10. Referring to Fig. 8.1, what environmental impacts might result from the two plumes shown on the figure?

11. Referring to Example 8.5, what are the principal sources of internal irreversibility?

12. Why is water the most commonly used working fluid in vapor power plants?

13. What do you think about using solar energy to generate electric power?

**Problems**

**Rankine Cycle**

8.1 Water is the working fluid in an ideal Rankine cycle. The condenser pressure is 8 kPa, and saturated vapor enters the turbine at (a) 18 MPa and (b) 4 MPa. The net power output of the cycle is 100 MW. Determine for each case the mass flow rate of steam, in kg/h, the heat transfer rates for the working fluid passing through the boiler and condenser, each in kW, and the thermal efficiency.

8.2 Water is the working fluid in an ideal Rankine cycle. Superheated vapor enters the turbine at 8 MPa, 480°C. The condenser pressure is 8 kPa. The net power output of the cycle is 100 MW. Determine for the cycle:
   (a) the rate of heat transfer to the working fluid passing through the steam generator, in kW,
   (b) the thermal efficiency,
   (c) the mass flow rate of condenser cooling water, in kg/h, if the cooling water enters the condenser at 15°C and exits at 35°C with negligible pressure change.

8.3 Water is the working fluid in a Carnot vapor power cycle. Saturated liquid enters the boiler at a pressure of 8 MPa, and saturated vapor enters the turbine. The condenser pressure is 8 kPa. Determine:
   (a) the thermal efficiency,
   (b) the back work ratio,
   (c) the heat transfer from the working fluid per unit mass passing through the condenser, in kW/kg.

8.4 Plot each of the quantities calculated in Problem 8.2 versus condenser pressure ranging from 6 kPa to 0.1 MPa. Discuss.

8.5 Plot each of the quantities calculated in Problem 8.2 versus steam generator pressure ranging from 4 MPa to 24 MPa. Maintain the turbine inlet temperature at 480°C. Discuss.

8.6 Water is the working fluid in an ideal Rankine cycle. Saturated vapor enters the turbine at 18 MPa. The condenser pressure is 6 kPa. Determine:
   (a) the net work per unit mass of steam flow, in kW/kg.
   (b) the heat transfer to the steam passing through the boiler, in kW/kg.
   (c) the thermal efficiency.
   (d) the heat transfer to cooling water passing through the condenser, in kW/kg.

8.7 Water is the working fluid in a Carnot vapor power cycle. Saturated liquid enters the boiler at a pressure of 18 MPa, and saturated vapor enters the turbine. The condenser pressure is 6 kPa. Determine:
   (a) the thermal efficiency,
   (b) the back work ratio,
   (c) the net work of the cycle per unit mass of water flowing, in kW/kg.
   (d) the heat transfer from the working fluid passing through the condenser, in kW/kg of steam flow.

8.8 Plot the results of parts (a)-(d) with those of Problem 8.6, respectively, and comment.

8.9 Water is the working fluid in an ideal Rankine cycle. The pressure and temperature at the turbine inlet are 1200 lb/in.² and 1000°F, respectively, and the condenser pressure is 1 lb/in.². The mass flow rate of steam entering the turbine is 1.4 × 10⁹ lb/h. The cooling water experiences a temperature increase from 60 to 80°F, with negligible pressure drop, as it passes through the condenser. Determine for the cycle:
   (a) the net power developed, in Btu/h.
   (b) the thermal efficiency.
   (c) the mass flow rate of cooling water, in lb/h.

8.10 Plot each of the quantities calculated in Problem 8.9 versus condenser pressure ranging from 0.4 lb/in.² to 14.7 lb/in.². Maintain a constant mass flow rate of steam. Discuss.

8.11 Plot each of the quantities calculated in Problem 8.9 versus steam generator pressure ranging from 600 to 3500 lb/in.². Maintain the turbine inlet temperature at 1000°F and a constant mass flow rate of steam. Discuss.

8.12 A power plant based on the Rankine cycle is under development to provide a net power output of 10 MW. Solar collectors are to be used to generate Refrigerating 22 vapor at 1.6 MPa, 50°C, for expansion through the turbine. Cooling water is available at 20°C. Specify the preliminary design of the cycle and estimate the thermal efficiency and the refrigerant and cooling water flow rates, in kg/h.
the rate of heat transfer from the line connecting the steam generator and the turbine, in kW.

(d) the mass flow rate of condenser cooling water, in kg/s, if the cooling water enters at 15°C and exits at 35°C with negligible pressure change.

8.22 Modify Problem 8.9 as follows. Steam leaves the steam generator at 1200 lbm/in², 1000°F, but due to heat transfer and frictional effects in the line connecting the steam generator and the turbine, the pressure and temperature at the turbine inlet are reduced to 1100 lbm/in² and 900°F, respectively. Also, condensate leaves the condenser at 0.8 lbm/in², 90°F and is pumped to 1250 lbm/in² before entering the steam generator. Determine for the cycle

(a) the net power developed, in Btu/h.

(b) the thermal efficiency.

(c) the heat rate, in Btu/kW·h.

(d) the mass flow rate of cooling water, in lbm/h.

8.23 Steam enters the turbine of a vapor power plant at 600 lbm/in², 1000°F and exits as a two-phase liquid–vapor mixture at temperature T. Condensate exits the condenser at a temperature 5°F lower than T and is pumped to 600 lbm/in². The turbine and pump isentropic efficiencies are 90 and 80%, respectively. The net power developed is 1 MW.

(a) For T = 80°F, determine the steam quality at the turbine exit, the steam mass flow rate, in lbm/h, and the thermal efficiency.

(b) Plot the quantities of part (a) versus T ranging from 80 to 105°F.

8.24 Superheated steam at 18 MPa, 560°C, enters the turbine of a vapor power plant. The pressure at the exit of the turbine is 0.045 bar, 26°C. The pressure is increased to 18.2 MPa across the pump. The turbine and pump have isentropic efficiencies of 82 and 77%, respectively. For the cycle, determine

(a) the net work per unit mass of steam flow, in kJ/kg.

(b) the heat transfer to steam passing through the boiler, in kJ/kg of steam flowing.

(c) the thermal efficiency.

(d) the heat transfer to cooling water passing through the condenser, in kJ/kg of steam condensed.

8.25 In the preliminary design of a power plant, water is chosen as the working fluid and it is determined that the turbine inlet temperature may not exceed 520°C. Based on expected cooling water temperatures, the condenser is to operate at a pressure of 0.06 bar. Determine the steam generator pressure required if the isentropic turbine efficiency is 80% and the quality of steam at the turbine exit must be at least 90%.

Reheat and Supercritical Cycles

8.26 Steam at 10 MPa, 600°C enters the first-stage turbine of an ideal Rankine cycle with reheat. The steam leaving the reheat section of the steam generator is at 500°C, and the condenser pressure is 6 kPa. If the quality at the exit of the second-stage turbine is 90%, determine the cycle thermal efficiency.

8.27 The ideal Rankine cycle of Problem 8.9 is modified to include reheat. In the modified cycle, steam expands through the first-stage turbine to saturated vapor and then is reheated to 900°F. If the mass flow rate of steam in the modified cycle is the same as in Problem 8.9, determine for the modified cycle

(a) the net power developed, in Btu/h.

(b) the rate of heat transfer to the working fluid in the reheat process, in Btu/h.

(c) the thermal efficiency.

8.28 The ideal Rankine cycle of Problem 8.2 is modified to include reheat. In the modified cycle, steam expands though the first-stage turbine to 0.7 MPa and then is reheated to 480°C. If the net power output of the modified cycle is 100 MW, determine for the modified cycle

(a) the rate of heat transfer to the working fluid passing through the steam generator, in MW.

(b) the thermal efficiency.

(c) the rate of heat transfer to cooling water passing through the condenser, in MW.

8.29 For the cycle of Problem 8.28, investigate the effects on cycle performance as the reheat pressure and final reheat temperature take on other values. Construct suitable plots and discuss. Reconsider the analysis assuming that the pump efficiency of each stage has an isentropic efficiency of 80%.

8.30 An ideal Rankine cycle with reheat uses water as the working fluid. The conditions at the inlet to the first-stage turbine are p₁ = 2500 lbm/in², T₁ = 1000°F. The steam is reheated at constant pressure p between the turbine stages to 1000°F. The condenser pressure is 1 lbm/in².

(a) If p/p₁ = 0.2, determine the cycle thermal efficiency and the steam quality at the exit of the second-stage turbine.

(b) Plot the quantities of part (a) versus the pressure ratio p/p₁ ranging from 0.05 to 1.0.

8.31 Steam at 32 MPa, 520°C enters the first stage of a supercritical reheat cycle including three turbine stages. Steam exiting the first-stage turbine at pressure p is reheated at constant pressure to 440°C, and steam exiting the second-stage turbine at 0.5 MPa is reheated at constant pressure to 360°C. Each turbine stage and the pump has an isentropic efficiency of 85%. The condenser pressure is 8 kPa.

(a) For p = 4 MPa, determine the net work per unit mass of steam flowing, in kJ/kg, and the thermal efficiency.

(b) Plot the quantities of part (a) versus p ranging from 0.5 to 10 MPa.

8.32 Propane at 100 bar, 147°C enters the turbine of a supercritical power plant proposed for use in Antarctica.
(b) Compare the binary cycle performance to that of a single Rankine cycle using water as the working fluid and condensing at 75°F. The turbine inlet state, isentropic turbine efficiency, and net power output all remain the same.

8.71 Figure P8.71 shows a vapor power cycle with reheating and regeneration. The steam generator produces vapor at 4000 lbm/hr, 800°F. Some of this steam expands through the first turbine stage to 1000 lbm/hr and the remainder is directed to the heat exchanger. The steam exiting the first turbine stage enters the flash chamber. Saturated vapor and saturated liquid at 100 lbm/hr exit the flash chamber as separate streams. The vapor is reheated in the heat exchanger to 530°F before entering the second turbine stage. The open feedwater heater operates at 100 lbm/hr, and the condenser pressure is 1 lbm/hr. Each turbine stage has an isentropic efficiency of 88% and the pumps operate isentropically. For a net power output of 5 × 10^{6} Btu/h, determine
(a) the mass flow rate through the steam generator, in lbm/hr.
(b) the thermal efficiency of the cycle.
(c) the rate of heat transfer to the cooling water passing through the condenser, in Btu/hr.

8.72 Water is the working fluid in a cogeneration cycle that generates electricity and provides heat for campus buildings. Steam at 2 MPa, 320°C, enters a two-stage turbine with a mass flow rate of 0.82 kg/s. A fraction of the total flow, 0.141, is extracted between the two stages at 0.15 MPa to provide for building heating, and the remainder expands through the second stage to the condenser pressure of 0.06 bar. Condensate returns from the campus buildings at 0.1 MPa, 60°C and passes through a trap into the condenser, where it is reunited with the main feedwater flow. Saturated liquid leaves the condenser at 0.06 bar. Each turbine stage has an isentropic efficiency of 80%, and the pumping process can be considered isentropic. Determine
(a) the rate of heat transfer to the cooling water passing through the condenser, in kW.
(b) the net power developed, in kW.
(c) the rate of heat transfer to the working fluid passing through the steam generator, in kW.
(d) the rate of heat transfer to the cooling water passing through the condenser, in kW.

8.73 Consider a cogeneration system operating as illustrated in Fig. 8.14. The steam generator provides a 10^6 kg/h of steam at 8 MPa, 480°C, of which 4 × 10^6 kg/h is extracted between the first and second turbine stages at 1 MPa and diverted to a process heating load. Condensate returns from the process heating load at 0.95 MPa, 120°C and is mixed with liquid exiting the lower-pressure pump at 0.95 MPa. The entire flow is then pumped to the steam generator pressure. Saturated liquid at 8 kPa leaves the condenser. The turbine stages and the pumps operate with isentropic efficiencies of 86 and 80%, respectively. Determine
(a) the heating load, in kJ/h.
(b) the power developed by the turbine, in kW.
(c) the rate of heat transfer to the working fluid passing through the steam generator, in kJ/h.

8.74 Figure P8.74 shows a cogeneration system providing turbine power and steam for process heating. The steam generator supplies 50,000 lbm/hr of steam at 600 lbm/hr, 700°F, to a two-stage turbine. Steam is extracted after the first stage at 30 lbm/hr. Some of the extracted steam is supplied at a rate of 30,000 lbm/hr to the process load. Due to condensate losses, only 90% of the condensate returns from the process at 120°F, 14.7 lbm/hr, and flows into the open feedwater heater. Make-up water enters the feedwater heater at 80°F, 14.7 lbm/hr. The remainder of the extracted steam enters the feedwater heater at such a rate that saturated liquid at 14.7 lbm/hr exits. Steam expands through the second-stage turbine to the condenser pressure of 1 lbm/hr. Saturated liquid at 1 lbm/hr leaves the condenser and is pumped into the feedwater heater. Each turbine stage has an isentropic efficiency of 80%. The pumping processes can be considered isentropic. Determine
(a) the rate at which steam is extracted, in lbm/hr.
(b) the net power developed by the cycle, in Btu/hr.
(c) the rate of heat transfer to the working fluid passing through the steam generator, in Btu/hr.
(d) the heat rate, in Btu/kW·h.
Figure P8.74
and saturated liquid leaves the condenser at 28°C. The mass flow rate of refrigerant is 5 kg/min. Determine
(a) the compressor power, in kW.
(b) the refrigerating capacity, in tons.
(c) the coefficient of performance.

10.7 Modify the cycle in Problem 10.6 to have saturated vapor entering the compressor at 1.6 bar and saturated liquid leaving the condenser at 9 bar. Answer the same questions for the modified cycle as in Problem 10.6.

10.8 Plot each of the quantities calculated in Problem 10.7 versus evaporator pressure ranging from 0.6 to 4 bar, while the condenser pressure remains fixed at 6, 9, and 12 bar.

10.9 An ideal vapor-compression refrigeration system operates at steady state with Refrigerant 134a as the working fluid. Superheated vapor enters the compressor at 30 lb/ft³, 20°F, and saturated liquid leaves the condenser at 140 lb/ft³. The refrigeration capacity is 5 tons. Determine
(a) the compressor power, in kW.
(b) the temperature of the working fluid leaving the condenser, in °F.
(c) the coefficient of performance.

10.10 Refrigerant 134a enters the compressor of an ideal vapor-compression refrigeration system as saturated vapor at −16°C with a volumetric flow rate of 1 m³/min. The refrigerant leaves the condenser at 36°C, 10 bar. Determine
(a) the compressor power, in kW.
(b) the refrigerating capacity, in tons.
(c) the coefficient of performance.

10.11 An ideal vapor-compression refrigeration cycle, with ammonia as the working fluid, has an evaporator temperature of −20°C and a condenser pressure of 12 bar. Saturated vapor enters the compressor, and saturated liquid exits the condenser. The mass flow rate of the refrigerant is 3 kg/min. Determine
(a) the coefficient of performance.
(b) the refrigerating capacity, in tons.

10.12 Refrigerant 134a enters the compressor of an ideal vapor-compression refrigeration cycle as saturated vapor at −10°F. The condenser pressure is 160 lb/ft³. The mass flow rate of refrigerant is 6 lb/min. Plot the coefficient of performance and the refrigerating capacity, in tons, versus the condenser exit temperature ranging from the saturation temperature at 160 lb/ft³ to 90°F.

10.13 To determine the effect of changing the evaporator temperature on the performance of an ideal vapor-compression refrigeration cycle, plot the coefficient of performance and the refrigerating capacity, in tons, for the cycle in Problem 10.11 for saturated vapor entering the compressor at temperatures ranging from −40 to −10°C. All other conditions are the same as in Problem 10.11.

10.14 To determine the effect of changing condenser pressure on the performance of an ideal vapor-compression refrigeration cycle, plot the coefficient of performance and the refrigerating capacity, in tons, for the cycle in Problem 10.11 for condenser pressures ranging from 8 to 16 bar. All other conditions are the same as in Problem 10.11.

10.15 Modify the cycle in Problem 10.7 to have an isentropic compressor efficiency of 85% and let the temperature of the liquid leaving the condenser be 32°C. Determine, for the modified cycle,
(a) the compressor power, in kW.
(b) the refrigerating capacity, in tons.
(c) the coefficient of performance.
(d) the rate of heat transfer from the working fluid to the condenser, in Btu/min.

10.16 Modify the cycle in Problem 10.9 to have an isentropic compressor efficiency of 85% and let the temperature of the liquid leaving the condenser be 95°F. Determine, for the modified cycle,
(a) the compressor power, in horsepower.
(b) the rate of heat transfer from the working fluid passing through the condenser, in Btu/min.
(c) the coefficient of performance.
(d) the rate of exergy destruction in the compressor and expansion valve, each in Btu/min.

10.17 A vapor-compression refrigeration system circulates Refrigerant 134a at a rate of 6 kg/min. The refrigerant enters the compressor at −10°C, 1.4 bar, and exits at 7 bar. The isentropic compressor efficiency is 67%. There are no appreciable pressure drops as the refrigerant flows through the condenser and evaporator. The refrigerant leaves the condenser at 7 bar, 24°C. Ignoring heat transfer between the compressor and its surroundings, determine
(a) the coefficient of performance.
(b) the refrigerating capacity, in tons.
(c) the rate of exergy destruction in the compressor and expansion valve, each in kW.
(d) the change in specific flow exergy of the refrigerant passing through the evaporator and condenser, respectively, each in kJ/kg.

Let \( T_e = 21°C, p_e = 1 \) bar.

10.18 A vapor-compression refrigeration system, using ammonia as the working fluid, has evaporator and condenser pressures of 2 and 12 bar, respectively. The refrigerant passes through each heat exchanger with a negligible pressure drop. At the inlet and exit of the compressor, the temperatures are −10°C and 140°C, respectively. The heat transfer rate from the working fluid passing through the condenser is 15 kW, and liquid exists at 12 bar, 28°C. If the compressor operates adiabatically, determine
(a) the compressor power input, in kW.
(b) the coefficient of performance.

10.19 If the minimum and maximum allowed refrigerant pressures are 1 and 10 bar, respectively, which of the following can be used as the working fluid in a vapor-
versus the direct-contact heat exchanger pressure ranging from 20 to 200 lb/in.². Discuss.

10.30 Figure P10.30 shows a Refrigerant 22 vapor-compression refrigeration system with [mechanical subcooling](#). A countercflow heat exchanger subcools a portion of the refrigerant leaving the condenser below the ambient temperature as follows: Saturated liquid exits the condenser at 180 lb/in.². A portion of the flow exiting the condenser is diverted through an expansion valve and passes through the countercflow heat exchanger with no pressure drop, leaving as saturated vapor at 20°F. The diverted flow is then compressed isentropically to 180 lb/in.² and reenters the condenser. The remainder of the flow exiting the condenser passes through the other side of the heat exchanger and exits at 40°F, 180 lb/in.². The evaporator has a capacity of 50 tons and produces −20°F saturated vapor at its exit. In the main compressor, the refrigerant is compressed isentropically to 180 lb/in.². Determine at steady state
(a) the mass flow rate at the inlet to each compressor, in lb/min.
(b) the power input to each compressor, in Btu/min.
(c) the coefficient of performance.

10.31 Figure P10.31 shows the schematic diagram of a vapor-compression refrigeration system with two evaporators using Refrigerant 134a as the working fluid. This arrangement is used to achieve refrigeration at two different temperatures with a single compressor and a single condenser. The low-temperature evaporator operates at −18°C with saturated vapor at its exit and has a refrigerating capacity of 3 tons. The higher-temperature evaporator produces saturated vapor at 3.2 bar at its exit and has a refrigerating capacity of 2 tons. Compression is isentropic to the condenser pressure of 10 bar. There are no significant pressure drops in the flows through the condenser and the two evaporators, and the refrigerant leaves the condenser as saturated liquid at 10 bar. Calculate
(a) the mass flow rate of refrigerant through each evaporator, in kg/min.
10.32 An ideal vapor-compression refrigeration cycle is modified to include a counterflow heat exchanger, as shown in Fig. P10.32. Refrigerant 134a leaves the evaporator as saturated vapor at 1.4 bar and is heated at constant pressure to 20°C before entering the compressor. Following isentropic compression to 12 bar, the refrigerant passes through the condenser, exiting at 44°C, 12 bar. The liquid then passes through the heat exchanger, entering the expansion valve at 12 bar. If the mass flow rate of refrigerant is 6 kg/min, determine
(a) the refrigeration capacity, in tons of refrigeration.
(b) the compressor power input, in kW.
(c) the coefficient of performance.
Discuss possible advantages and disadvantages of this arrangement.

![Diagram of vapor-compression heat pump cycle](image)

(a) the power input to the compressor, in kW.
(b) the coefficient of performance.
(c) the coefficient of performance of a Carnot heat pump cycle operating between thermal reservoirs at 20 and 5°C.

10.34 Ammonia is the working fluid in a vapor-compression heat pump system with a heating capacity of 24,000 Btu/h. The condenser operates at 250 lb/ft²·h, and the evaporator temperature is -10°F. The refrigerant is a saturated vapor at the evaporator exit and a liquid at 105°F at the condenser exit. Pressure drops in the flows through the evaporator and condenser are negligible. The compression process is adiabatic, and the temperature at the compressor exit is 360°F. Determine
(a) the mass flow rate of refrigerant, in lb/min.
(b) the compressor power input, in horsepower.
(c) the isentropic compressor efficiency.
(d) the coefficient of performance.

10.35 A vapor-compression heat pump system uses Refrigerant 134a as the working fluid. The refrigerant enters the compressor at 2.4 bar, 6°C, with a volumetric flow rate of 0.6 m³/min. Compression is adiabatic to 9 bar, 60°C, and saturated liquid exits the condenser at 9 bar. Determine
(a) the power input to the compressor, in kW.
(b) the heating capacity of the system, in kW and tons.
(c) the coefficient of performance.
(d) the isentropic compressor efficiency.

10.36 On a particular day when the outside temperature is 5°C, a house requires a heat transfer rate of 12 kW to maintain the inside temperature at 20°C. A vapor-compression heat pump with Refrigerant 22 as the working fluid is to be used to provide the necessary heating. Specify appropriate evaporator and condenser pressures of a cycle for this purpose. Let the refrigerant be saturated vapor at the evaporator exit and saturated liquid at the condenser exit. Calculate
(a) the mass flow rate of refrigerant, in kg/min.
(b) the compressor power, in kW.
(c) the coefficient of performance.

10.37 Repeat the calculations of Problem 10.36 for Refrigerant 134a as the working fluid. Compare the results with those of Problem 10.36 and discuss.

10.38 A process requires a heat transfer rate of $2 \times 10^6$ Btu/h at 150°F. It is proposed that a Refrigerant 134a vapor-compression heat pump be used to develop the process heat using a waste water stream at 100°F as the lower-temperature source. Specify appropriate evaporator and condenser pressures of a cycle for this purpose. Let the refrigerant be saturated vapor at the evaporator exit and saturated liquid at the condenser exit. Calculate
(a) the mass flow rate of refrigerant, in lb/h.
(b) the compressor power, in horsepower.
(c) the coefficient of performance.