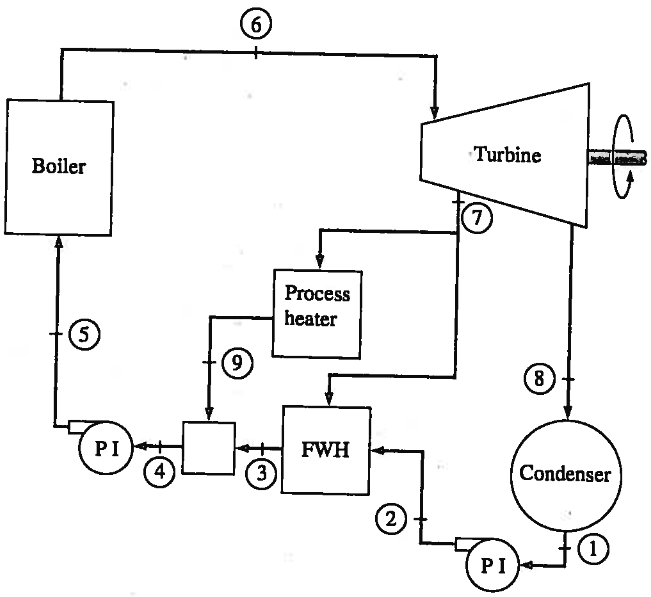

FIGURE P10–72

and determine the mass flow rate of steam through the boiler for a net power output of 15 MW. *Answer:* 17.7 kg/s

10–73 Reconsider Prob. 10–72. Using EES (or other) software, investigate the effect of the extraction pressure for removing steam from the turbine to be used for the process heater and open feedwater heater on the required mass flow rate. Plot the mass flow rate through the boiler as a function of the extraction pressure, and discuss the results.

10–74 Steam is generated in the boiler of a cogeneration plant at 4 MPa and 400°C at a rate of 8 kg/s. The plant is to produce power while meeting the process steam requirements for a certain industrial application. One-third of the steam leaving the boiler is throttled to a pressure of 0.8 MPa and is routed to the process heater. The rest of the steam is expanded in an isentropic turbine to a pressure of 0.8 MPa and is also routed to the process heater. Steam leaves the process heater at 115°C. Neglecting the pump work, determine (*a*) the net power produced, (*b*) the rate of process heat supply, and (*c*) the utilization factor of this plant.

10–75 An ideal cogeneration steam plant is to generate power and 8600 kJ/s of process heat. Steam enters the turbine from the boiler at 7 MPa and 500°C. One-fourth of the steam is extracted from the turbine at 600-kPa pressure for process heating. The remainder of the steam continues to expand and exhausts to the condenser at 10 kPa. The steam extracted for the process heater is condensed in the heater and mixed with the feedwater at 600 kPa. The mixture is pumped to the boiler pressure of 7 MPa. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the mass flow rate of steam that must be supplied by the boiler, (*b*) the net power produced by the plant, and (*c*) the utilization factor.

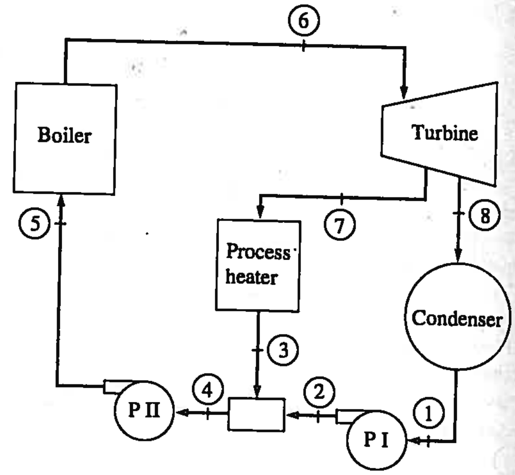

FIGURE P10–75

Combined Gas–Vapor Power Cycles

10–76C In combined gas–steam cycles, what is the energy source for the steam?

10–77C Why is the combined gas–steam cycle more efficient than either of the cycles operated alone?

10–78 Consider a combined gas–steam power plant that has a net power output of 450 MW. The pressure ratio of the gas-turbine cycle is 14. Air enters the compressor at 300 K and the turbine at 1400 K. The combustion gases leaving the gas turbine are used to heat the steam at 8 MPa to 400°C in a heat exchanger. The combustion gases leave the heat exchanger at 460 K. An open feedwater

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heater incorporated with the steam cycle operates at a pressure of 0.6 MPa. The condenser pressure is 20 kPa. Assuming all the compression and expansion processes to be isentropic, determine (*a*) the mass flow rate ration of air to steam, (*b*) the required rate of heat input in the combustion chamber, and (*c*) thermal efficiency of the combined cycle.

10–79 Reconsider Prob. 10–78. Using EES (or other) software, study the effects of the gas cycle pressure ratio as it is varied from 10 to 20 on the ratio of gas flow rate to steam flow rate and cycle thermal efficiency. Plot your results as functions of gas cycle pressure ratio, and discuss the results.

10–80 A combined gas–steam power cycle uses a simple gas turbine for the topping cycle and simple Rankine cycle for the bottoming cycle. Atmospheric air enters the gas turbine at 101 kPa and 20°C, and the maximum gas cycle temperature is 1100°C. The compressor pressure ratio is 8; the compressor isentropic efficiency is 85 percent; and the gas turbine isentropic efficiency is 90 percent. The gas stream leaves the heat exchanger at the saturation temperature of the steam flowing through the heat exchanger. Steam flows through the heat exchanger with a pressure of 6000 kPa, and leaves at 320°C. The steam-cycle condenser operates at 20 kPa, and the isentropic efficiency of the steam turbine is 90 percent. Determine the mass flow rate of air through the air compressor required for this system to produce 100 MW of power. Use constant specific heats for air at room temperature. *Answer:* 279 kg/s

10–81 An ideal regenerator is added to the gas cycle portion of the combined cycle in Prob. 10–80. How much does this change the efficiency of this combined cycle?

10–82 Determine which components of the combined cycle in Prob. 10–80 are the most wasteful of work potential.

10–83 Consider a combined gas–steam power plant that has a net power output of 450 MW. The pressure ratio of the gas-turbine cycle is 14. Air enters the compressor at 300 K and the turbine at 1400 K. The combustion gases leaving the gas turbine are used to heat the steam at 8 MPa to 400°C in a heat exchanger. The combustion gases leave the heat exchanger at 460 K. An open feedwater heater incorporated with the steam cycle operates at a pressure of 0.6 MPa. The condenser pressure is 20 kPa. Assuming isentropic efficiences of 100 percent for the pump, 82 percent for the compressor, and 86 percent for the gas and steam turbines, determine (*a*) the mass flow rate ratio of air to steam, (*b*) the required rate of heat input in the combustion chamber, and (c) the thermal efficiency of the combined cycle.

10–84 Reconsider Prob. 10–83. Using EES (or other) software, study the effects of the gas cycle pressure ratio as it is varied from 10 to 20 on the ratio of gas flow rate to steam flow rate and cycle thermal efficiency. Plot your results as functions of gas cycle pressure ratio, and discuss the results.

10–85 Consider a combined gas–steam power cycle. The topping cycle is a simple Brayton cycle that has a pressure ratio of 7. Air enters the compressor at 15°C at a rate of 10 kg/s and the gas turbine at 950°C. The bottoming cycle is a reheat Rankine cycle between the pressure limits of 6 MPa and 10 kPa. Steam is heated in a heat exchanger at a rate of 1.15 kg/s by the exhaust gases leaving the gas turbine and the exhaust gases leave the heat exchanger at 200°C. Steam leaves the high-pressure turbine at 1.0 MPa and is reheated to 400°C in the heat exchanger before it expands in the low-pressure turbine. Assuming 80 percent isentropic efficiency for all pumps and turbines, determine (*a*) the moisture content at the exit of the low-pressure turbine, (*b*) the steam temperature at the inlet of the high-pressure turbine, (*c*) the net power output and the thermal efficiency of the combined plant.

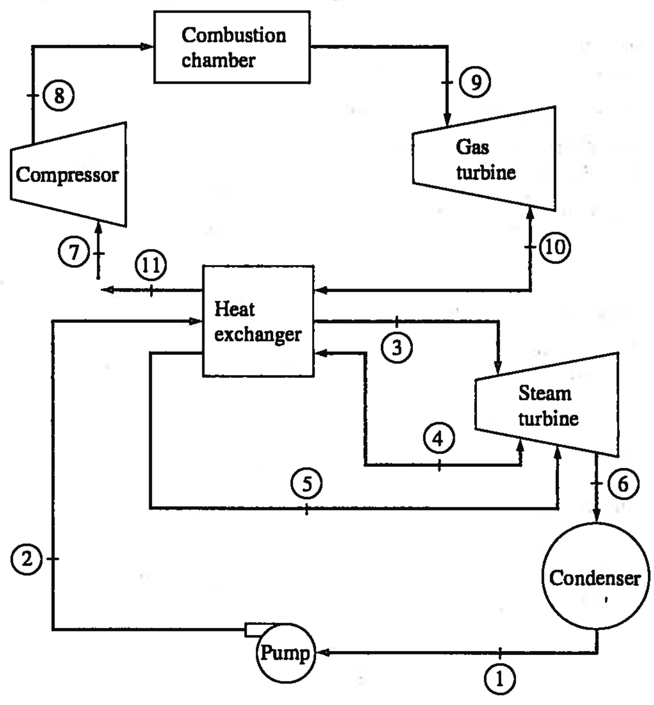

FIGURE P10–85

Special Topic: Binary Vapor Cycles

10–86C What is a binary power cycle? What is its purpose?

10–87C By writing an energy balance on the heat exchanger of a binary vapor power cycle, obtain a relation for the ratio of mass flow rates of two fluids in terms of their enthalpies.

10–88C Why is steam not an ideal working fluid for vapor power cycles?

10–89C Why is mercury a suitable working fluid for the topping portion of a binary vapor cycle but not for the bottoming cycle?

10–90C What is the difference between the binary vapor power cycle and the combined gas–steam power cycle?

Review Problems

10–91 Show that the thermal efficiency of a combined gas–steam power plant η_{cc} can be expressed as

$$\eta_{cc} = \eta_g + \eta_s - \eta_g \eta_s$$

where $\eta_g = W_g/Q_{in}$ and $\eta_s = W_s/Q_{g,out}$ are the thermal efficiencies of the gas and steam cycles, respectively. Using this relation, determine the thermal efficiency of a combined power cycle that consists of a topping gas-turbine cycle with an efficiency of 40 percent and a bottoming steam-turbine cycle with an efficiency of 30 percent.

10–92 It can be shown that the thermal efficiency of a combined gas–steam power plant η_{cc} can be expressed in terms of the thermal efficiencies of the gas- and the steam-turbine cycles as

$$\eta_{cc} = \eta_g + \eta_s - \eta_g \eta_s$$

Prove that the value of η_{cc} is greater than either of η_g or η_s. That is, the combined cycle is more efficient than either of the gas-turbine or steam-turbine cycles alone.

10–93 Consider a steam power plant operating on the ideal Rankine cycle with reheat between the pressure limits of 25 MPa and 10 kPa with a maximum cycle temperature of 600°C and a moisture content of 8 percent at the turbine exit. For a reheat temperature of 600°C, determine the reheat pressures of the cycle for the cases of (*a*) single and (*b*) double reheat.

10–94 A steam power plant operates on an ideal Rankine cycle with two stages of reheat and has a net power output of 120 MW. Steam enters all three stages of the turbine at 500°C. The maximum pressure in the cycle is 15 MPa, and the minimum pressure is 5 kPa. Steam is reheated at 5 MPa the first time and at 1 MPa the second time. 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 mass flow rate of the steam. *Answers:* (*a*) 45.5 percent, (*b*) 64.4 kg/s

10–95 A steam power plant operating on a simple ideal Rankine cycle maintains the boiler at 6000 kPa, the turbine inlet at 600°C, and the condenser at 50 kPa. Compare the thermal efficiency of this cycle when it is operated so that the liquid enters the pump as a saturated liquid against that when the liquid enters the pump 11.3°C cooler than a saturated liquid at the condenser pressure.

10–96 Consider a steam power plant that operates on a regenerative Rankine cycle and has a net power output of 150 MW. Steam enters the turbine at 10 MPa and 500°C and the condenser at 10 kPa. The isentropic efficiency of the turbine is 80 percent, and that of the pumps is 95 percent. Steam is extracted from the turbine at 0.5 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 mass flow rate of steam through the boiler and (*b*) the thermal efficiency of the cycle. Also, determine the exergy destruction associated with the regeneration process. Assume a source temperature of 1300 K and a sink temperature of 303 K.

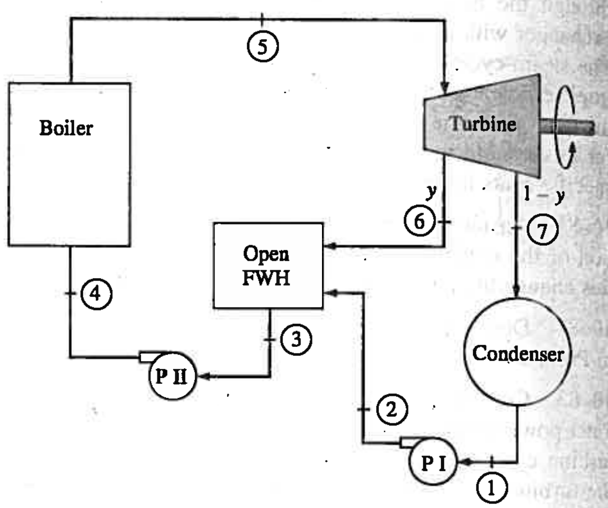

FIGURE P10–96

10–97 Repeat Prob. 10–96 assuming both the pump and the turbine are isentropic.

10–98 Consider an ideal reheat–regenerative Rankine cycle with one open feedwater heater. The boiler pressure is 10 MPa, the condenser pressure is 15 kPa, the reheater pressure is 1 MPa, and the feedwater pressure is 0.6 MPa. Steam enters both the high- and low-pressure turbines at 500°C. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the fraction of steam extracted for regeneration and (*b*) the thermal efficiency of the cycle. *Answers:* (*a*) 0.144, (*b*) 42.1 percent

10–99 Repeat Prob. 10–98 assuming an isentropic efficiency of 84 percent for the turbines and 100 percent for the pumps.

10–100 A steam power plant operating on the ideal reheat-regenerative Rankine cycle with three feedwater heaters as shown in the figure maintains the boiler at 8000 kPa, the condenser at 10 kPa, the reheater at 300 kPa, the high-pressure, closed feedwater heater at 6000 kPa, the low-pressure, closed feedwater heater at 3500 kPa, and the open feedwater heater at 100 kPa. The temperature at the inlet of both turbines is 400°C. Determine the following quantities for this system per unit mass flow rate through the boiler.

(*a*) The flow rate required to service the high-pressure, closed feedwater heater.
(*b*) The flow rate required to service the low-pressure, closed feedwater heater.
(*c*) The flow rate required to service the open feedwater heater.
(*d*) The flow through the condenser.
(*e*) The work produced by the high-pressure turbine.
(*f*) The work produced by the low-pressure turbine.
(*g*) The heat supplied in the boiler and reheater.
(*h*) The heat rejected in the condenser.
(*i*) The thermal efficiency.

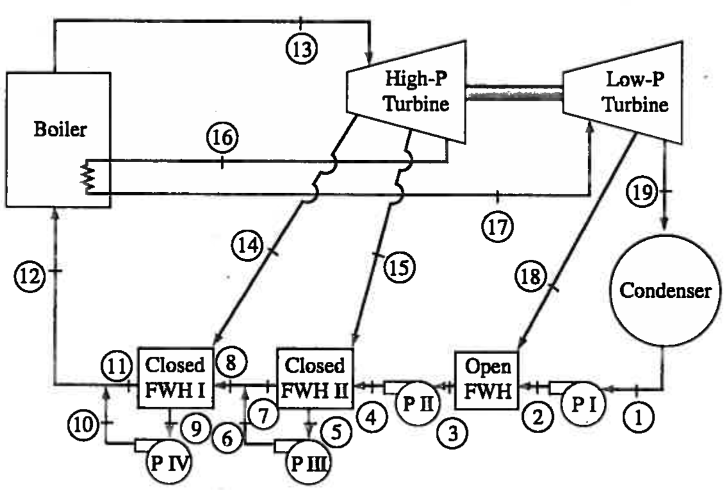

FIGURE P10–100

10–101 Reconsider Prob. 10–100. Using EES (or other) software, determine the optimum bleed pressure for the open feedwater heater that maximizes the thermal efficiency of the cycle.

10–102 Atmospheric air enters the air compressor of a simple combined gas-steam power system at 100 kPa and 27°C. The air compressor's compression ratio is 10; the gas cycle's maximum temperature is 1147°C; and the air compressor and turbine have an isentropic efficiency of 90 percent. The gas leaves the heat exchanger 30°C hotter than the saturation temperature of the steam in the heat exchanger. The steam pressure in the heat exchanger is 6 MPa, and the steam leaves the heat exchanger at 300°C. The steam-condenser pressure is 30 kPa and the isentropic efficiency of the steam turbine is 95 percent. Determine the overall thermal efficiency of this combined cycle. For air, use constant specific heats at room temperature. *Answer:* 46.3 percent

10–103 It has been suggested that the steam passing through the condenser of the combined cycle in Prob. 10–102 be routed to buildings during the winter to heat them. When this is done, the pressure in the heating system where the steam is now condensed will have to be increased to 60 kPa. How does this change the overall thermal efficiency of the combined cycle?

10–104 During winter, the system of Prob. 103 must supply 585 kW of heat to the buildings. What is the mass flow rate

of air through the air compressor and the system's total electrical power production in winter?
Answers: 3.61 kg/s, 1339 kW

10–105 The gas-turbine cycle of a combined gas–steam power plant has a pressure ratio of 8. Air enters the compressor at 290 K and the turbine at 1400 K. The combustion gases leaving the gas turbine are used to heat the steam at 15 MPa to 450°C in a heat exchanger. The combustion gases leave the heat exchanger at 247°C. Steam expands in a high-pressure turbine to a pressure of 3 MPa and is reheated in the combustion chamber to 500°C before it expands in a low-pressure turbine to 10 kPa. The mass flow rate of steam is 30 kg/s. Assuming all the compression and expansion processes to be isentropic, determine (*a*) the mass flow rate of air in the gas-turbine cycle, (*b*) the rate of total heat input, and (*c*) the thermal efficiency of the combined cycle.
Answers: (*a*) 263 kg/s, (*b*) 2.80×10^5 kJ/s, (*c*) 55.6 percent

10–106 Repeat Prob. 10–105 assuming isentropic efficiencies of 100 percent for the pump, 80 percent for the compressor, and 85 percent for the gas and steam turbines.

10–107 Starting with Eq. 10–20, show that the exergy destruction associated with a simple ideal Rankine cycle can be expressed as $i = q_{in}(\eta_{th,Carnot} - \eta_{th})$, where η_{th} is efficiency of the Rankine cycle and $\eta_{th,Carnot}$ is the efficiency of the Carnot cycle operating between the same temperature limits.

10–108 Steam is to be supplied from a boiler to a high-pressure turbine whose isentropic efficiency is 75 percent at conditions to be determined. The steam is to leave the high-pressure turbine as a saturated vapor at 1.4 MPa, and the turbine is to produce 1 MW of power. Steam at the turbine exit is extracted at a rate of 1000 kg/min and routed to a process heater while the rest of the steam is supplied to a low-pressure turbine whose isentropic efficiency is 60 percent. The low-pressure turbine allows the steam to expand to 10 kPa pressure and produces 0.8 MW of power. Determine the temperature, pressure, and the flow rate of steam at the inlet of the high-pressure turbine.

10–109 A textile plant requires 4 kg/s of saturated steam at 2 MPa, which is extracted from the turbine of a cogeneration plant. Steam enters the turbine at 8 MPa and 500°C at a rate of 11 kg/s and leaves at 20 kPa. The extracted steam leaves the process heater as a saturated liquid and mixes with the feedwater at constant pressure. The mixture is pumped to the boiler pressure. Assuming an isentropic efficiency of 88 percent for both the turbine and the pumps, determine (*a*) the rate of process heat supply, (*b*) the net power output, and (*c*) the utilization factor of the plant. *Answers:* (*a*) 8.56 MW, (*b*) 8.60 MW, (*c*) 53.8 percent

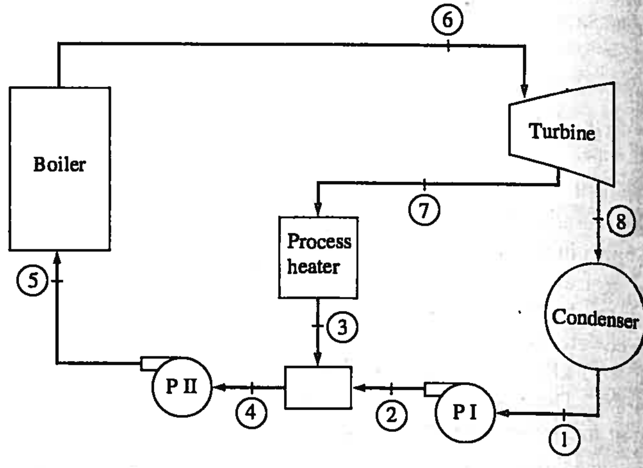

FIGURE P10–109

10–110 A Rankine steam cycle modified for reheat, a closed feedwater heater, and an open feedwater heater is shown below. The high-pressure turbine receives 100 kg/s of steam from the steam boiler. The feedwater heaters exit states for the boiler feedwater and the condensed steam are the normally assumed ideal states. The following data tables give the saturation data for the pressures and data for h and s at selected states. (*a*) Sketch the *T-s* diagram for the ideal cycle. (*b*) Determine the net power output of the cycle, in MW. (*c*) If cooling water is available at 25°C, what is the minimum flow rate of the cooling water required for the ideal cycle, in kg/s? Take $c_{p,\text{ water}} = 4.18$ kJ/kg·K.

Process states and selected data

State	*P*, kPa	*T*, °C	*h*, kJ/kg	*s*, kJ/kg·K
1	20			
2	1400			
3	1400			
4	1400			
5	5000			
6	5000	700	3894	7.504
7	1400		3400	7.504
8	1200		3349	7.504
9	1200	600	3692	7.938
10	245		3154	7.938
11	20		2620	7.938

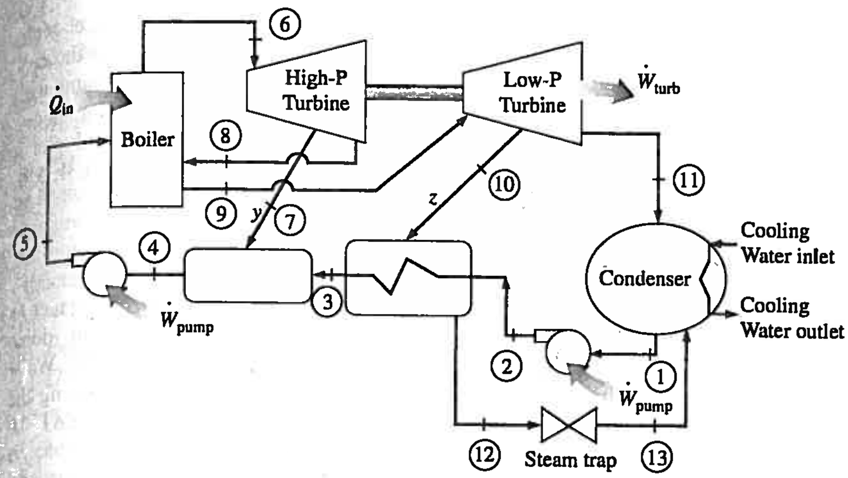

FIGURE P10–110

Saturation data				
P, kPa	T, °C	v_f, m³/kg	h_f, kJ/kg	s_g, kJ/kg · K
20	60.1	0.00102	251.4	7.791
245	126.7	0.00106	532	7.061
1200	188	0.00114	798	6.519
1400	195	0.00115	830	6.519
5000	264	0.00129	1154	5.979

10–111 A Rankine steam cycle modified for reheat and three closed feedwater heaters is shown below. The high-pressure turbine receives 100 kg/s of steam from the steam boiler. The feedwater heaters exit states for the boiler feedwater and the condensed steam are the normally assumed ideal states. The following data tables give the saturation data for the pressures and data for h and s at selected states. (*a*) Sketch the T-s diagram for the ideal cycle. (*b*) Determine the net power output of the cycle, in MW. (*c*) If the cooling water is limited to a 10°C temperature rise, what is the flow rate of the cooling water required for the ideal cycle, in kg/s? Take $c_{p,\text{water}}$ = 4.18 kJ/kg · K.

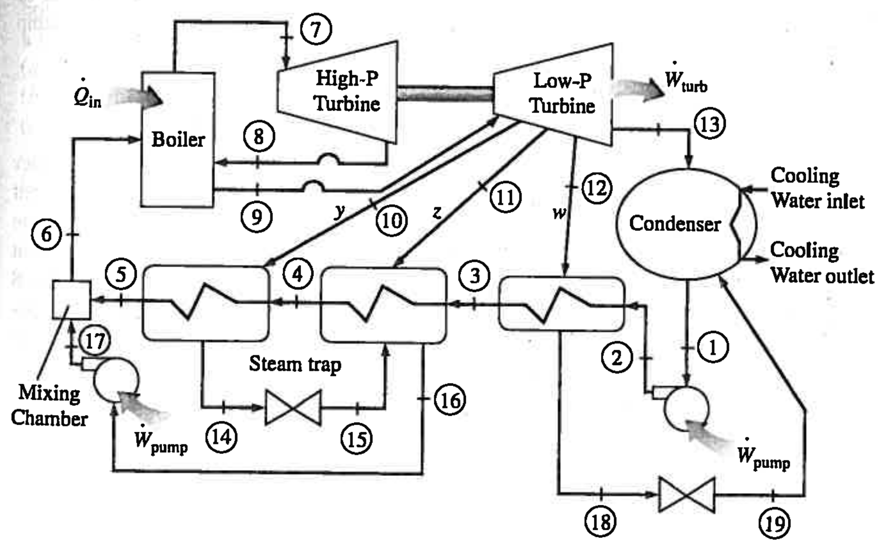

FIGURE P10–111

9–20 Repeat Prob. 9–19 using constant specific heats at room temperature.

9–21 Consider a Carnot cycle executed in a closed system with 0.003 kg of air. The temperature limits of the cycle are 300 and 900 K, and the minimum and maximum pressures that occur during the cycle are 20 and 2000 kPa. Assuming constant specific heats, determine the net work output per cycle.

9–22 Consider a Carnot cycle executed in a closed system with air as the working fluid. The maximum pressure in the cycle is 800 kPa while the maximum temperature is 750 K. If the entropy increase during the isothermal heat rejection process is 0.25 kJ/kg · K and the net work output is 100 kJ/kg, determine (a) the minimum pressure in the cycle, (b) the heat rejection from the cycle, and (c) the thermal efficiency of the cycle. (d) If an actual heat engine cycle operates between the same temperature limits and produces 5200 kW of power for an air flow rate of 90 kg/s, determine the second law efficiency of this cycle.

9–23 An ideal gas Carnot cycle uses air as the working fluid, receives heat from a heat reservoir at 1027°C, is repeated 1500 times per minute, and has a compression ratio of 12. The compression ratio is defined as the volume ratio during the compression process. Determine the maximum temperature of the low-temperature heat reservoir, the cycle's thermal efficiency, and the amount of heat that must be supplied per cycle if this device is to produce 500 kW of power. *Answers:* 481 K, 63.0 percent, 31.8 kJ

9–24 The thermal energy reservoirs of an ideal gas Carnot cycle are at 670°C and 4°C, and the device executing this cycle rejects 100 kJ of heat each time the cycle is executed. Determine the total heat supplied to and the total work produced by this cycle each time it is executed.

Otto Cycle

9–25C What four processes make up the ideal Otto cycle?

9–26C How do the efficiencies of the ideal Otto cycle and the Carnot cycle compare for the same temperature limits? Explain.

9–27C How is the rpm (revolutions per minute) of an actual four-stroke gasoline engine related to the number of thermodynamic cycles? What would your answer be for a two-stroke engine?

9–28C Are the processes that make up the Otto cycle analyzed as closed-system or steady-flow processes? Why?

9–29C How does the thermal efficiency of an ideal Otto cycle change with the compression ratio of the engine and the specific heat ratio of the working fluid?

9–30C Why are high compression ratios not used in spark-ignition engines?

9–31C An ideal Otto cycle with a specified compression ratio is executed using (*a*) air, (*b*) argon, and (*c*) ethane as the working fluid. For which case will the thermal efficiency be the highest? Why?

9–32C What is the difference between fuel-injected gasoline engines and diesel engines?

9–33 An ideal Otto cycle has a compression ratio of 12, takes in air at 100 kPa and 20°C, and is repeated 1000 times per minute. Using constant specific heats at room temperature, determine the thermal efficiency of this cycle and the rate of heat input if the cycle is to produce 200 kW of power.

9–34 Repeat Prob. 9–33 for a compression ratio of 10.

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

9–36 Repeat Prob. 9–35, but replace the isentropic expansion process by a polytropic expansion process with the polytropic exponent $n = 1.35$.

9–37 An ideal Otto cycle with air as the working fluid has a compression ratio of 8. The minimum and maximum temperatures in the cycle are 300 and 1340 K. Accounting for the variation of specific heats with temperature, determine (*a*) the amount of heat transferred to the air during the heat-addition process, (*b*) the thermal efficiency, and (*c*) the thermal efficiency of a Carnot cycle operating between the same temperature limits.

9–38 Repeat Prob. 9–37 using argon as the working fluid.

9–39 A four-cylinder, four-stroke, 2.2-L gasoline engine operates on the Otto cycle with a compression ratio of 10. The air is at 100 kPa and 60°C at the beginning of the compression process, and the maximum pressure in the cycle is 8 MPa. The compression and expansion processes may be modeled as polytropic with a polytropic constant of 1.3. Using constant specific heats at 850 K, determine (*a*) the temperature at the end of the expansion process, (*b*) the net work output and the thermal efficiency, (*c*) the mean effective pressure, (*d*) the engine speed for a net power output of 70 kW, and (*e*) the specific fuel consumption, in g/kWh, defined as the ratio of the mass of the fuel consumed to the net work produced. The air–fuel ratio, defined as the amount of air divided by the amount of fuel intake, is 16.

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9–40 Determine the mean effective pressure of an ideal Otto cycle that uses air as the working fluid; its state at the beginning of the compression is 96 kPa and 17°C; its temperature at the end of the combustion is 817°C; and its compression ratio is 9. Use constant specific heats at room temperature.

9–41 Determine the rate of heat addition and rejection for the Otto cycle of Prob. 9–40 when it produces 105 kW and the cycle is repeated 1400 times per minute.

9–42 When we double the compression ratio of an ideal Otto cycle, what happens to the maximum gas temperature and pressure when the state of the air at the beginning of the compression and the amount of heat addition remain the same? Use constant specific heats at room temperature.

9–43 In a spark-ignition engine, some cooling occurs as the gas is expanded. This may be modeled by using a polytropic process in lieu of the isentropic process. Determine if the polytropic exponent used in this model will be greater than or less than the isentropic exponent.

9–44 An ideal Otto cycle has a compression ratio of 7. At the beginning of the compression process, $P_1 = 90$ kPa, $T_1 =$ 27°C, and $V_1 = 0.004\ m^3$. The maximum cycle temperature is 1127°C. For each repetition of the cycle, calculate the heat rejection and the net work production. Also calculate the thermal efficiency and mean effective pressure for this cycle. Use constant specific heats at room temperature. *Answers:* 1.03 kJ, 1.21 kJ, 54.1 percent, 354 kPa

9–45 A six-cylinder, 4-L spark-ignition engine operating on the ideal Otto cycle takes in air at 90 kPa and 20°C. The minimum enclosed volume is 15 percent of the maximum enclosed volume. When operated at 2500 rpm, this engine produces 90 hp. Determine the rate of heat addition to this engine. Use constant specific heats at room temperature.

Diesel Cycle

9–46C How does a diesel engine differ from a gasoline engine?

9–47C How does the ideal Diesel cycle differ from the ideal Otto cycle?

9–48C For a specified compression ratio, is a diesel or gasoline engine more efficient?

9–49C Do diesel or gasoline engines operate at higher compression ratios? Why?

9–50C What is the cutoff ratio? How does it affect the thermal efficiency of a Diesel cycle?

9–51 Develop an expression for cutoff ratio r_c which expresses it in terms of $q_{in}/(c_p T_1 r^{k-1})$ for an air-standard Diesel cycle.

9–52 An ideal Diesel cycle has a compression ratio of 18 and a cutoff ratio of 1.5. Determine the maximum air temperature and the rate of heat addition to this cycle when it produces 200 hp of power; the cycle is repeated 1200 times per minute; and the state of the air at the beginning of the compression is 95 kPa and 17°C. Use constant specific heats at room temperature.

9–53 Rework Prob. 9–52 when the isentropic compression efficiency is 90 percent and the isentropic expansion efficiency is 95 percent.

9–54 An ideal Diesel cycle has a maximum cycle temperature of 2000°C and a cutoff ratio of 1.2. The state of the air at the beginning of the compression is $P_1 = 95$ kPa and $T_1 =$ 15°C. This cycle is executed in a four-stroke, eight-cylinder engine with a cylinder bore of 10 cm and a piston stroke of 12 cm. The minimum volume enclosed in the cylinder is 5 percent of the maximum cylinder volume. Determine the power produced by this engine when it is operated at 1600 rpm. Use constant specific heats at room temperature. *Answer:* 105 kW

9–55 An air-standard Diesel cycle has a compression ratio of 18.2. Air is at 27°C and 100 kPa at the beginning of the compression process and at 1700 K at the end of the heat-addition process. Accounting for the variation of specific heats with temperature, determine (*a*) the cutoff ratio, (*b*) the heat rejection per unit mass, and (*c*) the thermal efficiency.

9–56 Repeat Prob. 9–55 using constant specific heats at room temperature.

9–57 An ideal diesel engine has a compression ratio of 20 and uses air as the working fluid. The state of air at the beginning of the compression process is 95 kPa and 20°C. If the maximum temperature in the cycle is not to exceed 2200 K, determine (*a*) the thermal efficiency and (*b*) the mean effective pressure. Assume constant specific heats for air at room temperature. *Answers:* (*a*) 63.5 percent, (*b*) 933 kPa

9–58 Repeat Prob. 9–57, but replace the isentropic expansion process by polytropic expansion process with the polytropic exponent $n = 1.35$.

9–59 Reconsider Prob. 9–58. Using EES (or other) software, study the effect of varying the compression ratio from 14 to 24. Plot the net work output, mean effective pressure, and thermal efficiency as a function of the compression ratio. Plot the *T-s* and *P-v* diagrams for the cycle when the compression ratio is 20.

9–60 A four-cylinder two-stroke 2.4-L diesel engine that operates on an ideal Diesel cycle has a compression ratio of 17 and a cutoff ratio of 2.2. Air is at 55°C and 97 kPa at the beginning of the compression process. Using the cold-air-standard assumptions, determine how much power the engine will deliver at 1500 rpm.

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

9–62 An air-standard dual cycle has a compression ratio of 18 and a cutoff ratio of 1.1. The pressure ratio during constant-volume heat addition process is 1.1. At the beginning of the compression, P_1 = 90 kPa, T_1 = 18°C, and V_1 = 0.003 m^3. How much power will this cycle produce when it is executed 4000 times per minute? Use constant specific heats at room temperature.

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

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

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

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

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

Stirling and Ericsson Cycles

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

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

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

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

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

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

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

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

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

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

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

Ideal and Actual Gas-Turbine (Brayton) Cycles

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

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

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

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

10-31

10-34 *[Also solved by EES on enclosed CD]* A steam power plant that operates on the ideal reheat Rankine 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.

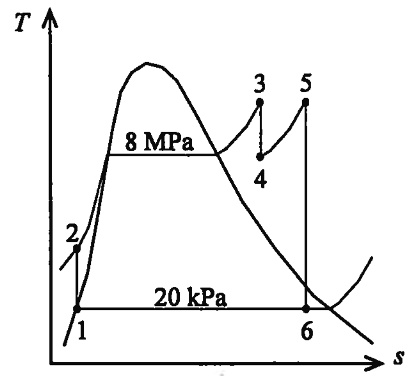
Analysis From the steam tables (Tables A-4, A-5, and A-6),

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

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

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

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



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

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

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

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

The turbine work output and the thermal efficiency are determined from

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

and

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

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

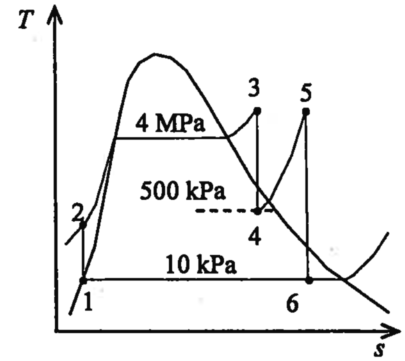
Thus,

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

10-35

[redacted] An ideal reheat Rankine with water as the working fluid is considered. The temperatures at the inlet of both turbines, 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),

$$h_1 = h_{f@\,10\,\text{kPa}} = 191.81\ \text{kJ/kg}$$
$$v_1 = v_{f@10\,\text{kPa}} = 0.001010\ \text{m}^3/\text{kg}$$

$$\begin{aligned} w_{\text{p,in}} &= v_1(P_2 - P_1) \\ &= (0.001010\ \text{m}^3/\text{kg})(4000-10)\text{kPa}\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= 4.03\ \text{kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{\text{p,in}} = 191.81 + 4.03 = 195.84\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 500\ \text{kPa} \\ x_4 = 0.90 \end{array}\right\} \begin{array}{l} h_4 = h_f + x_4 h_{fg} = 640.09 + (0.90)(2108.0) = 2537.3\ \text{kJ/kg} \\ s_4 = s_f + x_4 s_{fg} = 1.8604 + (0.90)(4.9603) = 6.3247\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_3 = 4000\ \text{kPa} \\ s_3 = s_4 \end{array}\right\} \begin{array}{l} h_3 = 2939.4\ \text{kJ/kg} \\ T_3 = \mathbf{292.2^\circ C} \end{array}$$

$$\left.\begin{array}{l} P_6 = 10\ \text{kPa} \\ x_6 = 0.90 \end{array}\right\} \begin{array}{l} h_6 = h_f + x_6 h_{fg} = 191.81 + (0.90)(2392.1) = 2344.7\ \text{kJ/kg} \\ s_6 = s_f + x_6 s_{fg} = 0.6492 + (0.90)(7.4996) = 7.3989\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_5 = 500\ \text{kPa} \\ s_5 = s_6 \end{array}\right\} \begin{array}{l} h_5 = 3029.2\ \text{kJ/kg} \\ T_5 = \mathbf{282.9^\circ C} \end{array}$$

Thus,

$$q_{\text{in}} = (h_3 - h_2) + (h_5 - h_4) = 2939.4 - 195.84 + 3029.2 - 2537.3 = 3235.4\ \text{kJ/kg}$$
$$q_{\text{out}} = h_6 - h_1 = 2344.7 - 191.81 = 2152.9\ \text{kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{2152.9}{3235.4} = \mathbf{0.335}$$

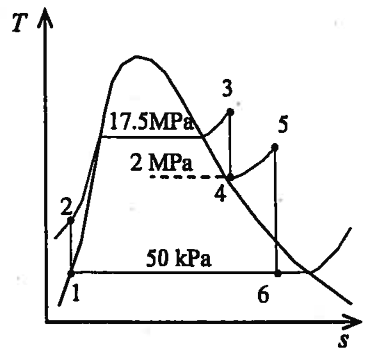
10-36

10-39 An ideal reheat Rankine cycle with water as the working fluid is considered. The thermal efficiency of the cycle 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 or EES),

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



$$\begin{aligned} w_{\text{p,in}} &= v_1(P_2 - P_1) \\ &= (0.001030 \text{ m}^3\text{/kg})(17500 - 50)\text{kPa}\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) \\ &= 17.97 \text{ kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{\text{p,in}} = 340.54 + 17.97 = 358.51 \text{ kJ/kg}$$

$$\left.\begin{aligned} P_3 &= 17{,}500 \text{ kPa} \\ T_3 &= 550°\text{C} \end{aligned}\right\} \begin{aligned} h_3 &= 3423.6 \text{ kJ/kg} \\ s_3 &= 6.4266 \text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_4 &= 2000 \text{ kPa} \\ s_4 &= s_3 \end{aligned}\right\} h_4 = 2841.5 \text{ kJ/kg}$$

$$\left.\begin{aligned} P_5 &= 2000 \text{ kPa} \\ T_5 &= 300°\text{C} \end{aligned}\right\} \begin{aligned} h_5 &= 3024.2 \text{ kJ/kg} \\ s_5 &= 6.7684 \text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_6 &= 50 \text{ kPa} \\ s_6 &= s_5 \end{aligned}\right\} \begin{aligned} x_6 &= \frac{s_6 - s_f}{s_{fg}} = \frac{6.7684 - 1.0912}{6.5019} = 0.8732 \\ h_6 &= h_f + x_6 h_{fg} = 340.54 + (0.8732)(2304.7) = 2352.9 \text{ kJ/kg} \end{aligned}$$

Thus,

$$q_{\text{in}} = (h_3 - h_2) + (h_5 - h_4) = 3423.6 - 358.51 + 3024.2 - 2841.5 = 3247.8 \text{ kJ/kg}$$
$$q_{\text{out}} = h_6 - h_1 = 2352.9 - 340.54 = 2012.4 \text{ kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{2012.4}{3247.8} = \mathbf{0.380}$$

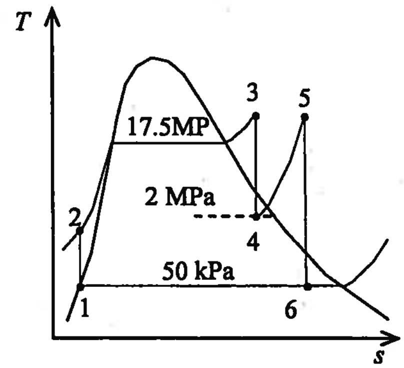
10-37

~~10-40~~ An ideal reheat Rankine cycle with water as the working fluid is considered. The thermal efficiency of the cycle 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 or EES),

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



$$\begin{aligned} w_{p,\text{in}} &= v_1(P_2 - P_1) \\ &= (0.001030\ \text{m}^3/\text{kg})(17500 - 50)\text{kPa}\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= 17.97\ \text{kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{p,\text{in}} = 340.54 + 17.97 = 358.52\ \text{kJ/kg}$$

$$\left.\begin{aligned} P_3 &= 17{,}500\ \text{kPa} \\ T_3 &= 550°\text{C} \end{aligned}\right\} \begin{aligned} h_3 &= 3423.6\ \text{kJ/kg} \\ s_3 &= 6.4266\ \text{kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_4 &= 2000\ \text{kPa} \\ s_4 &= s_3 \end{aligned}\right\} h_4 = 2841.5\ \text{kJ/kg}$$

$$\left.\begin{aligned} P_5 &= 2000\ \text{kPa} \\ T_5 &= 550°\text{C} \end{aligned}\right\} \begin{aligned} h_5 &= 3579.0\ \text{kJ/kg} \\ s_5 &= 7.5725\ \text{kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_6 &= 50\ \text{kPa} \\ s_6 &= s_5 \end{aligned}\right\} \begin{aligned} x_6 &= \frac{s_6 - s_f}{s_{fg}} = \frac{7.5725 - 1.0912}{6.5019} = 0.9968 \\ h_6 &= h_f + x_6 h_{fg} = 340.54 + (0.9968)(2304.7) = 2638.0\ \text{kJ/kg} \end{aligned}$$

Thus,

$$q_{\text{in}} = (h_3 - h_2) + (h_5 - h_4) = 3423.6 - 358.52 + 3579.0 - 2841.5 = 3802.6\ \text{kJ/kg}$$
$$q_{\text{out}} = h_6 - h_1 = 2638.0 - 340.54 = 2297.4\ \text{kJ/kg}$$

and

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{2297.4}{3802.6} = \mathbf{0.396}$$

The thermal efficiency was determined to be 0.380 when the temperature at the inlet of low-pressure turbine was 300°C. When this temperature is increased to 550°C, the thermal efficiency becomes 0.396. This corresponding to a percentage increase of 4.2% in thermal efficiency.

10-38

~~10-41~~ 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.

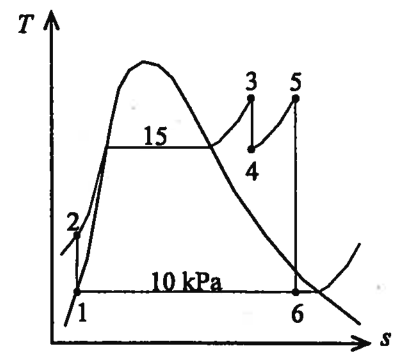
Analysis (*a*) From the steam tables (Tables A-4, A-5, and A-6),

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

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

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

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



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

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

$$\left.\begin{aligned} T_5 &= 500°\text{C} \\ s_5 &= s_6 \end{aligned}\right\} \begin{aligned} P_5 &= \mathbf{2150 \text{ kPa}} \text{ (the reheat pressure)} \\ h_5 &= 3466.61 \text{ kJ/kg} \end{aligned}$$

$$\left.\begin{aligned} P_4 &= 2.15 \text{ MPa} \\ s_4 &= s_3 \end{aligned}\right\} h_4 = 2817.2 \text{ kJ/kg}$$

(*b*) The rate of heat supply is

$$\begin{aligned} \dot{Q}_{\text{in}} &= \dot{m}[(h_3 - h_2) + (h_5 - h_4)] \\ &= (12 \text{ kg/s})(3310.8 - 206.95 + 3466.61 - 2817.2)\text{kJ/kg} = \mathbf{45{,}039 \text{ kW}} \end{aligned}$$

(*c*) The thermal efficiency is determined from

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

Thus,

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

10-47

10-91 The closed feedwater heater of a regenerative Rankine cycle is to heat feedwater to a saturated liquid. The required mass flow rate of bleed steam is to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** There are no work interactions. **4** Heat loss from the device to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid.

Properties From the steam tables (Tables A-4 through A-6),

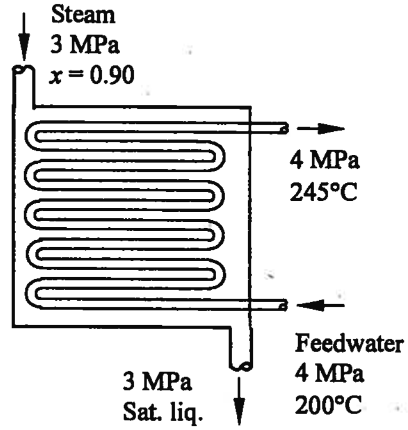
$$\left.\begin{array}{l} P_1 = 4000\text{ kPa} \\ T_1 = 200°\text{C} \end{array}\right\} h_1 \cong h_{f@200°\text{C}} = 852.26\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 4000\text{ kPa} \\ T_2 = 245°\text{C} \end{array}\right\} h_2 \cong h_{f@245°\text{C}} = 1061.5\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 3000\text{ kPa} \\ x_3 = 0.90 \end{array}\right\} h_3 = h_f + x_3 h_{fg}$$

$$= 1008.3 + (0.9)(1794.9) = 2623.7\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 3000\text{ kPa} \\ x_4 = 0 \end{array}\right\} h_4 = h_{f@3000\text{ kPa}} = 1008.3\text{ kJ/kg}$$



Analysis We take the heat exchanger as the system, which is a control volume. The mass and energy balances for this steady-flow system can be expressed in the rate form as

Mass balance (for each fluid stream):

$$\dot{m}_{in} - \dot{m}_{out} = \Delta\dot{m}_{system}^{\nearrow 0\text{ (steady)}} = 0 \rightarrow \dot{m}_{in} = \dot{m}_{out} \rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}_{fw} \text{ and } \dot{m}_3 = \dot{m}_4 = \dot{m}_s$$

Energy balance (for the heat exchanger):

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta\dot{E}_{system}^{\nearrow 0\text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

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

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \quad (\text{since } \dot{Q} = \dot{W} = \Delta\text{ke} \cong \Delta\text{pe} \cong 0)$$

Combining the two,

$$\dot{m}_{fw}(h_2 - h_1) = \dot{m}_s(h_3 - h_4)$$

Solving for $\dot{m}_s$:

$$\dot{m}_s = \frac{h_2 - h_1}{h_3 - h_4}\dot{m}_{fw}$$

Substituting,

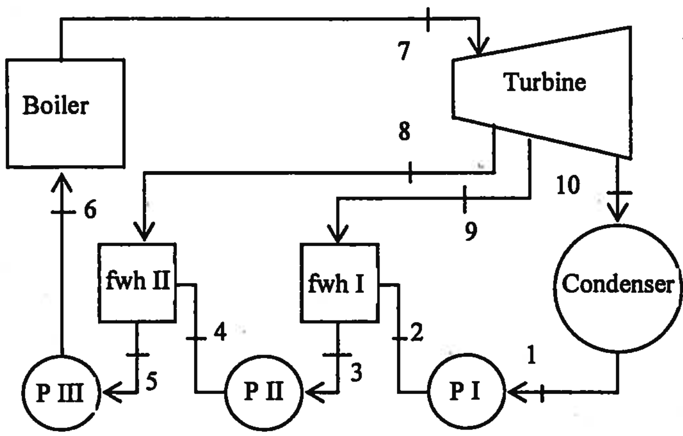
$$\dot{m}_s = \frac{1061.5 - 852.26}{2623.7 - 1008.3}(6\text{ kg/s}) = \mathbf{0.777\text{ kg/s}}$$

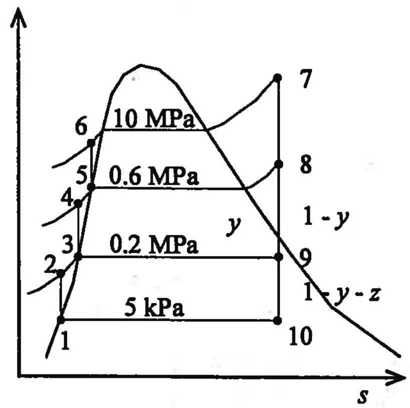
10-48

~~10-52~~ A steam power plant operates on an ideal regenerative Rankine cycle with two open feedwater heaters. The net power output of the power plant 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),

$$h_1 = h_{f@\,5\text{ kPa}} = 137.75 \text{ kJ/kg}$$
$$v_1 = v_{f@\,5\text{ kPa}} = 0.001005 \text{ m}^3/\text{kg}$$
$$w_{pI,\text{in}} = v_1(P_2 - P_1) = (0.001005 \text{ m}^3/\text{kg})(200 - 5 \text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 0.20 \text{ kJ/kg}$$
$$h_2 = h_1 + w_{pI,\text{in}} = 137.75 + 0.20 = 137.95 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 0.2 \text{ MPa} \\ \text{sat.liquid} \end{array}\right\} \begin{array}{l} h_3 = h_{f@\,0.2\text{ MPa}} = 504.71 \text{ kJ/kg} \\ v_3 = v_{f@\,0.2\text{ MPa}} = 0.001061 \text{ m}^3/\text{kg} \end{array}$$

$$w_{pII,\text{in}} = v_3(P_4 - P_3) = (0.001061 \text{ m}^3/\text{kg})(600 - 200 \text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$
$$= 0.42 \text{ kJ/kg}$$
$$h_4 = h_3 + w_{pII,\text{in}} = 504.71 + 0.42 = 505.13 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 0.6 \text{ MPa} \\ \text{sat.liquid} \end{array}\right\} \begin{array}{l} h_5 = h_{f@\,0.6\text{ MPa}} = 670.38 \text{ kJ/kg} \\ v_5 = v_{f@\,0.6\text{ MPa}} = 0.001101 \text{ m}^3/\text{kg} \end{array}$$

$$w_{pIII,\text{in}} = v_5(P_6 - P_5) = (0.001101 \text{ m}^3/\text{kg})(10{,}000 - 600 \text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$
$$= 10.35 \text{ kJ/kg}$$

$$h_6 = h_5 + w_{pIII,\text{in}} = 670.38 + 10.35 = 680.73 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_7 = 10 \text{ MPa} \\ T_7 = 600°\text{C} \end{array}\right\} \begin{array}{l} h_7 = 3625.8 \text{ kJ/kg} \\ s_7 = 6.9045 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_8 = 0.6 \text{ MPa} \\ s_8 = s_7 \end{array}\right\} h_8 = 2821.8 \text{ kJ/kg}$$

$$P_9 = 0.2 \text{ MPa} \atop s_9 = s_7 \left.\right\} \begin{array}{l} x_9 = \dfrac{s_9 - s_f}{s_{fg}} = \dfrac{6.9045 - 1.5302}{5.5968} = 0.9602 \\ h_9 = h_f + x_9 h_{fg} = 504.71 + (0.9602)(2201.6) = 2618.7 \text{ kJ/kg} \end{array}$$

$$P_{10} = 5 \text{ kPa} \atop s_{10} = s_7 \left.\right\} \begin{array}{l} x_{10} = \dfrac{s_{10} - s_f}{s_{fg}} = \dfrac{6.9045 - 0.4762}{7.9176} = 0.8119 \\ h_{10} = h_f + x_{10} h_{fg} = 137.75 + (0.8119)(2423.0) = 2105.0 \text{ kJ/kg} \end{array}$$

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

FWH-2:

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

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

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_8 h_8 + \dot{m}_4 h_4 = \dot{m}_5 h_5 \longrightarrow y h_8 + (1-y) h_4 = 1(h_5)$$

where y is the fraction of steam extracted from the turbine ($= \dot{m}_8 / \dot{m}_5$). Solving for y,

$$y = \frac{h_5 - h_4}{h_8 - h_4} = \frac{670.38 - 505.13}{2821.8 - 505.13} = 0.07133$$

FWH-1:

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_9 h_9 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \longrightarrow z h_9 + (1-y-z) h_2 = (1-y) h_3$$

where z is the fraction of steam extracted from the turbine ($= \dot{m}_9 / \dot{m}_5$) at the second stage. Solving for z,

$$z = \frac{h_3 - h_2}{h_9 - h_2}(1-y) = \frac{504.71 - 137.95}{2618.7 - 137.95}(1 - 0.07136) = 0.1373$$

Then,

$$q_{\text{in}} = h_7 - h_6 = 3625.8 - 680.73 = 2945.0 \text{ kJ/kg}$$
$$q_{\text{out}} = (1-y-z)(h_{10} - h_1) = (1 - 0.07133 - 0.1373)(2105.0 - 137.75) = 1556.8 \text{ kJ/kg}$$
$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 2945.0 - 1556.8 = 1388.2 \text{ kJ/kg}$$

and

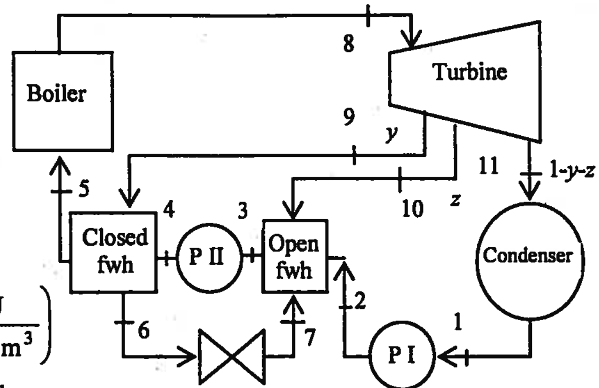
$$\dot{W}_{\text{net}} = \dot{m} w_{\text{net}} = (22 \text{ kg/s})(1388.2 \text{ kJ/kg}) = 30{,}540 \text{ kW} \cong \mathbf{30.5 \text{ MW}}$$

(*b*) $$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1556.8 \text{ kJ/kg}}{2945.0 \text{ kJ/kg}} = \mathbf{47.1\%}$$

10-49

~~10-58~~ [*Also solved by EES on enclosed CD*] A steam power plant operates on an ideal regenerative Rankine cycle with two feedwater heaters, one closed and one open. The mass flow rate of steam through the boiler for a net power output of 250 MW and the thermal efficiency of the cycle are to be determined.

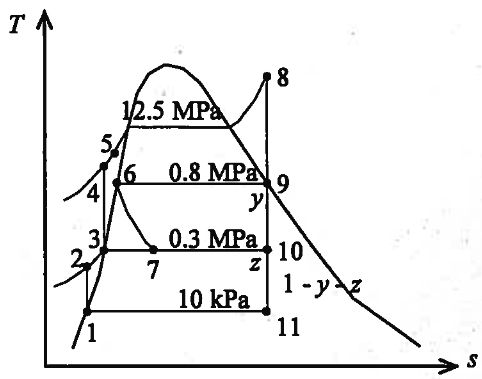
Assumptions 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are negligible.



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

$$h_1 = h_{f @ 10\text{ kPa}} = 191.81 \text{ kJ/kg}$$
$$v_1 = v_{f @ 10\text{ kPa}} = 0.00101 \text{ m}^3\text{/kg}$$
$$w_{pI,\text{in}} = v_1(P_2 - P_1)$$
$$= (0.00101 \text{ m}^3\text{/kg})(300 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$
$$= 0.29 \text{ kJ/kg}$$
$$h_2 = h_1 + w_{pI,\text{in}} = 191.81 + 0.29 = 192.10 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 0.3 \text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} h_3 = h_{f @ 0.3\text{ MPa}} = 561.43 \text{ kJ/kg} \\ v_3 = v_{f @ 0.3\text{ MPa}} = 0.001073 \text{ m}^3\text{/kg} \end{array}$$
$$w_{pII,\text{in}} = v_3(P_4 - P_3)$$
$$= (0.001073 \text{ m}^3\text{/kg})(12{,}500 - 300 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$
$$= 13.09 \text{ kJ/kg}$$
$$h_4 = h_3 + w_{pII,\text{in}} = 561.43 + 13.09 = 574.52 \text{ kJ/kg}$$



$$\left.\begin{array}{l} P_6 = 0.8 \text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} h_6 = h_7 = h_{f @ 0.8\text{ MPa}} = 720.87 \text{ kJ/kg} \\ v_6 = v_{f @ 0.8\text{ MPa}} = 0.001115 \text{ m}^3\text{/kg} \\ T_6 = T_{\text{sat} @ 0.8\text{ MPa}} = 170.4°\text{C} \end{array}$$

$$T_6 = T_5,\ P_5 = 12.5 \text{ MPa} \rightarrow h_5 = 727.83 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_8 = 12.5 \text{ MPa} \\ T_8 = 550°\text{C} \end{array}\right\} \begin{array}{l} h_8 = 3476.5 \text{ kJ/kg} \\ s_8 = 6.6317 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_9 = 0.8 \text{ MPa} \\ s_9 = s_8 \end{array}\right\} \begin{array}{l} x_9 = \dfrac{s_9 - s_f}{s_{fg}} = \dfrac{6.6317 - 2.0457}{4.6160} = 0.9935 \\ h_9 = h_f + x_9 h_{fg} = 720.87 + (0.9935)(2047.5) = 2755.0 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_{10} = 0.3 \text{ MPa} \\ s_{10} = s_8 \end{array}\right\} \begin{array}{l} x_{10} = \dfrac{s_{10} - s_f}{s_{fg}} = \dfrac{6.6317 - 1.6717}{5.3200} = 0.9323 \\ h_{10} = h_f + x_{10} h_{fg} = 561.43 + (0.9323)(2163.5) = 2578.5 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_{11} = 10 \text{ kPa} \\ s_{11} = s_8 \end{array}\right\} \begin{array}{l} x_{11} = \dfrac{s_{11} - s_f}{s_{fg}} = \dfrac{6.6317 - 0.6492}{7.4996} = 0.7977 \\ h_{11} = h_f + x_{11} h_{fg} = 191.81 + (0.7977)(2392.1) = 2100.0 \text{ kJ/kg} \end{array}$$

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

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\not{0}\,(steady)} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_9(h_9 - h_6) = \dot{m}_5(h_5 - h_4) \longrightarrow y(h_9 - h_6) = (h_5 - h_4)$$

where y is the fraction of steam extracted from the turbine ($= \dot{m}_{10} / \dot{m}_5$). Solving for y,

$$y = \frac{h_5 - h_4}{h_9 - h_6} = \frac{727.83 - 574.52}{2755.0 - 720.87} = 0.0753$$

For the open FWH,

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\not{0}\,(steady)} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_7 h_7 + \dot{m}_2 h_2 + \dot{m}_{10} h_{10} = \dot{m}_3 h_3 \longrightarrow y h_7 + (1 - y - z)h_2 + z h_{10} = (1)h_3$$

where z is the fraction of steam extracted from the turbine ($= \dot{m}_9 / \dot{m}_5$) at the second stage. Solving for z,

$$z = \frac{(h_3 - h_2) - y(h_7 - h_2)}{h_{10} - h_2} = \frac{561.43 - 192.10 - (0.0753)(720.87 - 192.10)}{2578.5 - 192.10} = 0.1381$$

Then,

$$q_{in} = h_8 - h_5 = 3476.5 - 727.36 = 2749.1 \text{ kJ/kg}$$
$$q_{out} = (1 - y - z)(h_{11} - h_1) = (1 - 0.0753 - 0.1381)(2100.0 - 191.81) = 1500.1 \text{ kJ/kg}$$
$$w_{net} = q_{in} - q_{out} = 2749.1 - 1500.1 = 1249 \text{ kJ/kg}$$

and

$$\dot{m} = \frac{\dot{W}_{net}}{w_{net}} = \frac{250{,}000 \text{ kJ/s}}{1249 \text{ kJ/kg}} = \mathbf{200.2\ kg/s}$$

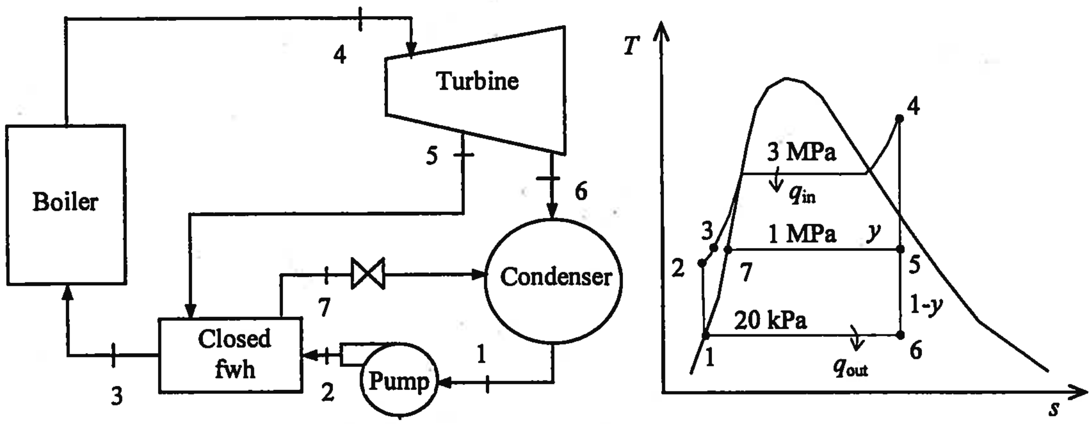
(*b*) $$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1500.1 \text{ kJ/kg}}{2749.1 \text{ kJ/kg}} = \mathbf{45.4\%}$$

10-51

~~10-55~~ An ideal regenerative Rankine cycle with a closed feedwater heater is considered. The work produced by the turbine, the work consumed by the pumps, and the heat added in the boiler 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),



$$h_1 = h_{f@\,20\,\text{kPa}} = 251.42 \text{ kJ/kg}$$
$$v_1 = v_{f@\,20\,\text{kPa}} = 0.001017 \text{ m}^3\text{/kg}$$

$$\begin{aligned} w_{\text{p,in}} &= v_1(P_2 - P_1) \\ &= (0.001017 \text{ m}^3\text{/kg})(3000 - 20)\text{kPa}\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) \\ &= 3.03 \text{ kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{\text{p,in}} = 251.42 + 3.03 = 254.45 \text{ kJ/kg}$$

$$\left.\begin{aligned} P_4 &= 3000 \text{ kPa} \\ T_4 &= 350°\text{C} \end{aligned}\right\} \begin{aligned} h_4 &= 3116.1 \text{ kJ/kg} \\ s_4 &= 6.7450 \text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_5 &= 1000 \text{ kPa} \\ s_5 &= s_4 \end{aligned}\right\} h_5 = 2851.9 \text{ kJ/kg}$$

$$\left.\begin{aligned} P_6 &= 20 \text{ kPa} \\ s_6 &= s_4 \end{aligned}\right\} \begin{aligned} x_6 &= \frac{s_6 - s_f}{s_{fg}} = \frac{6.7450 - 0.8320}{7.0752} = 0.8357 \\ h_6 &= h_f + x_6 h_{fg} = 251.42 + (0.8357)(2357.5) = 2221.7 \text{ kJ/kg} \end{aligned}$$

For an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure.

$$\left.\begin{aligned} P_7 &= 1000 \text{ kPa} \\ x_7 &= 0 \end{aligned}\right\} \begin{aligned} h_7 &= 762.51 \text{ kJ/kg} \\ T_7 &= 179.9°\text{C} \end{aligned}$$

$$\left.\begin{aligned} P_3 &= 3000 \text{ kPa} \\ T_3 &= T_7 = 209.9°\text{C} \end{aligned}\right\} h_3 = 763.53 \text{ kJ/kg}$$

An energy balance on the heat exchanger gives the fraction of steam extracted from the turbine ($= \dot{m}_5 / \dot{m}_4$) for closed feedwater heater:

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$
$$\dot{m}_5 h_5 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_7 h_7$$
$$y h_5 + 1 h_2 = 1 h_3 + y h_7$$

Rearranging,

$$y = \frac{h_3 - h_2}{h_5 - h_7} = \frac{763.53 - 254.45}{2851.9 - 762.51} = 0.2437$$

Then,

$$w_{\mathrm{T,out}} = h_4 - h_5 + (1-y)(h_5 - h_6) = 3116.1 - 2851.9 + (1 - 0.2437)(2851.9 - 2221.7) = \mathbf{740.9\ kJ/kg}$$
$$w_{\mathrm{P,in}} = \mathbf{3.03\ kJ/kg}$$
$$q_{\mathrm{in}} = h_4 - h_3 = 3116.1 - 763.53 = \mathbf{2353\ kJ/kg}$$

Also,

$$w_{\mathrm{net}} = w_{\mathrm{T,out}} - w_{\mathrm{P,in}} = 740.9 - 3.03 = 737.8 \text{ kJ/kg}$$

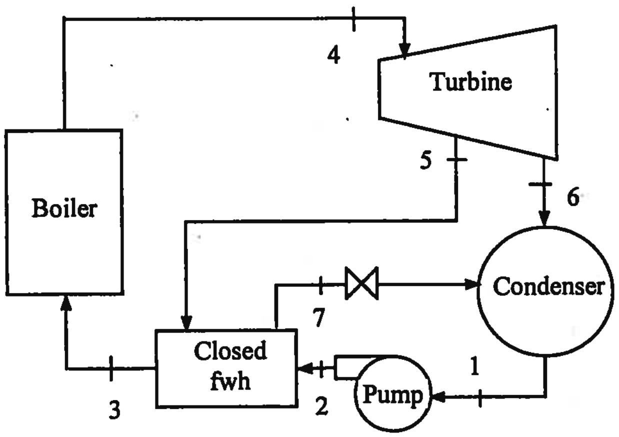
$$\eta_{\mathrm{th}} = \frac{w_{\mathrm{net}}}{q_{\mathrm{in}}} = \frac{737.8}{2353} = 0.3136$$

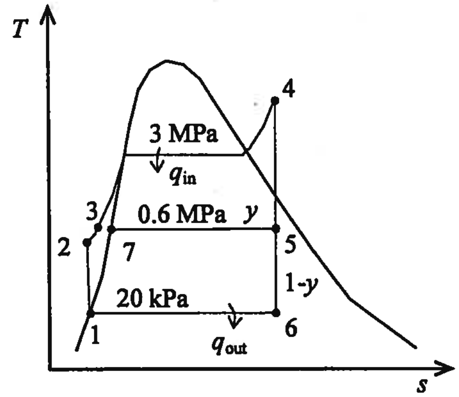
10-52

~~10-56~~ An ideal regenerative Rankine cycle with a closed feedwater heater is considered. The change in thermal efficiency when the steam serving the closed feedwater heater is extracted at 600 kPa rather than 1000 kPa 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 or EES),





$$h_1 = h_{f@\,20\,\text{kPa}} = 251.42\ \text{kJ/kg}$$
$$v_1 = v_{f@\,20\,\text{kPa}} = 0.001017\ \text{m}^3/\text{kg}$$

$$\begin{aligned} w_{p,\text{in}} &= v_1(P_2 - P_1) \\ &= (0.001017\ \text{m}^3/\text{kg})(3000-20)\text{kPa}\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= 3.03\ \text{kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{p,\text{in}} = 251.42 + 3.03 = 254.45\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 3000\ \text{kPa} \\ T_4 = 350^\circ\text{C} \end{array}\right\} \begin{array}{l} h_4 = 3116.1\ \text{kJ/kg} \\ s_4 = 6.7450\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_5 = 600\ \text{kPa} \\ s_5 = s_4 \end{array}\right\} \begin{array}{l} x_5 = \dfrac{s_5 - s_f}{s_{fg}} = \dfrac{6.7450 - 1.9308}{4.8285} = 0.9970 \\ h_5 = h_f + x_5 h_{fg} = 670.38 + (0.9970)(2085.8) = 2750.0\ \text{kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_6 = 20\ \text{kPa} \\ s_6 = s_4 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{6.7450 - 0.8320}{7.0752} = 0.8357 \\ h_6 = h_f + x_6 h_{fg} = 251.42 + (0.8357)(2357.5) = 2221.7\ \text{kJ/kg} \end{array}$$

For an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure.

$$\left.\begin{array}{l} P_7 = 600\ \text{kPa} \\ x_7 = 0 \end{array}\right\} \begin{array}{l} h_7 = 670.38\ \text{kJ/kg} \\ T_7 = 158.8^\circ\text{C} \end{array}$$

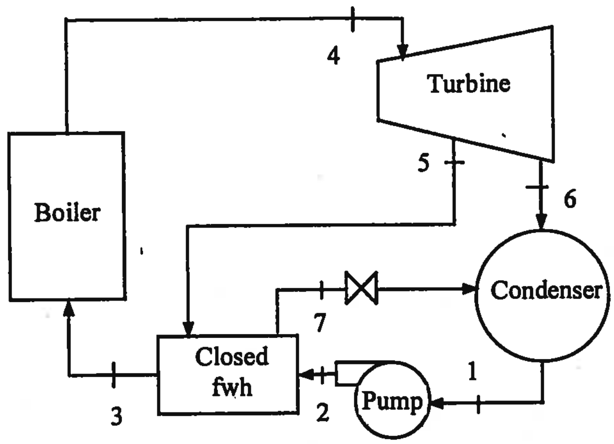
$$\left.\begin{array}{l} P_3 = 3000\ \text{kPa} \\ T_3 = T_7 = 158.8^\circ\text{C} \end{array}\right\} h_3 = 671.79\ \text{kJ/kg}$$

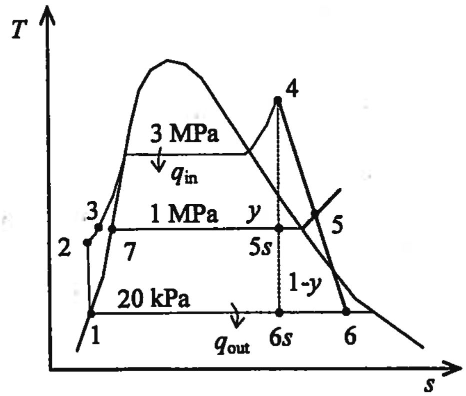
10-54

~~10-58~~ A regenerative Rankine cycle with a closed feedwater heater is considered. The thermal efficiency 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 or EES),





$$h_1 = h_{f@\,20\text{ kPa}} = 251.42\text{ kJ/kg}$$
$$v_1 = v_{f@\,20\text{ kPa}} = 0.001017\text{ m}^3\text{/kg}$$

$$\begin{aligned} w_{\text{p,in}} &= v_1(P_2 - P_1) \\ &= (0.001017\text{ m}^3\text{/kg})(3000-20)\text{kPa}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 3.03\text{ kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{\text{p,in}} = 251.42 + 3.03 = 254.45\text{ kJ/kg}$$

$$\left.\begin{aligned} P_4 &= 3000\text{ kPa} \\ T_4 &= 350°\text{C} \end{aligned}\right\} \begin{aligned} h_4 &= 3116.1\text{ kJ/kg} \\ s_4 &= 6.7450\text{ kJ/kg}\cdot\text{K} \end{aligned}$$

$$\left.\begin{aligned} P_5 &= 1000\text{ kPa} \\ s_{5s} &= s_4 \end{aligned}\right\} h_{5s} = 2851.9\text{ kJ/kg}$$

$$\left.\begin{aligned} P_6 &= 20\text{ kPa} \\ s_{6s} &= s_4 \end{aligned}\right\} \begin{aligned} x_{6s} &= \frac{s_{6s} - s_f}{s_{fg}} = \frac{6.7450 - 0.8320}{7.0752} = 0.8357 \\ h_{6s} &= h_f + x_{6s}h_{fg} = 251.42 + (0.8357)(2357.5) = 2221.7\text{ kJ/kg} \end{aligned}$$

$$\eta_T = \frac{h_4 - h_5}{h_4 - h_{5s}} \longrightarrow h_5 = h_4 - \eta_T(h_4 - h_{5s}) = 3116.1 - (0.90)(3116.1 - 2851.9) = 2878.3\text{ kJ/kg}$$

$$\eta_T = \frac{h_4 - h_6}{h_4 - h_{6s}} \longrightarrow h_6 = h_4 - \eta_T(h_4 - h_{6s}) = 3116.1 - (0.90)(3116.1 - 2221.7) = 2311.1\text{ kJ/kg}$$

For an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure.

$$\left.\begin{array}{l} P_7 = 1000 \text{ kPa} \\ x_7 = 0 \end{array}\right\} \begin{array}{l} h_7 = 762.51 \text{ kJ/kg} \\ T_7 = 179.9°\text{C} \end{array}$$

$$\left.\begin{array}{l} P_3 = 3000 \text{ kPa} \\ T_3 = T_7 = 209.9°\text{C} \end{array}\right\} h_3 = 763.53 \text{ kJ/kg}$$

An energy balance on the heat exchanger gives the fraction of steam extracted from the turbine ($= \dot{m}_5 / \dot{m}_4$) for closed feedwater heater:

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

$$\dot{m}_5 h_5 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_7 h_7$$

$$y h_5 + 1 h_2 = 1 h_3 + y h_7$$

Rearranging,

$$y = \frac{h_3 - h_2}{h_5 - h_7} = \frac{763.53 - 254.45}{2878.3 - 762.51} = 0.2406$$

Then,

$$w_{\text{T,out}} = h_4 - h_5 + (1-y)(h_5 - h_6) = 3116.1 - 2878.3 + (1 - 0.2406)(2878.3 - 2311.1) = 668.5 \text{ kJ/kg}$$

$$w_{\text{P,in}} = 3.03 \text{ kJ/kg}$$

$$q_{\text{in}} = h_4 - h_3 = 3116.1 - 763.53 = 2353 \text{ kJ/kg}$$

Also,

$$w_{\text{net}} = w_{\text{T,out}} - w_{\text{P,in}} = 668.5 - 3.03 = 665.5 \text{ kJ/kg}$$

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{665.5}{2353} = \mathbf{0.2829}$$

10-58

~~10-62~~ A steam power plant that operates on an ideal regenerative Rankine cycle with a closed feedwater heater is considered. The temperature of the steam at the inlet of the closed feedwater heater, the mass flow rate of the steam extracted from the turbine for the closed feedwater heater, 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.

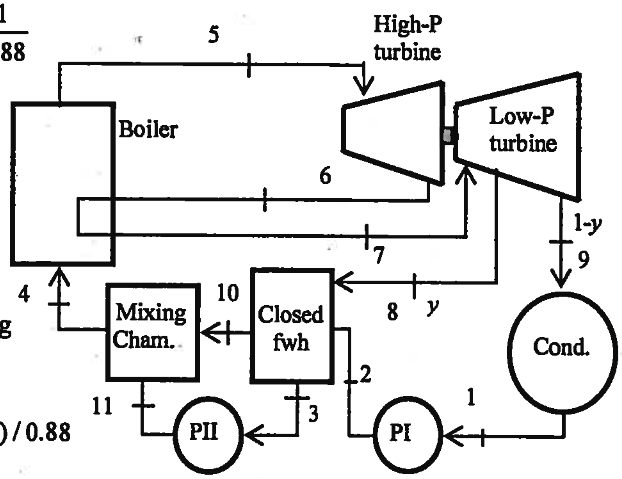
Analysis (*a*) From the steam tables (Tables A-4, A-5, and A-6),

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

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

$$\begin{aligned} w_{pI,\text{in}} &= v_1(P_2 - P_1)/\eta_p \\ &= (0.001017 \text{ m}^3\text{/kg})(12{,}500 - 20 \text{ kPa})\frac{1}{0.88} \\ &= 14.43 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} h_2 &= h_1 + w_{pI,\text{in}} \\ &= 251.42 + 14.43 \\ &= 265.85 \text{ kJ/kg} \end{aligned}$$



$$\left.\begin{array}{l} P_3 = 1 \text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} h_3 = h_{f@\,1\text{ MPa}} = 762.51 \text{ kJ/kg} \\ v_3 = v_{f@\,1\text{ MPa}} = 0.001127 \text{ m}^3\text{/kg} \end{array}$$

$$\begin{aligned} w_{pII,\text{in}} &= v_3(P_{11} - P_3)/\eta_p \\ &= (0.001127 \text{ m}^3\text{/kg})(12{,}500 - 1000 \text{ kPa})/0.88 \\ &= 14.73 \text{ kJ/kg} \end{aligned}$$

$$h_{11} = h_3 + w_{pII,\text{in}} = 762.51 + 14.73 = 777.25 \text{ kJ/kg}$$

Also, $h_4 = h_{10} = h_{11} = 777.25$ kJ/kg since the two fluid streams which are being mixed have the same enthalpy.

$$\left.\begin{array}{l} P_5 = 12.5 \text{ MPa} \\ T_5 = 550°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3476.5 \text{ kJ/kg} \\ s_5 = 6.6317 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 5 \text{ MPa} \\ s_6 = s_5 \end{array}\right\} h_{6s} = 3185.6 \text{ kJ/kg}$$

$$\eta_T = \frac{h_5 - h_6}{h_5 - h_{6s}} \longrightarrow h_6 = h_5 - \eta_T(h_5 - h_{6s})$$
$$= 3476.5 - (0.88)(3476.5 - 3185.6) = 3220.5 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_7 = 5 \text{ MPa} \\ T_7 = 550°\text{C} \end{array}\right\} \begin{array}{l} h_7 = 3550.9 \text{ kJ/kg} \\ s_7 = 7.1238 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_8 = 1 \text{ MPa} \\ s_8 = s_7 \end{array}\right\} h_{8s} = 3051.1 \text{ kJ/kg}$$

$$\eta_T = \frac{h_7 - h_8}{h_7 - h_{8s}} \longrightarrow h_8 = h_7 - \eta_T(h_7 - h_{8s})$$
$$= 3550.9 - (0.88)(3550.9 - 3051.1) = 3111.1 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_8 = 1 \text{ MPa} \\ h_8 = 3111.1 \text{ kJ/kg} \end{array}\right\} T_8 = \mathbf{328°C}$$

$$\left.\begin{array}{l} P_9 = 20\text{ kPa} \\ s_9 = s_7 \end{array}\right\} h_{9s} = 2347.9\text{ kJ/kg}$$

$$\eta_T = \frac{h_7 - h_9}{h_7 - h_{9s}} \longrightarrow h_9 = h_7 - \eta_T(h_7 - h_{9s})$$
$$= 3550.9 - (0.88)(3550.9 - 2347.9) = 2492.2\text{ kJ/kg}$$

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

$$(1-y)(h_{10} - h_2) = y(h_8 - h_3)$$

$$(1-y)(777.25 - 265.85) = y(3111.1 - 762.51) \longrightarrow y = 0.1788$$

The corresponding mass flow rate is

$$\dot{m}_8 = y\dot{m}_5 = (0.1788)(24\text{ kg/s}) = \mathbf{4.29\text{ kg/s}}$$

(*c*) Then,

$$q_{\text{in}} = h_5 - h_4 + h_7 - h_6 = 3476.5 - 777.25 + 3550.9 - 3220.5 = 3029.7\text{ kJ/kg}$$
$$q_{\text{out}} = (1-y)(h_9 - h_1) = (1 - 0.1788)(2492.2 - 251.42) = 1840.1\text{ kJ/kg}$$

and

$$\dot{W}_{\text{net}} = \dot{m}(q_{\text{in}} - q_{\text{out}}) = (24\text{ kg/s})(3029.7 - 1840.1)\text{kJ/kg} = \mathbf{28{,}550\text{ kW}}$$

(*b*) The thermal efficiency is determined from

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1840.1\text{ kJ/kg}}{3029.7\text{ kJ/kg}} = 0.393 = \mathbf{39.3\%}$$

10-70

~~10-75~~ 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.

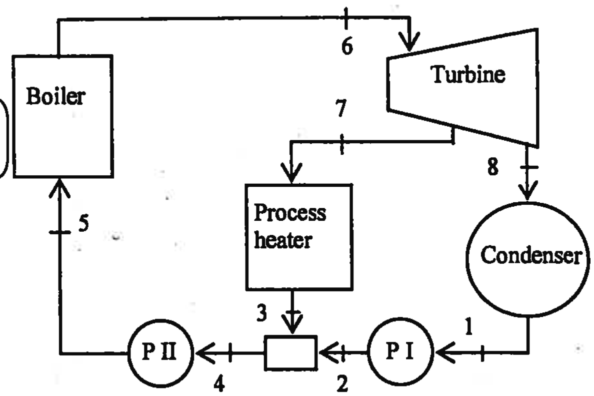
Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

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:

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

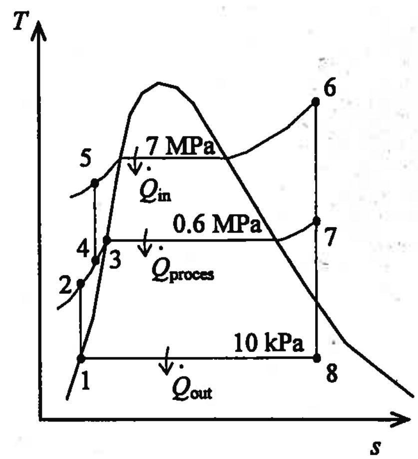
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_4 h_4 = \dot{m}_2 h_2 + \dot{m}_3 h_3$$

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

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

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

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



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

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

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

Then,

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

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

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

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

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

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

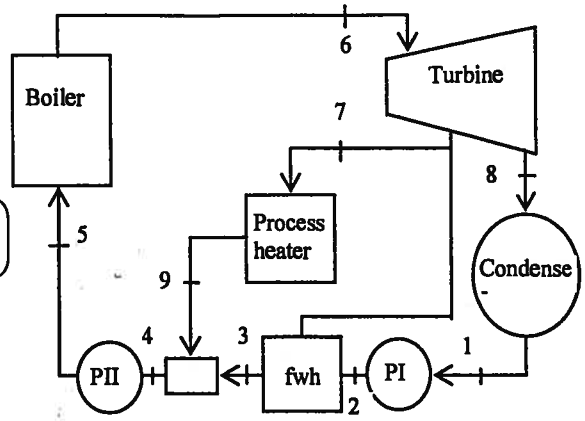
10-72

~~10-78~~ 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

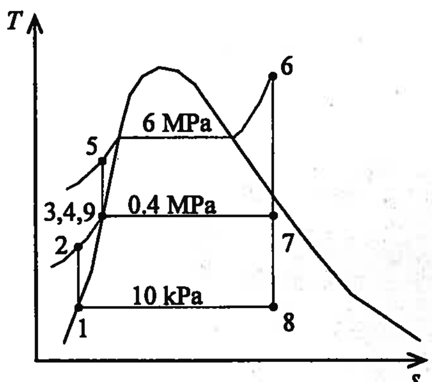
From the steam tables (Tables A-4, A-5, and A-6),



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

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

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



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

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

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

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

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

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

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

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

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

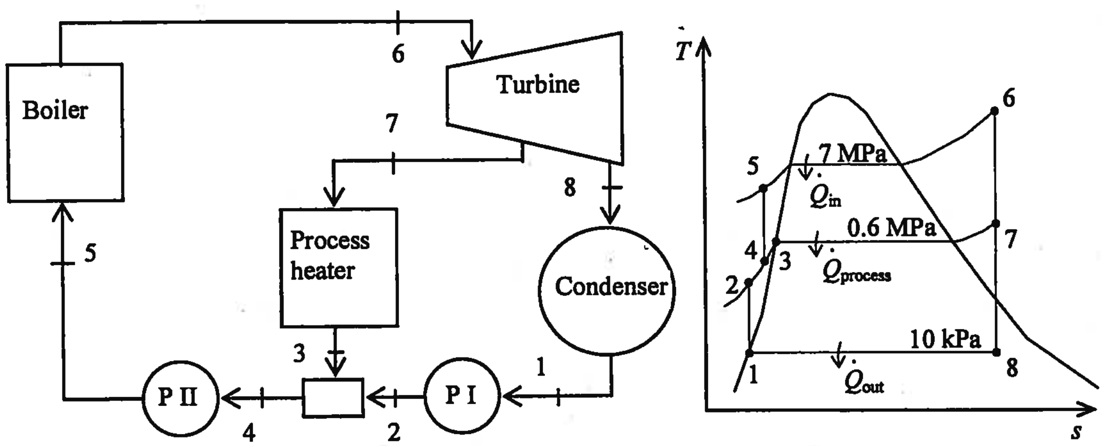
Thus,

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

10-75

~~10-81~~ 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 mass flow rate of steam that must be supplied by the boiler, 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),

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

$$\begin{aligned} w_{\text{pI,in}} &= v_1(P_2 - P_1) \\ &= (0.00101\text{ m}^3/\text{kg})(600-10\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 0.596\text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 191.81 + 0.596 = 192.40\text{ kJ/kg}$$

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

Mixing chamber:

$$\dot{m}_3 h_3 + \dot{m}_2 h_2 = \dot{m}_4 h_4$$
$$(0.25)(670.38\text{ kJ/kg}) + (0.75)(192.40\text{ kJ/kg})) = (1)h_4 \longrightarrow h_4 = 311.90\text{ kJ/kg}$$

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

$$\begin{aligned} w_{\text{pII,in}} &= v_4(P_5 - P_4) \\ &= (0.001026\text{ m}^3/\text{kg})(7000-600\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ &= 6.563\text{ kJ/kg} \end{aligned}$$

$$h_5 = h_4 + w_{\text{pII,in}} = 311.90 + 6.563 = 318.47\text{ kJ/kg}$$

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

$$\left.\begin{array}{l} P_7 = 0.6\text{ MPa} \\ s_7 = s_6 \end{array}\right\} h_7 = 2773.9\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_8 = 10\text{ kPa} \\ s_8 = s_6 \end{array}\right\} h_8 = 2153.6\text{ kJ/kg}$$

$$\dot{Q}_{\text{process}} = \dot{m}_7(h_7 - h_3)$$
$$8600\text{ kJ/s} = \dot{m}_7(2773.9 - 670.38)\text{kJ/kg}$$
$$\dot{m}_7 = 4.088\text{ kg/s}$$

This is one-fourth of the mass flowing through the boiler. Thus, the mass flow rate of steam that must be supplied by the boiler becomes

$$\dot{m}_6 = 4\dot{m}_7 = 4(4.088\text{ kg/s}) = \mathbf{16.35\ kg/s}$$

(*b*) Cycle analysis:

$$\begin{aligned}\dot{W}_{\text{T,out}} &= \dot{m}_7(h_6 - h_7) + \dot{m}_8(h_6 - h_8) \\ &= (4.088\text{ kg/s})(3411.4 - 2773.9)\text{kJ/kg} + (16.35 - 4.088\text{ kg/s})(3411.4 - 2153.6)\text{kJ/kg} \\ &= 18{,}033\text{ kW}\end{aligned}$$

$$\begin{aligned}\dot{W}_{\text{p,in}} &= \dot{m}_1 w_{\text{pI,in}} + \dot{m}_4 w_{\text{pII,in}} \\ &= (16.35 - 4.088\text{ kg/s})(0.596\text{ kJ/kg}) + (16.35\text{ kg/s})(6.563\text{ kJ/kg}) = 114.6\text{ kW}\end{aligned}$$

$$\dot{W}_{\text{net}} = \dot{W}_{\text{T,out}} - \dot{W}_{\text{p,in}} = 18{,}033 - 115 = \mathbf{17{,}919\ kW}$$

(*c*) Then,

$$\dot{Q}_{\text{in}} = \dot{m}_5(h_6 - h_5) = (16.35\text{ kg/s})(3411.4 - 318.46) = 50{,}581\text{ kW}$$

and

$$\varepsilon_u = \frac{\dot{W}_{\text{net}} + \dot{Q}_{\text{process}}}{\dot{Q}_{\text{in}}} = \frac{17{,}919 + 8600}{50{,}581} = 0.524 = \mathbf{52.4\%}$$

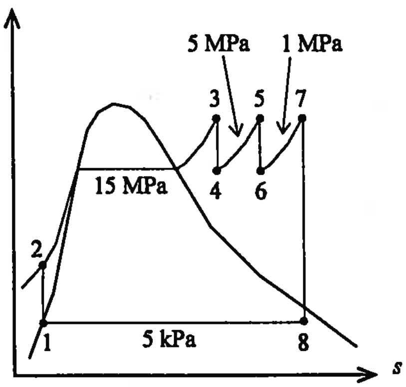
10-94

~~10-101~~ A steam power plant operating on an ideal Rankine cycle with two stages of reheat is considered. 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),

$$h_1 = h_{f\ @\ 5\ \text{kPa}} = 137.75\ \text{kJ/kg}$$
$$v_1 = v_{f\ @\ 5\ \text{kPa}} = 0.001005\ \text{m}^3/\text{kg}$$
$$\begin{aligned} w_{\text{p,in}} &= v_1(P_2 - P_1) \\ &= \left(0.001005\ \text{m}^3/\text{kg}\right)\left(15{,}000 - 5\ \text{kPa}\right)\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= 15.07\ \text{kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{\text{p,in}} = 137.75 + 15.07 = 152.82\ \text{kJ/kg}$$



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

$$\left.\begin{array}{l} P_4 = 5\ \text{MPa} \\ s_4 = s_3 \end{array}\right\} h_4 = 3007.4\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 5\ \text{MPa} \\ T_5 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3434.7\ \text{kJ/kg} \\ s_5 = 6.9781\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 1\ \text{MPa} \\ s_6 = s_5 \end{array}\right\} h_6 = 2971.3\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_7 = 1\ \text{MPa} \\ T_7 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_7 = 3479.1\ \text{kJ/kg} \\ s_7 = 7.7642\ \text{kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_8 = 5\ \text{kPa} \\ s_8 = s_7 \end{array}\right\} \begin{array}{l} x_8 = \dfrac{s_8 - s_f}{s_{fg}} = \dfrac{7.7642 - 0.4762}{7.9176} = 0.9204 \\ h_8 = h_f + x_8 h_{fg} = 137.75 + (0.9204)(2423.0) = 2367.9\ \text{kJ/kg} \end{array}$$

Then,

$$\begin{aligned} q_{\text{in}} &= (h_3 - h_2) + (h_5 - h_4) + (h_7 - h_6) \\ &= 3310.8 - 152.82 + 3434.7 - 3007.4 + 3479.1 - 2971.3 = 4093.1\ \text{kJ/kg} \end{aligned}$$
$$q_{\text{out}} = h_8 - h_1 = 2367.9 - 137.75 = 2230.2\ \text{kJ/kg}$$
$$w_{\text{net}} = q_{\text{in}} - q_{\text{out}} = 4093.1 - 2230.2 = 1862.9\ \text{kJ/kg}$$

Thus,

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1862.9\ \text{kJ/kg}}{4093.1\ \text{kJ/kg}} = \mathbf{45.5\%}$$

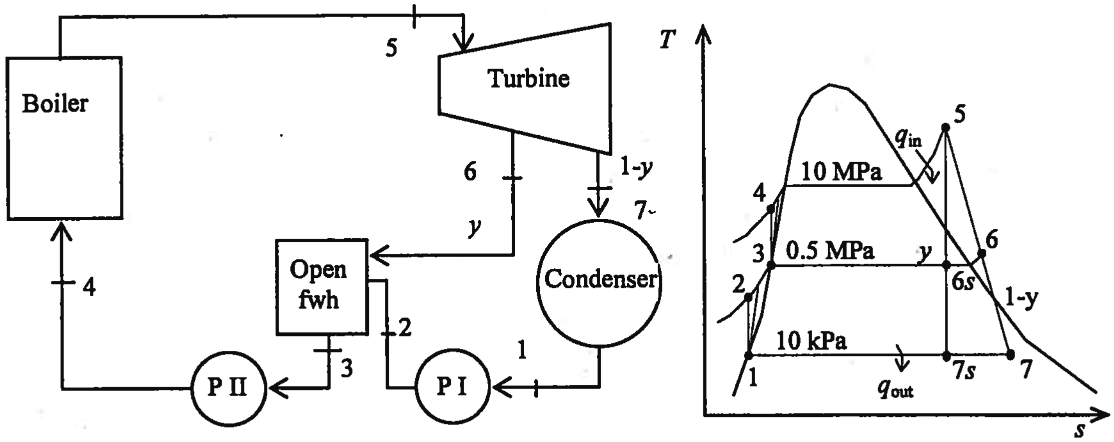
(*b*) $$\dot{m} = \frac{\dot{W}_{\text{net}}}{w_{\text{net}}} = \frac{120{,}000\ \text{kJ/s}}{1862.9\ \text{kJ/kg}} = \mathbf{64.4\ kg/s}$$

10-96

~~10-103~~ An 150-MW steam power plant operating on a regenerative Rankine cycle with an open feedwater heater is considered. The mass flow rate of steam through the boiler, the thermal efficiency of the cycle, and the irreversibility associated with the regeneration process 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),

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

$$\begin{aligned} w_{pI,in} &= v_1(P_2 - P_1)/\eta_p \\ &= \left(0.00101\ \text{m}^3\text{/kg}\right)(500-10\ \text{kPa})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)/(0.95) \\ &= 0.52\ \text{kJ/kg} \end{aligned}$$
$$h_2 = h_1 + w_{pI,in} = 191.81 + 0.52 = 192.33\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 0.5\ \text{MPa} \\ \text{sat liquid} \end{array}\right\} \begin{array}{l} h_3 = h_{f\,@0.5\,\text{MPa}} = 640.09\ \text{kJ/kg} \\ v_3 = v_{f\,@0.5\,\text{MPa}} = 0.001093\ \text{m}^3\text{/kg} \end{array}$$

$$\begin{aligned} w_{pII,in} &= v_3(P_4 - P_3)/\eta_p \\ &= \left(0.001093\ \text{m}^3\text{/kg}\right)(10{,}000 - 500\ \text{kPa})\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)/(0.95) \\ &= 10.93\ \text{kJ/kg} \end{aligned}$$
$$h_4 = h_3 + w_{pII,in} = 640.09 + 10.93 = 651.02\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 10\ \text{MPa} \\ T_5 = 500^\circ\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3375.1\ \text{kJ/kg} \\ s_5 = 6.5995\ \text{kJ/kg}\cdot\text{K} \end{array}$$

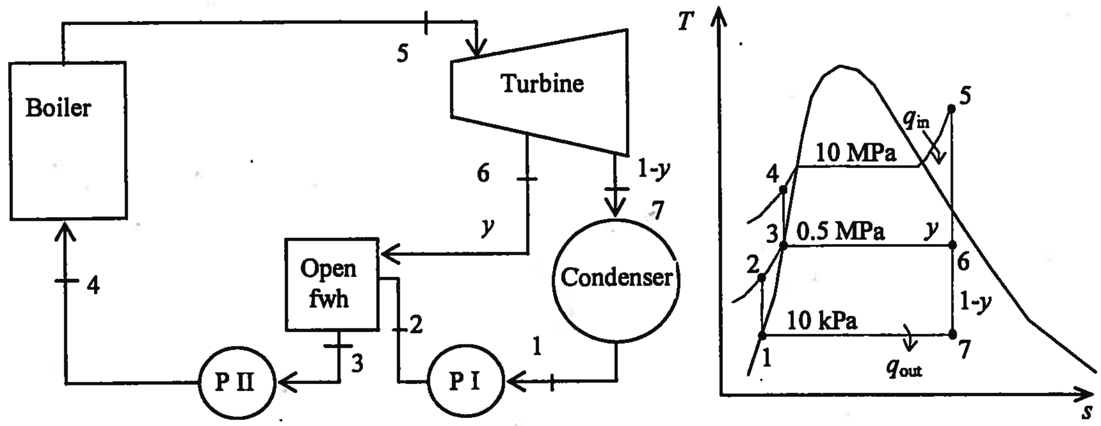
$$\left.\begin{array}{l} P_{6s} = 0.5\ \text{MPa} \\ s_{6s} = s_5 \end{array}\right\} \begin{array}{l} x_{6s} = \dfrac{s_{6s} - s_f}{s_{fg}} = \dfrac{6.5995 - 1.8604}{4.9603} = 0.9554 \\ h_{6s} = h_f + x_{6s}h_{fg} = 640.09 + (0.9554)(2108.0) \\ \quad = 2654.1\ \text{kJ/kg} \end{array}$$

10·97

~~10-104~~ An 150-MW steam power plant operating on an ideal regenerative Rankine cycle with an open feedwater heater is considered. The mass flow rate of steam through the boiler, the thermal efficiency of the cycle, and the irreversibility associated with the regeneration process 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),

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

$$w_{pI,in} = v_1(P_2 - P_1)$$
$$= (0.00101 \text{ m}^3\text{/kg})(500-10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 0.50 \text{ kJ/kg}$$
$$h_2 = h_1 + w_{pI,in} = 191.81 + 0.50 = 192.30 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 0.5 \text{ MPa} \\ \text{sat.liquid} \end{array}\right\} \begin{array}{l} h_3 = h_{f\,@\,0.5\text{ MPa}} = 640.09 \text{ kJ/kg} \\ v_3 = v_{f\,@\,0.5\text{ MPa}} = 0.001093 \text{ m}^3\text{/kg} \end{array}$$

$$w_{pII,in} = v_3(P_4 - P_3)$$
$$= (0.001093 \text{ m}^3\text{/kg})(10{,}000 - 500 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 10.38 \text{ kJ/kg}$$
$$h_4 = h_3 + w_{pII,in} = 640.09 + 10.38 = 650.47 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_5 = 10 \text{ MPa} \\ T_5 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_5 = 3375.1 \text{ kJ/kg} \\ s_5 = 6.5995 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_6 = 0.5 \text{ MPa} \\ s_6 = s_5 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{6.5995 - 1.8604}{4.9603} = 0.9554 \\ h_6 = h_f + x_6 h_{fg} = 640.09 + (0.9554)(2108.0) = 2654.1 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_7 = 10 \text{ kPa} \\ s_7 = s_5 \end{array}\right\} \begin{array}{l} x_7 = \dfrac{s_7 - s_f}{s_{fg}} = \dfrac{6.5995 - 0.6492}{7.4996} = 0.7934 \\ h_7 = h_f + x_7 h_{fg} = 191.81 + (0.7934)(2392.1) = 2089.7 \text{ kJ/kg} \end{array}$$

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

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

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

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

$$y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{640.09 - 192.31}{2654.1 - 192.31} = 0.1819$$

Then,
$$q_{in} = h_5 - h_4 = 3375.1 - 650.47 = 2724.6 \text{ kJ/kg}$$
$$q_{out} = (1-y)(h_7 - h_1) = (1 - 0.1819)(2089.7 - 191.81) = 1552.7 \text{ kJ/kg}$$
$$w_{net} = q_{in} - q_{out} = 2724.6 - 1552.7 = 1172.0 \text{ kJ/kg}$$

and
$$\dot{m} = \frac{\dot{W}_{net}}{w_{net}} = \frac{150{,}000 \text{ kJ/s}}{1171.9 \text{ kJ/kg}} = \mathbf{128.0\ kg/s}$$

(*b*) The thermal efficiency is determined from

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1552.7 \text{ kJ/kg}}{2724.7 \text{ kJ/kg}} = \mathbf{43.0\%}$$

Also,

$$s_6 = s_5 = 6.5995 \text{ kJ/kg} \cdot \text{K}$$
$$s_3 = s_{f\,@\,0.5\text{ MPa}} = 1.8604 \text{ kJ/kg} \cdot \text{K}$$
$$s_2 = s_1 = s_{f\,@\,10\text{ kPa}} = 0.6492 \text{ kJ/kg} \cdot \text{K}$$

Then the irreversibility (or exergy destruction) associated with this regeneration process is

$$i_{regen} = T_0 s_{gen} = T_0 \left(\sum m_e s_e - \sum m_i s_i + \frac{q_{surr}}{T_L}^{\nearrow 0} \right) = T_0 [s_3 - y s_6 - (1-y) s_2]$$
$$= (303 \text{ K})[1.8604 - (0.1819)(6.5995) - (1 - 0.1819)(0.6492)] = \mathbf{39.0\ kJ/kg}$$

10-98

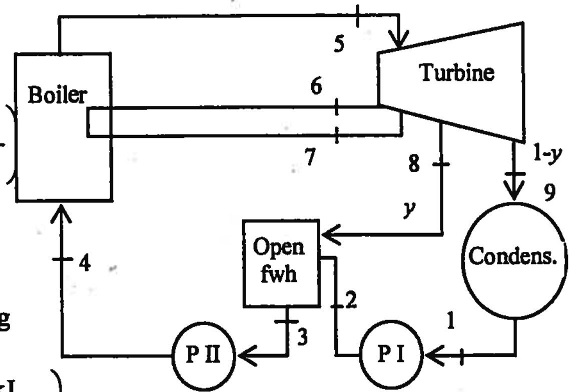
~~10-105~~ An ideal reheat-regenerative Rankine cycle with one open feedwater heater is considered. The fraction of steam extracted for regeneration and the thermal efficiency of the cycle are to be determined.

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),

$$h_1 = h_{f\,@\,15\text{ kPa}} = 225.94\text{ kJ/kg}$$

$$v_1 = v_{f\,@\,15\text{ kPa}} = 0.001014\text{ m}^3\text{/kg}$$



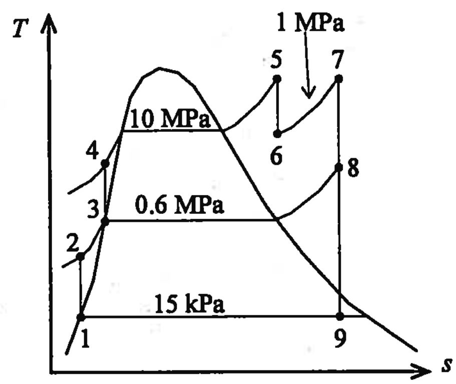
$$w_{\text{pI,in}} = v_1(P_2 - P_1) = (0.001014\text{ m}^3\text{/kg})(600 - 15\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 0.59\text{ kJ/kg}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 225.94 + 0.59 = 226.53\text{ kJ/kg}$$

$$\left.\begin{array}{l}P_3 = 0.6\text{ MPa}\\ \text{sat. liquid}\end{array}\right\} \begin{array}{l}h_3 = h_{f\,@\,0.6\text{ MPa}} = 670.38\text{ kJ/kg}\\ v_3 = v_{f\,@\,0.6\text{ MPa}} = 0.001101\text{ m}^3\text{/kg}\end{array}$$

$$w_{\text{pII,in}} = v_3(P_4 - P_3) = (0.001101\text{ m}^3\text{/kg})(10{,}000 - 600\text{ kPa})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 10.35\text{ kJ/kg}$$

$$h_4 = h_3 + w_{\text{pII,in}} = 670.38 + 10.35 = 680.73\text{ kJ/kg}$$



$$\left.\begin{array}{l}P_5 = 10\text{ MPa}\\ T_5 = 500°\text{C}\end{array}\right\} \begin{array}{l}h_5 = 3375.1\text{ kJ/kg}\\ s_5 = 6.5995\text{ kJ/kg}\cdot\text{K}\end{array}$$

$$\left.\begin{array}{l}P_6 = 1.0\text{ MPa}\\ s_6 = s_5\end{array}\right\} h_6 = 2783.8\text{ kJ/kg}$$

$$\left.\begin{array}{l}P_7 = 1.0\text{ MPa}\\ T_7 = 500°\text{C}\end{array}\right\} \begin{array}{l}h_7 = 3479.1\text{ kJ/kg}\\ s_7 = 7.7642\text{ kJ/kg}\cdot\text{K}\end{array}$$

$$\left.\begin{array}{l}P_8 = 0.6\text{ MPa}\\ s_8 = s_7\end{array}\right\} h_8 = 3310.2\text{ kJ/kg}$$

$$\left.\begin{array}{l}P_9 = 15\text{ kPa}\\ s_9 = s_7\end{array}\right\} \begin{array}{l}x_9 = \dfrac{s_9 - s_f}{s_{fg}} = \dfrac{7.7642 - 0.7549}{7.2522} = 0.9665\\ h_9 = h_f + x_9 h_{fg} = 225.94 + (0.9665)(2372.3) = 2518.8\text{ kJ/kg}\end{array}$$

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

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

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_8 h_8 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \longrightarrow y h_8 + (1 - y) h_2 = 1(h_3)$$

where y is the fraction of steam extracted from the turbine ($= \dot{m}_8 / \dot{m}_3$). Solving for y,

$$y = \frac{h_3 - h_2}{h_8 - h_2} = \frac{670.38 - 226.53}{3310.2 - 226.53} = \mathbf{0.144}$$

(*b*) The thermal efficiency is determined from

$$q_{\text{in}} = (h_5 - h_4) + (h_7 - h_6) = (3375.1 - 680.73) + (3479.1 - 2783.8) = 3389.7\text{ kJ/kg}$$

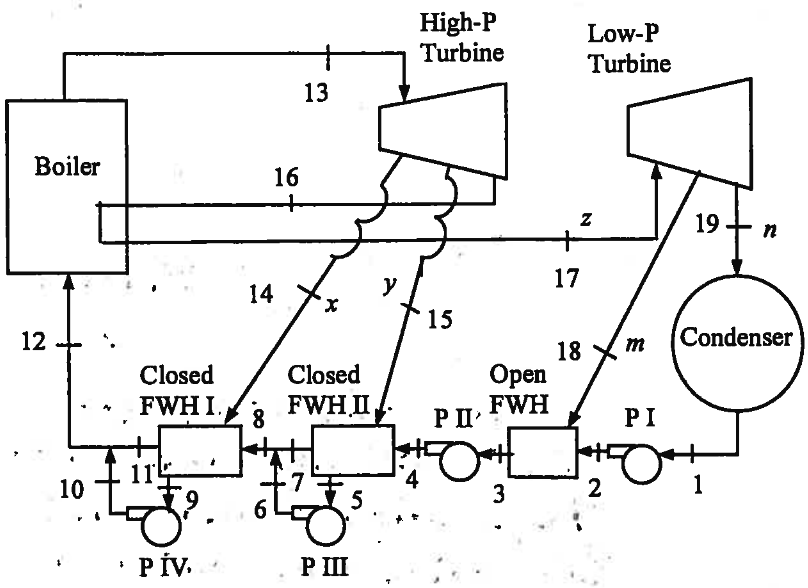
$$q_{\text{out}} = (1 - y)(h_9 - h_1) = (1 - 0.1440)(2518.8 - 225.94) = 1962.7\text{ kJ/kg}$$

and $$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1962.7\text{ kJ/kg}}{3389.7\text{ kJ/kg}} = \mathbf{42.1\%}$$

10-100

~~10-107~~ A steam power plant operating on the ideal reheat-regenerative Rankine cycle with three feedwater heaters is considered. Various items for this system per unit of mass flow rate through the boiler are to be determined.

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



Analysis The compression processes in the pumps and the expansion processes in the turbines are isentropic. Also, the state of water at the inlet of pumps is saturated liquid. Then, from the steam tables (Tables A-4, A-5, and A-6),

$$
\begin{aligned}
h_1 &= 191.81 \text{ kJ/kg} & h_{13} &= 3139.4 \text{ kJ/kg} \\
h_2 &= 191.90 \text{ kJ/kg} & h_{14} &= 3062.8 \text{ kJ/kg} \\
h_3 &= 417.51 \text{ kJ/kg} & h_{15} &= 2931.8 \text{ kJ/kg} \\
h_4 &= 421.05 \text{ kJ/kg} & h_{16} &= 2470.4 \text{ kJ/kg} \\
h_5 &= 1049.7 \text{ kJ/kg} & h_{17} &= 3275.5 \text{ kJ/kg} \\
h_6 &= 1052.8 \text{ kJ/kg} & h_{18} &= 2974.6 \text{ kJ/kg} \\
h_9 &= 1213.8 \text{ kJ/kg} & h_{19} &= 2547.5 \text{ kJ/kg} \\
h_{10} &= 1216.2 \text{ kJ/kg} & &
\end{aligned}
$$

For an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure. Then,

$$
\left.\begin{array}{l} P_7 = 3500 \text{ kPa} \\ T_7 = T_5 = 242.6^\circ\text{C} \end{array}\right\} h_7 = 1050.0 \text{ kJ/kg}
$$

$$
\left.\begin{array}{l} P_{11} = 6000 \text{ kPa} \\ T_{11} = T_9 = 275.6^\circ\text{C} \end{array}\right\} h_{11} = 1213.1 \text{ kJ/kg}
$$

Enthalpies at other states and the fractions of steam extracted from the turbines can be determined from mass and energy balances on cycle components as follows:

Mass Balances:

$$x + y + z = 1$$

$$m + n = z$$

Open feedwater heater:

$$mh_{18} + nh_2 = zh_3$$

Closed feedwater heater-II:

$$zh_4 + yh_{15} = zh_7 + yh_5$$

Closed feedwater heater-I:

$$(y+z)h_8 + xh_{14} = (y+z)h_{11} + xh_9$$

Mixing chamber after closed feedwater heater II:

$$zh_7 + yh_6 = (y+z)h_8$$

Mixing chamber after closed feedwater heater I:

$$xh_{10} + (y+z)h_{11} = 1h_{12}$$

Matlab

Substituting the values and solving the above equations simultaneously using ~~EES~~, we obtain

$$h_8 = 1050.7 \text{ kJ/kg}$$
$$h_{12} = 1213.3 \text{ kJ/kg}$$
$$x = \mathbf{0.08072}$$
$$y = \mathbf{0.2303}$$
$$z = 0.6890$$
$$m = \mathbf{0.05586}$$
$$n = \mathbf{0.6332}$$

well this why you need ENGR 391 to solve 7 eqs with 7 unknowns. You write this under a matrix form.

Note that these values may also be obtained by a hand solution by using the equations above with some rearrangements and substitutions. Other results of the cycle are

$$w_{\text{T,out,HP}} = x(h_{13} - h_{14}) + y(h_{13} - h_{15}) + z(h_{13} - h_{16}) = \mathbf{514.9 \text{ kJ/kg}}$$
$$w_{\text{T,out,LP}} = m(h_{17} - h_{18}) + n(h_{17} - h_{19}) = \mathbf{477.8 \text{ kJ/kg}}$$
$$q_{\text{in}} = h_{13} - h_{12} + z(h_{17} - h_{16}) = \mathbf{2481 \text{ kJ/kg}}$$
$$q_{\text{out}} = n(h_{19} - h_1) = \mathbf{1492 \text{ kJ/kg}}$$
$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{1492}{2481} = \mathbf{0.3986}$$

10-111

~~10-118~~ A Rankine steam cycle modified for reheat and three closed feedwater heaters is considered. The *T*-*s* diagram for the ideal cycle is to be sketched. The net power output of the cycle and the flow rate of the cooling water required are to be determined.

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

Analysis (*b*) Using the data from the problem statement, the enthalpies at various states are

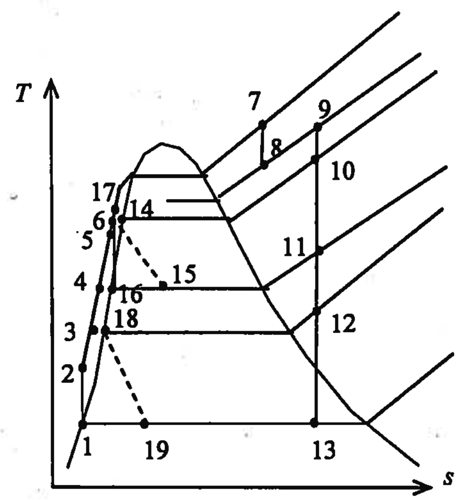
$$h_1 = h_{f\,@\,10\text{ kPa}} = 191.8 \text{ kJ/kg}$$
$$v_1 = v_{f\,@\,10\text{ kPa}} = 0.001010 \text{ m}^3\text{/kg}$$

$$\begin{aligned} w_{\text{pI,in}} &= v_1(P_2 - P_1) \\ &= (0.001010 \text{ m}^3\text{/kg})(5000 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) \\ &= 5.04 \text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{\text{pI,in}} = 191.8 + 5.04 = 196.8 \text{ kJ/kg}$$
$$h_{16} = h_{f\,@\,300\text{ kPa}} = 561.4 \text{ kJ/kg}$$
$$v_{16} = v_{f\,@300\text{ kPa}} = 0.001073 \text{ m}^3\text{/kg}$$

$$\begin{aligned} w_{\text{pII,in}} &= v_{16}(P_{17} - P_{16}) \\ &= (0.001073 \text{ m}^3\text{/kg})(5000 - 300 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) \\ &= 5.04 \text{ kJ/kg} \end{aligned}$$

$$h_{17} = h_{16} + w_{\text{pII,in}} = 561.4 + 5.04 = 566.4 \text{ kJ/kg}$$



Also,

$$h_3 = h_{18} = h_{f\,@75\text{ kPa}} = 384.4 \text{ kJ/kg}$$
$$h_4 = h_{16} = h_{f\,@300\text{ kPa}} = 561.4 \text{ kJ/kg}$$
$$h_5 = h_{14} = h_{f\,@925\text{ kPa}} = 747.7 \text{ kJ/kg}$$
$$h_{15} = h_{14} \quad \text{(throttle valve operation)}$$
$$h_{19} = h_{18} \quad \text{(throttle valve operation)}$$

Energy balances on three closed feedwater heaters give

$$yh_{10} + (1-y-z)h_4 = (1-y-z)h_5 + yh_{15}$$

$$zh_{11} + (1-y-z)h_3 + yh_{15} = (1-y-z)h_4 + (y+z)h_{16}$$

$$wh_{12} + (1-y-z)h_2 = (1-y-z)h_3 + wh_{18}$$

The enthalpies are known, and thus there are three unknowns (y, z, w) and three equations. Solving these equations using EES, we obtain

$$y = 0.06335$$
$$z = 0.05863$$
$$w = 0.07063$$

The enthalpy at state 6 may be determined from an energy balance on mixing chamber:

$$\begin{aligned} h_6 &= (1-y-z)h_5 + (y+z)h_{17} \\ &= (1 - 0.06335 - 0.05863)(747.7) + (0.06335 + 0.05863)(566.4) = 725.6 \text{ kJ/kg} \end{aligned}$$

The heat input in the boiler is

$$\begin{aligned} q_{\text{in}} &= (h_7 - h_6) + (h_9 - h_8) \\ &= (3900 - 725.6) + (3687 - 3615) = 3246 \text{ kJ/kg} \end{aligned}$$

The work output from the turbines is

$$
\begin{aligned}
w_{\mathrm{T,out}} &= h_7 - h_8 + h_9 - yh_{10} - zh_{11} - wh_{12} - (1-y-z-w)h_{13} \\
&= 3900 - 3615 + 3687 - (0.06335)(3330) - (0.05863)(3011) \\
&\quad - (0.07063)(2716) - (1 - 0.06335 - 0.05863 - 0.07063)(2408) \\
&= 1448 \text{ kJ/kg}
\end{aligned}
$$

The net work output from the cycle is

$$
\begin{aligned}
w_{\mathrm{net}} &= w_{\mathrm{T,out}} - (1-y-z)w_{\mathrm{PI,in}} - (y+z)w_{\mathrm{PII,in}} \\
&= 1448 - (1 - 0.06335 - 0.05863)(5.04) - (0.06335 + 0.05863)(5.04) \\
&= 1443 \text{ kJ/kg}
\end{aligned}
$$

The net power output is

$$
\begin{aligned}
\dot{W}_{\mathrm{net}} &= \dot{m}w_{\mathrm{net}} = (100 \text{ kg/s})(1443 \text{ kJ/kg}) \\
&= 144{,}300 \text{ kW} = \mathbf{144.3\ MW}
\end{aligned}
$$

(*c*) The heat rejected from the condenser is

$$
\begin{aligned}
q_{\mathrm{out}} &= (1-y-z-w)h_{13} + wh_{19} - (1-y-z)h_1 \\
&= (1 - 0.06335 - 0.05863 - 0.07063)(2408) + (0.07063)(384.4) - (1 - 0.06335 - 0.05863)(191.8) \\
&= 1803 \text{ kJ/kg}
\end{aligned}
$$

Then an energy balance on the condenser gives

$$
\dot{m}q_{\mathrm{out}} = \dot{m}_w c_{\mathrm{p,w}}(T_{\mathrm{w},2} - T_{\mathrm{w},1})
$$

$$
\dot{m}_w = \frac{\dot{m}q_{\mathrm{out}}}{c_{\mathrm{p,w}}(T_{\mathrm{w},2} - T_{\mathrm{w},1})} = \frac{(100 \text{ kg/s})(1803 \text{ kJ/kg})}{(4.18 \text{ kJ/kg}\cdot\text{K})(10 \text{ K})} = \mathbf{4313\ kg/s}
$$

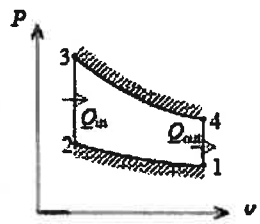
Problem #9.35

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

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

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

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



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

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

Process 3-4: isentropic expansion.

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

Process 2-3: v = constant heat addition.

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

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

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

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

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

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

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

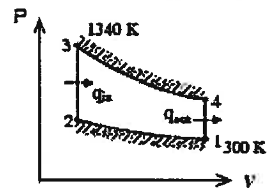
(*d*)
$$V_{min} = V_2 = \frac{V_{max}}{r}$$

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

Problem #9.37

An ideal Otto cycle with air as the working fluid has a compression ratio of 8. The amount of heat transferred to the air during the heat addition process, the thermal efficiency, and the thermal efficiency of a Carnot cycle operating between the same temperature limits are to be determined.

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



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

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

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

$$v_{r_2} = \frac{v_2}{v_1} v_{r_1} = \frac{1}{r} v_{r_1} = \frac{1}{8}(621.2) = 77.65 \longrightarrow u_2 = 491.44 \text{ kJ/kg}$$

Process 2-3: v = constant heat addition.

$$T_3 = 1340 \text{ K} \longrightarrow \begin{array}{l} u_3 = 1058.94 \text{ kJ/kg} \\ v_{r_3} = 10.247 \end{array}$$

$$q_{in} = u_3 - u_2 = (1058.94 - 491.44) \text{ kJ/kg} = \mathbf{567.5 \text{ kJ/kg}}$$

(b) Process 3-4: isentropic expansion.

$$v_{r_4} = \frac{v_4}{v_3} v_{r_3} = r v_{r_3} = (8)(10.247) = 81.98 \longrightarrow u_4 = 480.82 \text{ kJ/kg}$$

Process 4-1: v = constant heat rejection.

$$q_{out} = u_4 - u_1 = 480.82 - 214.07 = 266.75 \text{ kJ/kg}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{266.75 \text{ kJ/kg}}{567.5 \text{ kJ/kg}} = \mathbf{53\%}$$

(c) $$\eta_{th,C} = 1 - \frac{T_H}{T_L} = 1 - \frac{300 \text{ K}}{1340 \text{ K}} = \mathbf{77.6\%}$$

Assignment 5

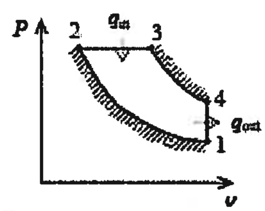
Problem #9.54

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

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

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

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

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

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

while the thermal efficiency is

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

The power produced by this engine is then

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

Problem #9.55
(Note: using a pressure of 101.325kpa instead of 100, and a temperature of 1667K instead of 1700)

An air-standard Diesel cycle with a compression ratio of 18.2 is considered. The cutoff ratio, the heat rejection per unit mass, and the thermal efficiency are to be determined. √

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

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

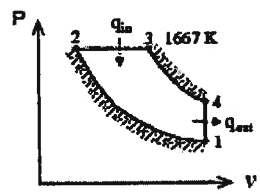
Analysis (*a*) Process 1-2: isentropic compression.

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

$$v_{r_2} = \frac{v_2}{v_1} v_{r_1} = \frac{1}{r} v_{r_1} = \frac{1}{18.2}(621.2) = 34.13 \longrightarrow \begin{array}{l} T_2 = 901.7 \text{ K} \\ h_2 = 934.83 \text{ kJ/kg} \end{array}$$

Process 2-3: P = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow \frac{v_3}{v_2} = \frac{T_3}{T_2} = \frac{1667 \text{ K}}{901.7 \text{ K}} = 1.848$$



$$(b) \qquad T_3 = 1667 \text{ K} \longrightarrow \begin{array}{l} h_3 = 1839.55 \text{ kJ/kg} \\ v_{r_3} = 5.216 \end{array}$$

$$q_{in} = h_3 - h_2 = 1839.55 - 934.83 = 904.72 \text{ kJ/kg}$$

Process 3-4: isentropic expansion.

$$v_{r_4} = \frac{v_4}{v_3} v_{r_3} = \frac{v_4}{1.848 v_2} v_{r_3} = \frac{r}{1.848} v_{r_3} = \frac{18.2}{1.848}(5.216) = 51.37 \longrightarrow u_4 = 577.35 \text{ kJ/kg}$$

Process 4-1: v = constant heat rejection.

$$q_{out} = u_4 - u_1 = 577.35 - 214.07 = 363.28 \text{ kJ/kg}$$

$$(c) \qquad \eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{363.25 \text{ kJ/kg}}{904.72 \text{ kJ/kg}} = 59.8\%$$

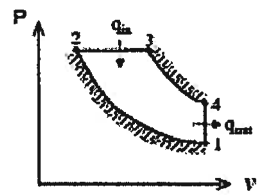
Problem #9.57

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

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

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

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



$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} = (293\text{K})(20)^{0.4} = 971.1\text{K}$$

Process 2-3: P = constant heat addition.

$$\frac{P_3V_3}{T_3} = \frac{P_2V_2}{T_2} \longrightarrow \frac{V_3}{V_2} = \frac{T_3}{T_2} = \frac{2200\text{ K}}{971.1\text{ K}} = 2.265$$

Process 3-4: isentropic expansion.

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1} = T_3\left(\frac{2.265V_2}{V_4}\right)^{k-1} = T_3\left(\frac{2.265}{r}\right)^{k-1} = (2200\text{ K})\left(\frac{2.265}{20}\right)^{0.4} = 920.6\text{ K}$$

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

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

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

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

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

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

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