Exercises: things engineers think about

1. Many utility companies offer special rates for “green power.” What does that mean?
2. Referring to your monthly electric bills, make a plot of your monthly kW · h usage for the last year. Comment.
3. How much does the temperature of condenser cooling water vary in your area throughout the year? How would that affect the thermal efficiency of local power plants?
4. Power plants located in arid areas may accomplish condensation by air cooling instead of cooling with water flowing through the condenser. How might air cooling affect the thermal efficiency?
5. How does the Rankine cycle differ from the Carnot cycle of Fig. 5.15?
6. Keeping states 1 and 2 fixed, how would Fig. 8.6 be modified if the frictional pressure drops through the boiler and condenser were considered? How would the pressure drops affect the net power of the cycle?
7. Brainstorm some ways to use the cooling water exiting the condenser of a large power plant.
8. What effects on a river’s ecology might result from a power plant’s use of river water for condenser cooling?
9. Referring to Fig. 8.1, what environmental impacts might result from the two plumes shown on the figure?
10. Referring to Example 8.5, what are the principal sources of internal irreversibility?
11. Some prototype binary cycle power plants have been built in the last 50 years, but to date they have not found commercial application. Why?
12. There are many locations where solar energy is plentiful, yet to date there is no widespread use of solar energy for electric power generation. What issues have kept solar energy from being widely used?

Problems: developing engineering skills

Analyzing Rankine Cycles

8.1 Water is the working fluid in an ideal Rankine cycle. The condenser pressure is 6 kPa, and saturated vapor enters the turbine at 10 MPa. Determine the heat transfer rates, in kJ per kg of steam flowing, for the working fluid passing through the boiler and condenser and calculate the thermal efficiency.
8.2 Water is the working fluid in an ideal Rankine cycle. Superheated vapor enters the turbine at 10 MPa, 480°C, and the condenser pressure is 6 kPa. Determine for the cycle
(a) the rate of heat transfer to the working fluid passing through the steam generator, in kJ per kg of steam flowing,
(b) the thermal efficiency,
(c) the rate of heat transfer from the working fluid passing through the condenser to the cooling water, in kJ per kg of steam flowing.
8.3 Water is the working fluid in a Carnot vapor power cycle. Saturated liquid enters the boiler at a pressure of 10 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 heat transfer to the working fluid per unit mass passing through the boiler, in kJ/kg,
(d) the heat transfer from the working fluid per unit mass passing through the condenser, in kJ/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 20 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 16 MPa, and the condenser pressure is 8 kPa. The mass flow rate of steam entering the turbine is 120 kg/s. Determine
(a) the net power developed, in kW.
(b) the rate of heat transfer to the steam passing through the boiler, in kW.
(c) the thermal efficiency.
(d) the mass flow rate of condenser cooling water, in kg/s, if the cooling water undergoes a temperature increase of 18°C with negligible pressure change in passing through the condenser.
8.7 Water is the working fluid in a Carnot vapor power cycle. Saturated liquid enters the boiler at 16 MPa, and saturated vapor enters the turbine. The condenser pressure is 8 kPa. The mass flow rate of steam entering the turbine is 120 kg/s. Determine
(a) the thermal efficiency.
(b) the back work ratio.
(c) the net power developed, in kW.
(d) the rate of heat transfer from the working fluid passing through the condenser, in kW.
8.8 Plot each of the quantities calculated in Problem 8.6 versus turbine inlet temperature ranging from the saturation temperature at 16 MPa to 560°C. Discuss.
8.9 Water is the working fluid in an ideal Rankine cycle. The pressure and temperature at the turbine inlet are 1600 lb/in.² and 1100°F, respectively, and the condenser pressure is 1 lb/in.². The mass flow rate of steam entering the turbine is 1.4 × 10⁶ lb/h. The cooling water experiences a temperature increase from 60 to 80°F, with negligible
8.26 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%.

Considering Reheat and Supercritical Cycles

8.27 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.

8.28 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 1000°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.

8.29 Water is the working fluid in an ideal Rankine cycle with reheat. Superheated vapor enters the turbine at 10 MPa, 480°C, and the condenser pressure is 6 kPa. Steam expands through the first-stage turbine to 0.7 MPa and then is reheated to 480°C. Determine for the cycle

(a) the rate of heat addition, in kJ per kg of steam entering the first-stage turbine.
(b) the thermal efficiency.
(c) the rate of heat transfer from the working fluid passing through the condenser to the cooling water, in kJ per kg of steam entering the first-stage turbine.

8.30 For the cycle of Problem 8.29, reconsider the analysis assuming the pump and each turbine stage has an isentropic efficiency of 80%. Answer the same questions as in Problem 8.29 for the modified cycle.

8.31 Investigate the effects on cycle performance as the reheat pressure and final reheat temperature take on other values. Construct suitable plots and discuss for the cycle of

(a) Problem 8.29.
(b) Problem 8.30.

8.32 An ideal Rankine cycle with reheat uses water as the working fluid. The conditions at the inlet to the first-stage turbine are \( p_1 = 2500 \text{ lb/in}^2 \), \( T_1 = 1000°F \). The steam is reheated at constant pressure \( p \) between the turbine stages to 1000°F. The condenser pressure is 1 lb/in.\(^2\).

(a) If \( p/p_1 = 0.2 \), 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 \( p/p_1 \) ranging from 0.05 to 1.0.

8.33 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 \( p = 4 \text{ MPa} \), 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.

8.34 Steam at 4800 lb/in.\(^2\), 1000°F enters the first stage of a supercritical reheat cycle including two turbine stages. The steam exiting the first-stage turbine at 600 lb/in.\(^2\) is reheated at constant pressure to 1000°F. Each turbine stage and the pump has an isentropic efficiency of 85%. The condenser pressure is 1 lb/in.\(^2\).

If the net power output of the cycle is 100 MW, determine

(a) the rate of heat transfer to the working fluid passing through the steam generator, in MW.
(b) the rate of heat transfer from the working fluid passing through the condenser, in MW.
(c) the cycle thermal efficiency.

8.35 An ideal Rankine cycle with reheat uses water as the working fluid. The conditions at the inlet to the first-stage turbine are 14 MPa, 600°C and the steam is reheated between the turbine stages to 600°C. For a condenser pressure of 6 kPa, plot the cycle thermal efficiency versus reheat pressure for pressures ranging from 2 to 12 MPa.

8.36 An ideal Rankine cycle with reheat uses water as the working fluid. The conditions at the inlet to the first turbine stage are 1600 lb/in.\(^2\), 1200°F and the steam is reheated between the turbine stages to 1200°F. For a condenser pressure of 1 lb/in.\(^2\), plot the cycle thermal efficiency versus reheat pressure for pressures ranging from 60 to 1200 lb/in.\(^2\).

Analyzing Regenerative Cycles

8.37 Water is the working fluid in an ideal regenerative Rankine cycle. Superheated vapor enters the turbine at 10 MPa, 480°C, and the condenser pressure is 6 kPa. Steam expands through the first-stage turbine to 0.7 MPa where some of the steam is extracted and diverted to an open feedwater heater operating at 0.7 MPa. The remaining steam expands through the second-stage turbine to the condenser pressure of 6 kPa. Saturated liquid exits the feedwater heater at 0.7 MPa.

Determine for the cycle

(a) the rate of heat addition, in kJ per kg of steam entering the first-stage turbine.
(b) the thermal efficiency.
(c) the rate of heat transfer from the working fluid passing through the condenser to the cooling water, in kJ per kg of steam entering the first-stage turbine.

8.38 For the cycle of Problem 8.37, reconsider the analysis assuming the pump and each turbine stage has an isentropic efficiency of 80%. Answer the same questions as in Problem 8.37 for the modified cycle.

8.39 Investigate the effects on cycle performance as the feedwater heater pressure takes on other values. Construct suitable plots and discuss for the cycle of

(a) Problem 8.37.
(b) Problem 8.38.
8.40 A power plant operates on a regenerative vapor power cycle with one open feedwater heater. Steam enters the first

8.41 Reconsider the cycle of Problem 8.40 as the feedwater heater pressure takes on other values. Plot the thermal efficiency and the rate of exergy destruction within the feedwater heater, in kW, versus the feedwater heater pressure ranging from 0.5 to 10 MPa. Let \( T_0 = 293 \) K.

8.42 Compare the results of Problem 8.40 with those for an ideal Rankine cycle having the same turbine inlet conditions and condenser pressure, but no regenerator.

8.43 For the cycle of Problem 8.40, investigate the effects on cycle performance as the feedwater heater pressure takes on other values. Construct suitable plots and discuss. Assume that each turbine stage and each pump has an isentropic efficiency of 80%.

8.44 Modify the ideal Rankine cycle of Problem 8.9 to include one open feedwater heater operating at 100 lbf/in.\(^2\). Saturated liquid exits the open feedwater heater at 100 lbf/in.\(^2\). The mass flow rate of steam into the first turbine stage is the same as the mass flow rate of steam in Problem 8.9. Answer the same questions about the modified cycle as in Problem 8.9 and discuss the results.

8.45 Reconsider the cycle of Problem 8.44, but include in the analysis that the isentropic efficiency of each turbine stage is 88% and of each pump is 80%.

8.46 Water is the working fluid in an ideal regenerative Rankine cycle with one open feedwater heater. Superheated vapor enters the first-stage turbine at 16 MPa, 560°C, and the condenser pressure is 8 kPa. The mass flow rate of steam entering the first-stage turbine is 120 kg/s. Steam expands through the first-stage turbine to 1 MPa where some of the steam is extracted and diverted to an open feedwater heater operating at 1 MPa. The remainder expands through the second-stage turbine to the condenser pressure of 8 kPa. Saturated liquid exits the feedwater heater at 1 MPa. Determine (a) the net power developed, in kW, (b) the rate of heat transfer to the steam passing through the boiler, in kW, (c) the thermal efficiency, (d) the mass flow rate of condenser cooling water, in kg/s, if the cooling water undergoes a temperature increase of 18°C with negligible pressure change in passing through the condenser.

8.47 Reconsider the cycle of Problem 8.46, but include in the analysis that each turbine stage and pump has an isentropic efficiency of 85%.

8.48 For the cycle of Problem 8.47, investigate the effects on cycle performance as the feedwater heater pressure takes on other values. Construct suitable plots and discuss.

8.49 Water is the working fluid in an ideal regenerative Rankine cycle with one closed feedwater heater. Superheated vapor enters the turbine at 10 MPa, 480°C, and the condenser pressure is 6 kPa. Steam expands through the first-stage turbine where some is extracted and diverted to a closed feedwater heater at 0.7 MPa. Condensate drains from the feedwater heater as saturated liquid at 0.7 MPa and is trapped into the condenser. The feedwater leaves the heater at 10 MPa and a temperature equal to the saturation temperature at 0.7 MPa. Determine for the cycle (a) the rate of heat transfer to the working fluid passing through the steam generator, in kJ per kg of steam entering the first-stage turbine, (b) the thermal efficiency, (c) the rate of heat transfer from the working fluid passing through the condenser to the cooling water, in kJ per kg of steam entering the first-stage turbine.

8.50 For the cycle of Problem 8.49, reconsider the analysis assuming the pump and each turbine stage have isentropic efficiencies of 80%. Answer the same questions as in Problem 8.49 for the modified cycle.

8.51 For the cycle of Problem 8.50, investigate the effects on cycle performance as the extraction pressure takes on other values. Assume that condensate drains from the closed feedwater heater as saturated liquid at the extraction pressure. Also, feedwater leaves the heater at 10 MPa and a temperature equal to the saturation temperature at the extraction pressure. Construct suitable plots and discuss.

8.52 A power plant operates on a regenerative vapor power cycle with one closed feedwater heater. Steam enters the first turbine stage at 120 bar, 520°C and expands to 10 bar, where some of the steam is extracted and diverted to a closed feedwater heater. Condensate exiting the feedwater heater as saturated liquid at 10 bar passes through a trap into the condenser. The feedwater exits the heater at 120 bar with a temperature of 170°C. The condenser pressure is 0.06 bar. For isentropic processes in each turbine stage and the pump, determine for the cycle (a) the thermal efficiency and (b) the mass flow rate into the first-stage turbine, in kg/h, if the net power developed is 320 MW.

8.53 Reconsider the cycle of Problem 8.52, but include in the analysis that each turbine stage has an isentropic efficiency of 82%. The pump efficiency remains 100%.

8.54 Modify the cycle of Problem 8.49 such that the saturated liquid condensate from the feedwater heater at 0.7 MPa is pumped into the feedwater line rather than being trapped into the condenser. Answer the same questions about the modified cycle as in Problem 8.49. List advantages and disadvantages of each scheme for removing condensate from the closed feedwater heater.

8.55 Modify the ideal Rankine cycle of Problem 8.9 to include one closed feedwater heater using extracted steam at 100 lbf/in.\(^2\). Condensate exiting the heater as saturated liquid at 100 lbf/in.\(^2\) passes through a trap into the condenser. The feedwater leaves the heater at 1600 lbf/in.\(^2\) and a temperature equal to the saturation temperature at 100 lbf/in.\(^2\). The mass flow rate of steam entering the first-stage turbine is the same as the steam flow rate in Problem 8.9. Answer the same
8.80 Consider a cogeneration system operating as illustrated in Fig. 8.14. The steam generator provides $10^6$ kg/h of steam at 8 MPa, 480°C, of which $4 \times 10^6$ 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 kW.

8.81 Figure P8.81 shows a combined heat and power system (CHP) providing turbine power, process steam, and steam for a factory space heating load. Operating data are given on the figure at key states in the cycle. For the system, determine

(a) the rates that steam is extracted as process steam and for the heating load, each in lb/h.
(b) the rates of heat transfer for the process steam and the heating load, each in Btu/h.
(c) the net power developed, in Btu/h.

Devisce and evaluate an overall energy-based efficiency for the combined heat and power system.

8.82 Figure P8.82 shows the schematic diagram of a cogeneration cycle. In the steam cycle, superheated vapor enters the turbine with a mass flow rate of 5 kg/s at 40 bar, 440°C and expands isentropically to 1.5 bar. Half of the flow is extracted at 1.5 bar and used for industrial process heating. The rest of the steam passes through a heat exchanger, which serves as the boiler of the Refrigerant 134a cycle and

![Diagram](image-url)
Exercises: things engineers think about

1. Diesel engines are said to produce higher torque than gasoline engines. What does that mean?

2. Formula One race cars have 2.4 liter engines. What does that signify? How is your automobile's engine sized in liters?

3. A car magazine says that your car's engine has more power when the ambient temperature is low. Do you agree?

4. When operating at high elevations, cars can lose power. Why?

5. Why are the external surfaces of a lawn mower engine covered with fins?

6. The ideal Brayton and Rankine cycles are composed of the same four processes, yet look different when represented on a T-s diagram. Explain.

7. The term regeneration is used to describe the use of regenerative feedwater heaters in vapor power plants and regenerative heat exchangers in gas turbines. In what ways are the purposes of these devices similar? How do they differ?

8. What is the overall thermal efficiency of the combined cycle of Example 9.13?


10. How would the T-s diagram of Fig. 9.20 appear if frictional effects for flow through the diffuser, compressor, turbine, and nozzle were considered?

11. How do internal and external combustion engines differ?

12. In which of the following media is the sonic velocity the greatest: air, steel, or water? Does sound propagate in a vacuum?

13. Can a shock stand upstream of the throat of a converging-diverging nozzle?

Problems: developing engineering skills

Otto, Diesel, and Dual Cycles

9.1 An air-standard Otto cycle has a compression ratio of 9. At the beginning of compression, \( p_1 = 100 \) kPa and \( T_1 = 300 \) K. The heat addition per unit mass of air is 1350 \( \text{kJ/kg} \). Determine

(a) the net work, in \( \text{kJ} \) per \( \text{kg} \) of air.

(b) the thermal efficiency of the cycle.

(c) the mean effective pressure, in kPa.

(d) the maximum temperature in the cycle, in K.

(e) To investigate the effects of varying compression ratio, plot each of the quantities calculated in parts (a) through (d) for compression ratios ranging from 1 to 12.

9.2 Solve Problem 9.1 on a cold air-standard basis with specific heats evaluated at 300 K.

9.3 At the beginning of the compression process of an air-standard Otto cycle, \( p_1 = 1 \) bar, \( T_1 = 290 \) K, \( V_1 = 400 \) cm\(^3\). The maximum temperature in the cycle is 2200 K and the compression ratio is 8. Determine

(a) the heat addition, in \( \text{kJ} \).

(b) the net work, in \( \text{kJ} \).

(c) the thermal efficiency.

(d) the mean effective pressure, in bar.

(e) Develop a full accounting of the exergy transferred to the air during the heat addition, in \( \text{kJ} \).

(f) Devise and evaluate an exergetic efficiency for the cycle. Let \( T_0 = 290 \) K, \( p_0 = 1 \) bar.

9.4 Plot each of the quantities specified in parts (a) through (d) of Problem 9.3 versus the compression ratio ranging from 2 to 12.

9.5 Solve Problem 9.3 on a cold air-standard basis with specific heats evaluated at 300 K.

9.6 A four-cylinder, four-stroke internal combustion engine operates at 2800 RPM. The processes within each cylinder are modeled as an air-standard Otto cycle with a pressure of 14.7 lbf/in\(^2\), a temperature of 80°F, and a volume of 0.0196 ft\(^3\) at the beginning of compression. The compression ratio is 10, and maximum pressure in the cycle is 1080 lbf/in\(^2\). Determine, using a cold air-standard analysis with \( k = 1.4 \), the power developed by the engine, in horsepower, and the mean effective pressure, in lbf/in\(^2\).

9.7 An air-standard Otto cycle has a compression ratio of 8 and the temperature and pressure at the beginning of the compression process are 520°F and 14.2 lbf/in\(^2\), respectively. The mass of air is 0.0015 lb. The heat addition is 0.9 Btu. Determine
9.8 Solve Problem 9.7 on a cold air-standard basis with specific heats evaluated at 520°F.

9.9 At the beginning of the compression process in an air-standard Otto cycle, $p_1 = 14.7$ lb/ft$^2$ and $T_1 = 530°F$. Plot the thermal efficiency and mean effective pressure, in lb/ft$^2$, for maximum cycle temperatures ranging from 2000 to 5000°F and compression ratios of 6, 8, and 10.

9.10 Solve Problem 9.9 on a cold air-standard basis using $k = 1.4$.

9.11 An air-standard Otto cycle has a compression ratio of 7.5. At the beginning of compression, $p_1 = 85$ kPa and $T_1 = 32°C$. The mass of air is 2 g, and the maximum temperature in the cycle is 960 K. Determine
(a) the heat rejection, in kJ.
(b) the net work, in kJ.
(c) the thermal efficiency.
(d) the mean effective pressure, in kPa.

9.12 The compression ratio of a cold air-standard Otto cycle is 9. At the end of the expansion process, the pressure is 95 lb/ft$^2$ and the temperature is 1000°F. The heat rejection from the cycle is 86 Btu per lb of air. Assuming $k = 1.4$, determine
(a) the net work, in Btu per lb of air.
(b) the thermal efficiency.
(c) the mean effective pressure, in lb/ft$^2$.

9.13 Consider a modification of the air-standard Otto cycle in which the isentropic compression and expansion processes are each replaced with polytropic processes having $n = 1.3$. The compression ratio is 9 for the modified cycle. At the beginning of compression, $p_1 = 1$ bar and $V_1 = 300$ K and $V_1 = 2270$ cm$^3$. The maximum temperature during the cycle is 2000 K. Determine
(a) the heat transfer and work in kJ, for each process in the modified cycle.
(b) the thermal efficiency.
(c) the mean effective pressure, in bar.

9.14 A four-cylinder, four-stroke internal combustion engine has a bore of 2.55 in. and a stroke of 2.10 in. The clearance volume is 12% of the cylinder volume at bottom dead center and the crankshaft rotates at 3600 RPM. The processes within each cylinder are modeled as an air-standard Otto cycle with a pressure of 14.6 lb/ft$^2$ and a temperature of 100°F at the beginning of compression. The maximum temperature in the cycle is 5200°F. Based on this model, calculate the net work per cycle, in Btu, and the power developed by the engine, in horsepower.

9.15 At the beginning of the compression process in an air-standard Otto cycle, $p_1 = 1$ bar and $T_1 = 300$ K. The maximum cycle temperature is 2000 K. Plot the net work per unit of mass, in kJ/kg, the thermal efficiency, and the mean effective pressure, in bar, versus the compression ratio ranging from 2 to 14.

9.16 Investigate the effect of maximum cycle temperature on the net work per unit mass of air for air-standard Otto cycles with compression ratios of 5, 8, and 11. At the beginning of the compression process, $p_1 = 1$ bar and $T_1 = 295$ K. Let the maximum temperature in each case vary from 1000 to 2200 K.

9.17 The pressure-specific volume diagram of the air-standard Lenoir cycle is shown in Fig. P9.17. The cycle consists of constant volume heat addition, isentropic expansion, and constant pressure compression. For the cycle, $p_1 = 147$ lb/ft$^2$ and $T_1 = 540°F$. The mass of air is $4.24 \times 10^{-3}$ lb, and the maximum cycle temperature is 1600°F. Assuming $c_v = 0.171$ Btu/lb·°R, determine for the cycle
(a) the net work, in Btu.
(b) the thermal efficiency.

9.18 The pressure-specific volume diagram of the air-standard Atkinson cycle is shown in Fig. P9.18. The cycle consists of isentropic compression, constant volume heat addition, isentropic expansion, and constant pressure compression. For a particular Atkinson cycle, the compression ratio during isentropic compression is 8.5. At the beginning of this compression process, $p_1 = 100$ kPa and $T_1 = 360$ K. The constant volume heat addition per unit mass of air is 1400 kJ/kg. (a) Sketch the cycle on $T$-$s$ coordinates. Determine (b) the net work, in kJ per kg of air, (c) the thermal efficiency of the cycle, and (d) the mean effective pressure, in kPa.

9.19 On a cold air-standard basis, derive an expression for the thermal efficiency of the Atkinson cycle (see Fig. P9.18) in...
terms of the volume ratio during the isentropic compression, the pressure ratio for the constant volume process, and the specific heat ratio. Compare the thermal efficiencies of the cold air-standard Atkinson and Otto cycles, each having the same compression ratio and maximum temperature. Discuss.

9.20 The pressure and temperature at the beginning of compression of an air-standard Diesel cycle are 95 kPa and 300 K, respectively. At the end of the heat addition, the pressure is 7.2 MPa and the temperature is 2150 K. Determine
(a) the compression ratio.
(b) the cutoff ratio.
(c) the thermal efficiency of the cycle.
(d) the mean effective pressure, in kPa.

9.21 Solve Problem 9.20 on a cold air-standard basis with specific heats evaluated at 300 K.

9.22 The compression ratio of an air-standard Diesel cycle is 17 and the conditions at the beginning of compression are \( p_1 = 14.0 \, \text{lbf/in}^2 \), \( V_1 = 2 \, \text{ft}^3 \), and \( T_1 = 520^\circ \text{R} \). The maximum temperature in the cycle is 4000^\circ \text{R}. Calculate
(a) the net work for the cycle, in Btu.
(b) the thermal efficiency.
(c) the mean effective pressure, in \text{lbf/in}^2.
(d) the cutoff ratio.

9.23 Solve Problem 9.22 on a cold air-standard basis with specific heats evaluated at 520^\circ \text{R}.

9.24 The conditions at the beginning of compression in an air-standard Diesel cycle are fixed by \( p_1 = 200 \, \text{kPa}, T_1 = 380 \, \text{K} \). The compression ratio is 20 and the cutoff ratio is 1.8. For \( k = 1.4 \), determine
(a) the maximum temperature, in K.
(b) the heat addition per unit mass, in kJ/kg.
(c) the net work per unit mass, in kJ/kg.
(d) the thermal efficiency.
(e) the mean effective pressure, in kPa.
(f) To investigate the effects of varying compression ratio, plot each of the quantities calculated in parts (a) through (e) for compression ratios ranging from 5 to 25.

9.25 For the Diesel cycle of Problem 9.24 with a compression ratio of 20 and a cutoff ratio of 1.8
(a) evaluate the exergy transfers accompanying heat and work for each process, in kJ/kg.
(b) devise and evaluate an exergetic efficiency for the cycle.
Let \( T_0 = 300 \, \text{K}, \rho_0 = 100 \, \text{kPa} \).

9.26 An air-standard Diesel cycle has a compression ratio of 16 and a cutoff ratio of 2. At the beginning of compression, \( p_1 = 14.2 \, \text{lbf/in}^2, V_1 = 0.5 \, \text{ft}^3 \), and \( T_1 = 520^\circ \text{R} \). Calculate
(a) the heat added, in Btu.
(b) the maximum temperature in the cycle, in \text{R}.
(c) the thermal efficiency.
(d) the mean effective pressure, in \text{lbf/in}^2.
(e) To investigate the effects of varying compression ratio, plot each of the quantities calculated in parts (a) through (d) for compression ratios ranging from 5 to 18 and for cutoff ratios of 1.5, 2, and 2.5.

9.27 For the Diesel cycle of Problem 9.26 with a compression ratio of 16 and a cutoff ratio of 2
(a) evaluate the exergy transfers accompanying heat and work for each process, in Btu.
(b) devise and evaluate an exergetic efficiency for the cycle.
Let \( T_0 = 520^\circ \text{R}, \rho_0 = 14.2 \, \text{lbf/in}^2 \).

9.28 The displacement volume of an internal combustion engine is 5.6 liters. The processes within each cylinder of the engine are modeled as an air-standard Diesel cycle with a cutoff ratio of 2.4. The state of the air at the beginning of compression is fixed by \( p_1 = 95 \, \text{kPa}, T_1 = 27^\circ \text{C}, \text{and} V_1 = 6.0 \, \text{liters} \). Determine the net work per cycle, in kJ, the power developed by the engine, in kW, and the thermal efficiency, if the cycle is executed 1500 times per min.

9.29 The state at the beginning of compression of an air-standard Diesel cycle is fixed by \( p_1 = 100 \, \text{kPa} \) and \( T_1 = 310 \, \text{K} \). The compression ratio is 15. For cutoff ratios ranging from 1.5 to 2.5, plot
(a) the maximum temperature, in K.
(b) the pressure at the end of the expansion, in kPa.
(c) the net work per unit mass of air, in kJ/kg.
(d) the thermal efficiency.

9.30 An air-standard Diesel cycle has a maximum temperature of 1800 K. At the beginning of compression, \( p_1 = 95 \, \text{kPa} \) and \( T_1 = 300 \, \text{K} \). The mass of air is 12 g. For compression ratios ranging from 15 to 25, plot
(a) the net work of the cycle, in kJ.
(b) the thermal efficiency.
(c) the mean effective pressure, in kPa.

9.31 At the beginning of compression in an air-standard Diesel cycle, \( p_1 = 170 \, \text{kPa}, V_1 = 0.016 \, \text{m}^3 \), and \( T_1 = 315 \, \text{K} \). The compression ratio is 15 and the maximum cycle temperature is 1400 K. Determine
(a) the mass of air, in kg.
(b) the heat addition and heat rejection per cycle, each in kJ.
(c) the net work, in kJ, and the thermal efficiency.

9.32 At the beginning of the compression process in an air-standard Diesel cycle, \( p_1 = 1 \, \text{bar}, \text{and} T_1 = 300 \, \text{K} \). For maximum cycle temperatures of 1200, 1500, 1800, and 2100 K, plot the heat addition per unit of mass, in kJ/kg, the net work per unit of mass, in kJ/kg, the mean effective pressure, in bar, and the thermal efficiency, each versus compression ratio ranging from 5 to 20.

9.33 An air-standard dual cycle has a compression ratio of 9. At the beginning of compression, \( p_1 = 100 \, \text{kPa}, T_1 = 300 \, \text{K} \), and \( V_1 = 14 \, \text{L} \). The heat addition is 22.7 kJ, with one half added at constant volume and one half added at constant pressure. Determine
(a) the temperatures at the end of each heat addition process, in K.
(b) the net work of the cycle per unit mass of air, in kJ/kg.
(c) the thermal efficiency.
(d) the mean effective pressure, in kPa.

9.34 For the cycle in Problem 9.33, plot each of the quantities calculated in parts (a) through (d) versus the ratio of constant-volume heat addition to total heat addition varying from 0 to 1. Discuss.
9.35 Solve Problem 9.33 on a cold air-standard basis with specific heats evaluated at 300 K.

9.36 The thermal efficiency, \( \eta \), of a cold air-standard dual cycle can be expressed as

\[
\eta = 1 - \frac{\frac{r_p}{r_c}^k - 1}{\frac{r_p}{r_c} - 1 + kr_p(r_c - 1)}
\]

where \( r \) is compression ratio, \( r_c \) is cutoff ratio, and \( r_p \) is the pressure ratio for the constant volume heat addition. Derive this expression.

9.37 An air-standard dual cycle has a compression ratio of 16 and a cutoff ratio of 1.15. At the beginning of compression, \( p_1 = 95 \text{ kPa} \) and \( T_1 = 300 \text{ K} \). The pressure increases by a factor of 2.2 during the constant volume heat addition process. If the mass of air is 0.04 kg, determine

(a) the heat addition at constant volume and at constant pressure, each in kJ.
(b) the net work of the cycle, in kJ.
(c) the heat rejection, in kJ.
(d) the thermal efficiency.

9.38 The pressure and temperature at the beginning of compression in an air-standard dual cycle are \( 14.0 \text{ lbf/in}^2 \) and \( 520^\circ R \), respectively. The compression ratio is 15 and the heat addition per unit mass of air is 800 Btu/lb. At the end of the cycle, the constant volume heat addition process, the pressure is 1200 lbf/in\(^2\). Determine

(a) the net work of the cycle per unit mass of air, in Btu/lb.
(b) the heat rejection for the cycle per unit mass of air, in Btu/lb.
(c) the thermal efficiency.
(d) the cutoff ratio.
(e) To investigate the effects of varying compression ratio, plot each of the quantities calculated in parts (a) through (d) for compression ratios ranging from 10 to 28.

9.39 An air-standard dual cycle has a compression ratio of 16. At the beginning of compression, \( p_1 = 14.5 \text{ lbf/in}^2 \), \( V_1 = 0.5 \text{ ft}^3 \), and \( T_1 = 50^\circ F \). The pressure doubles during the constant volume heat addition process. For a maximum cycle temperature of \( 300^\circ R \), determine

(a) the heat addition to the cycle, in Btu.
(b) the work of the cycle, in Btu.
(c) the thermal efficiency.
(d) the mean effective pressure, in lbf/in\(^2\).
(e) To investigate the effects of varying maximum cycle temperature, plot each of the quantities calculated in parts (a) through (d) for maximum cycle temperatures ranging from 3000 to 4000\( ^\circ R \).

9.40 At the beginning of the compression process in an air-standard dual cycle, \( p_1 = 1 \text{ bar} \) and \( T_1 = 300 \text{ K} \). The total heat addition is 1000 kJ/kg. Plot the net work per unit mass, in kJ/kg, the mean effective pressure, in bar, and the thermal efficiency versus compression ratio for different fractions of constant volume and constant pressure heat addition. Consider compression ratio ranging from 10 to 20.

Brayton Cycle

9.41 Air enters the compressor of an ideal cold air-standard Brayton cycle at 100 kPa, 300 K, with a mass flow rate of 6 kg/s. The compressor pressure ratio is 10, and the turbine inlet temperature is 1400 K. For \( k = 1.4 \), calculate

(a) the thermal efficiency of the cycle.
(b) the back work ratio.
(c) the net power developed, in kW.

9.42 For the Brayton cycle of Problem 9.41, investigate the effects of varying compressor pressure ratio and turbine inlet temperature. Plot the same quantities calculated in Problem 9.41 for

(a) a compressor pressure ratio of 10 and turbine inlet temperatures ranging from 1000 to 1600 K.
(b) a turbine inlet temperature of 1400 K and compressor pressure ratios ranging from 2 to 20.

Discuss.

9.43 The rate of heat addition to an air-standard Brayton cycle is \( 3.4 \times 10^6 \text{ Btu/h} \). The pressure ratio for the cycle is 14 and the minimum and maximum temperatures are \( 520^\circ R \) and \( 3000^\circ R \), respectively. Determine

(a) the thermal efficiency of the cycle.
(b) the mass flow rate of air, in lb/h.
(c) the net power developed by the cycle, in Btu/h.

9.44 Solve Problem 9.43 on a cold air-standard basis with specific heats evaluated at \( 520^\circ R \).

9.45 Consider an ideal air-standard Brayton cycle with minimum and maximum temperatures of 300 K and 1500 K, respectively. The pressure ratio is that which maximizes the net work developed by the cycle per unit mass of air flow. On a cold air-standard basis, calculate

(a) the compressor and turbine work per unit mass of air flow, each in kJ/kg.
(b) the thermal efficiency of the cycle.
(c) Plot the thermal efficiency versus the maximum cycle temperature ranging from 1200 to 1800 K.

9.46 On the basis of a cold air-standard analysis, show that the back work ratio of an ideal air-standard Brayton cycle equals the ratio of absolute temperatures at the compressor inlet and the turbine outlet.

9.47 The compressor inlet temperature of an ideal air-standard Brayton cycle is \( 520^\circ R \) and the maximum allowable turbine inlet temperature is \( 2600^\circ R \). Plot the net work developed per unit mass of air flow, in Btu/lb, and the thermal efficiency versus compressor pressure ratio for pressure ratios ranging from 12 to 24. Using your plots, estimate the pressure ratio for maximum net work and the corresponding value of thermal efficiency. Compare the results to those obtained in analyzing the cycle on a cold air-standard basis.

9.48 The compressor inlet temperature for an ideal Brayton cycle is \( T_1 \) and the turbine inlet temperature is \( T_p \). Using a cold air-standard analysis, show that the temperature \( T_1 \) at the compressor exit that maximizes the net work developed per unit mass of air flow is \( T_1 = (T_1 T_p)^{1/2} \).

9.49 Air enters the compressor of a cold air-standard Brayton cycle at 100 kPa, 300 K, with a mass flow rate of 6 kg/s. The compressor pressure ratio is 10, and the turbine inlet temperature is 1400 K. The turbine and compressor
each have isentropic efficiencies of 80%. For \( k = 1.4 \),

(a) the thermal efficiency of the cycle.
(b) the back work ratio.
(c) the net power developed, in kW.
(d) the rates of exergy destruction in the compressor and
turbine, respectively, each in kW, for \( T_0 = 300 \text{ K}\).

Plot the quantities calculated in parts (a) through (d) versus
isentropic efficiency for equal compressor and turbine isentropic
efficiencies ranging from 70 to 100%. Discuss.

9.50 Air enters the compressor of an air-standard Brayton
cycle with a volumetric flow rate of 60 m\(^3\)/s at 0.8 bar, 280 K.
The compressor pressure ratio is 20, and the maximum cycle
temperature is 2100 K. For the compressor, the isentropic
efficiency is 92\% and for the turbine the isentropic efficiency
is 95\%. Determine

(a) the net power developed, in MW.
(b) the rate of heat addition in the combustor, in MW.
(c) the thermal efficiency of the cycle.

9.51 Air enters the compressor of a simple gas turbine at
\( p_1 = 14 \text{ lbf/in.}^2, T_1 = 520^\circ\text{R} \). The isentropic efficiencies of
the compressor and turbine are 83 and 87\%, respectively.
The compressor pressure ratio is 14 and the temperature at
the turbine inlet is 2500^\circ\text{R}. The net power developed is
5 \times 10^6 \text{ Btu/h}. On the basis of an air-standard analysis, calculate

(a) the volumetric flow rate of the air entering the compressor, in ft\(^3\)/min.
(b) the temperatures at the compressor and turbine exits, each in \(^\circ\text{R}\).
(c) the thermal efficiency of the cycle.

9.52 Solve Problem 9.51 on a cold air-standard basis with specific
heats evaluated at 520^\circ\text{R}.

9.53 Air enters the compressor of a simple gas turbine at 100
kPa, 300 K, with a volumetric flow rate of 5 m\(^3\)/s. The compressor
pressure ratio is 10 and its isentropic efficiency is
85\%. At the inlet to the turbine, the pressure is 950 kPa, and
the temperature is 1400 K. The turbine has an isentropic
efficiency of 88\% and the exit pressure is 100 kPa. On the basis of
an air-standard analysis,

(a) develop a full accounting of the net exergy increase of
the air passing through the gas turbine combustor, in kW.
(b) devise and evaluate an exergetic efficiency for the gas
turbine cycle.

Let \( T_0 = 300 \text{ K}, p_0 = 100 \text{ kPa}\).

9.54 Air enters the compressor of a simple gas turbine at
14.5 lbf/in.\(^2\), 80\(^\circ\text{F}\), and exits at 87 lbf/in.\(^2\), 514\(^\circ\text{F}\). The air
enters the turbine at 1540\(^\circ\text{F}\), 87 lbf/in.\(^2\) and expands to
917\(^\circ\text{F}\), 14.5 lbf/in.\(^2\). The compressor and turbine operate adiabatically, and kinetic and potential energy effects are
negligible. On the basis of an air-standard analysis,

(a) develop a full accounting of the net exergy increase of
the air passing through the gas turbine combustor, in Btu/lb.
(b) devise and evaluate an exergetic efficiency for the gas
turbine cycle.

Let \( T_0 = 80^\circ\text{F}, p_0 = 14.5 \text{ lbf/in.}^2\).

Regeneration, Reheat, and Compression with Intercooling

9.55 Air enters the compressor of a cold air-standard Brayton
cycle with regeneration at 100 kPa, 300 K, with a mass
flow rate of 6 kg/s. The compressor pressure ratio is 10, and
the turbine inlet temperature is 1400 K. The turbine and
compressor each have isentropic efficiencies of 80\% and the
regenerator effectiveness is 80\%. For \( k = 1.4 \), calculate

(a) the thermal efficiency of the cycle.
(b) the back work ratio.
(c) the net power developed, in kW.
(d) the rate of exergy destruction in the regenerator, in kW
for \( T_0 = 300 \text{ K}\).

9.56 Air enters the compressor of a regenerative air-standard
Brayton cycle with a volumetric flow rate of 60 m\(^3\)/s at 0.8 bar,
280 K. The compressor pressure ratio is 20, and the maximum cycle
temperature is 2100 K. For the compressor, the isentropic
efficiency is 92\% and for the turbine the isentropic efficiency
is 95\%. For a regenerator effectiveness of 85\%, determine

(a) the net power developed, in MW.
(b) the rate of heat addition in the combustor, in MW.
(c) the thermal efficiency of the cycle.

Plot the quantities calculated in parts (a) through (c) for regenerator effectiveness values ranging from 0 to 100\%. Discuss.

9.57 Reconsider Problem 9.51, but include a regenerator in
the cycle. For regenerator effectiveness values ranging from 0 to 100\%, plot

(a) the thermal efficiency.
(b) the percent decrease in heat addition to the air.

9.58 On the basis of a cold air-standard analysis, show that the
thermal efficiency of an ideal regenerative gas turbine can be expressed as

\[
\eta = 1 - \left( \frac{T_1}{T_f} \right) (r^{k - 1}) \eta_k
\]

where \( r \) is the compressor pressure ratio, and \( T_1 \) and \( T_f \)
denote the temperatures at the compressor and turbine
inlets, respectively.

9.59 An air-standard Brayton cycle has a compressor pressure
ratio of 10. Air enters the compressor at \( p_1 = 14.7 \text{ lbf/in.}^2\),
\( T_1 = 70^\circ\text{F} \) with a mass flow rate of 90,000 lb/h. The turbine
inlet temperature is 2200^\circ\text{R}. Calculate the thermal efficiency and
the net power developed, in horsepower, if

(a) the turbine and compressor isentropic efficiencies are
each 100\%.

(b) the turbine and compressor isentropic efficiencies are 88
and 84\%, respectively.

(c) the turbine and compressor isentropic efficiencies are 88
and 84\%, respectively, and a regenerator with an effective-
ness of 80\% is incorporated.

9.60 Fig. P9.60 illustrates a gas turbine power plant that uses
sicar energy as the source of heat addition (see U.S. Patent
no. 4,262,484). Operating data are given on the figure. Modeling
the cycle as a Brayton cycle, and assuming no pressure drops in the heat-exchanger or interconnecting piping,
determine
diffuser inlet and the nozzle exit. On the basis of air-
standard analysis, determine
(a) the pressures, in kPa, and temperatures, in K, at each
principal state.
(b) the rate of heat addition to the air passing through the
combustor, in kJ/kg.
(c) the velocity at the nozzle exit, in m/s.

9.78 For the turbojet in Problem 9.77, plot the velocity at the
nozzle exit, in m/s, the pressure at the turbine exit, in kPa, and
the rate of heat input to the combustor, in kW, each as a func-
tion of compressor pressure ratio in the range of 6 to 14.
Repeat for turbine inlet temperatures of 1200 K and 1000 K.

9.79 Air enters the diffuser of a turbojet engine with a mass
flow rate of 85 lb/s at 9 lb/in.\(^2\), 420°F, and a velocity of 750
ft/s. The pressure ratio for the compressor is 12, and its isen-
tropic efficiency is 88%. Air enters the turbine at 2400°F
with the same pressure as at the exit of the compressor.
Air exits the nozzle at 9 lb/in.\(^2\). The diffuser operates isentrop-
cally and the nozzle and turbine have isentropic efficiencies
of 92% and 90%, respectively. On the basis of an air-stand-
ard analysis, calculate
(a) the rate of heat addition, in Btu/h.
(b) the pressure at the turbine exit, in lb/in.\(^2\).
(c) the compressor power input, in Btu/h.
(d) the velocity at the nozzle exit, in ft/s.

Neglect kinetic energy except at the diffuser inlet and the
nozzle exit.

9.80 Consider the addition of an afterburner to the turbojet
in Problem 9.77 that raises the temperature at the inlet of the
nozzle to 1300 K. Determine the velocity at the nozzle
exit, in m/s.

9.81 Consider the addition of an afterburner to the turbojet
in Problem 9.79 that raises the temperature at the inlet of the
nozzle to 2200°F. Determine the velocity at the nozzle
exit, in ft/s.

9.82 Air enters the diffuser of a ramjet engine at 6 lb/in.\(^2\),
420°F, with a velocity of 1600 ft/s, and decelerates essentially
to zero velocity. After combustion, the gases reach a tem-
perature of 2000°F before being discharged through the
nozzle at 6 lb/in.\(^2\). On the basis of an air-standard analysis, determine
(a) the pressure at the diffuser exit, in lb/in.\(^2\).
(b) the velocity at the nozzle exit, in ft/s.

Neglect kinetic energy except at the diffuser inlet and the
nozzle exit.

9.83 Air enters the diffuser of a ramjet engine at 40 kPa, 240 K,
with a velocity of 2500 km/h and decelerates to negligible
velocity. On the basis of an air-standard analysis, the heat
addition is 1080 kJ per kg of air passing through the engine.
Air exits the nozzle at 40 kPa. Determine
(a) the pressure at the diffuser exit, in kPa.
(b) the velocity at the nozzle exit, in m/s.

Neglect kinetic energy except at the diffuser inlet and the
nozzle exit.

9.84 A turboprop engine consists of a diffuser, compressor,
combustor, turbine, and nozzle. The engine drives a prop-
eller as well as the compressor. Air enters the diffuser with a
volumetric flow rate of 83.7 m\(^3\)/s at 40 kPa, 240 K, and a
velocity of 180 m/s, and decelerates essentially to zero veloc-
ity. The compressor pressure ratio is 10 and the compressor
has an isentropic efficiency of 85%. The turbine inlet tem-
perature is 1140 K, and its isentropic efficiency is 85%. The
turbine exit pressure is 50 kPa. Flow through the diffuser
and nozzle is isentropic. Using an air-standard analysis, determine
(a) the power delivered to the propeller, in MW.
(b) the velocity at the nozzle exit, in m/s.

Neglect kinetic energy except at the diffuser inlet and the
nozzle exit.

9.85 A turboprop engine consists of a diffuser, compressor,
combustor, turbine, and nozzle. The engine drives a prop-
eller as well as the compressor. Air enters the diffuser at
12 lb/in.\(^2\), 460°F, with a volumetric flow rate of
30,000 ft\(^3\)/min and a velocity of 520 ft/s. In the diffuser, the
air decelerates isentropically to negligible velocity. The com-
pressor pressure ratio is 9, and the turbine inlet temperature
is 2100°F. The turbine exit pressure is 25 lb/in.\(^2\), and the air
expands to 12 lb/in.\(^2\) through a nozzle. The compressor and
air each has an isentropic efficiency of 87%, and the nozz-
le has an isentropic efficiency of 95%. Using an air-standard
analysis, determine
(a) the power delivered to the propeller, in hp.
(b) the velocity at the nozzle exit, in ft/s.

Neglect kinetic energy except at the diffuser inlet and the
nozzle exit.

9.86 Helium is used in a combined cycle power plant as the
working fluid in a simple closed gas turbine serving as the
topping cycle for a vapor power cycle. A nuclear reactor
is the source of energy input to the helium. Figure P9.86
provides steady-state operating data. Helium enters the
compressor of the gas turbine at 200 lb/in.\(^2\), 180°F with
a mass flow rate of 8 \times 10\(^5\) lb/h and is compressed to
800 lb/in.\(^2\). The isentropic efficiency of the compressor is
80%. The helium then passes through the reactor with a
negligible decrease in pressure, exiting at 1400°F. Next, the
helium expands through the turbine, which has an isen-
tropic efficiency of 80%, to a pressure of 200 lb/in.\(^2\). The
helium then passes through the interconnecting heat
exchanger. A separate stream of liquid water enters the
heat exchanger and exits as saturated vapor at 1200 lb/in.\(^2\).
The vapor is superheated before entering the turbine at
800°F, 1200 lb/in.\(^2\). The steam expands through the turbine
to 1 lb/in.\(^2\) and a quality of 0.9. Saturated liquid exits the
condenser at 1 lb/in.\(^2\). Cooling water passing through the
condenser experiences a temperature rise from 60 to 90°F.
The isentropic pump efficiency is 100%. Stray heat trans-
fer and kinetic and potential energy effects can be ignored.

Determine
(a) the mass flow rates of the steam and the cooling water,
each in lb/h.
9.89 A combined gas turbine–vapor power plant (Fig. 9.23) has a net power output of 100 MW. Air enters the compressor of the gas turbine at 100 kPa, 300 K, and is compressed to 1200 kPa. The isentropic efficiency of the compressor is 84%. The conditions at the inlet to the turbine are 1200 kPa and 1400 K. Air expands through the turbine, which has an isentropic efficiency of 88%, to a pressure of 100 kPa. The air then passes through the interconnecting heat exchanger, and is finally discharged at 480 K. Steam enters the turbine of the vapor power cycle at 8 MPa, 400°C, and expands to the condenser pressure of 8 kPa. Water enters the pump as saturated liquid at 8 kPa. The turbine and pump have isentropic efficiencies of 90 and 80%, respectively. Determine
(a) the mass flow rates of air and steam, each in kg/s.
(b) the thermal efficiency of the combined cycle.
(c) a full accounting of the net exergy increase of the air passing through the combustor of the gas turbine, \( m_{\text{air}}(e_L - e_R) \), in MW. Discuss.

Let \( T_0 = 300 \) K, \( p_0 = 100 \) kPa.

9.90 A simple gas turbine is the topping cycle for a simple vapor power cycle (Fig. 9.23). Air enters the compressor of the gas turbine at 60°F, 14.7 lb./in.², with a volumetric flow rate of 40,000 ft³/min. The compressor pressure ratio is 12 and the turbine inlet temperature is 2600°F. The compressor and turbine each have isentropic efficiencies of 88%. The air leaves the interconnecting heat exchanger at 840°F, 14.7 lb./in.². Steam enters the turbine of the vapor cycle at 1000 lb./in.², 900°F, and expands to the condenser pressure of 1 lb./in.². Water enters the pump as saturated liquid at 1 lb./in.². The turbine and pump efficiencies are 90 and 70%, respectively. Cooling water passing through the condenser experiences a temperature rise from 60 to 80°F with a negligible change in pressure. Determine
(a) the mass flow rates of the air, steam, and cooling water, each in lb./h.
(b) the net power developed by the gas turbine cycle and the vapor cycle, respectively, each in Btu/h.
(c) the thermal efficiency of the combined cycle.
(d) a full accounting of the net exergy increase of the air passing through the combustor of the gas turbine, \( m_{\text{air}}(e_L - e_R) \), in Btu/h. Discuss.

Let \( T_0 = 520°F, p_0 = 14.7 \) lb./in.².

9.91 Air enters the compressor of an Ericsson cycle at 300 K, 1 bar, with a mass flow rate of 5 kg/s. The pressure and temperature at the inlet to the turbine are 10 bar and 1400 K, respectively. Determine
(a) the net power developed, in kW.
(b) the thermal efficiency.
(c) the back work ratio.

9.92 For the cycle in Problem 9.91, plot the net power developed, in kW, for compressor pressure ratios ranging from 2 to 15. Repeat for turbine inlet temperatures of 1200 K and 1000 K.

9.93 Air is the working fluid in an Ericsson cycle. Expansion through the turbine takes place at a constant temperature of 2250°F. Heat transfer from the compressor occurs at 560°F. The compressor pressure ratio is 12. Determine
(a) the net work, in Btu per lb of air flowing.
(b) the thermal efficiency.

9.94 Nitrogen (N₂) is the working fluid of a Stirling cycle with a compression ratio of nine. At the beginning of the isothermal compression, the temperature, pressure, and volume are 310 K, 1 bar, and 0.008 m³, respectively. The temperature during the isothermal expansion is 1000 K. Determine
(a) the net work, in kJ.
(b) the thermal efficiency.
(c) the mean effective pressure, in bar.

9.95 Helium is the working fluid in a Stirling cycle. In the isothermal compression, the helium is compressed from 15 lb./in.², 100°F, to 150 lb./in.². The isothermal expansion occurs at 1500°F. Determine
(a) the work and heat transfer, in Btu per lb of helium, for each process in the cycle.
(b) the thermal efficiency.

**Compressible Flow**

9.96 Calculate the thrust developed by the turbojet engine in Problem 9.77, in kN.

9.97 Calculate the thrust developed by the turbojet engine in Problem 9.79, in lbf.
9.98 Calculate the thrust developed by the turbojet engine with afterburner in Problem 9.80, in kN.

9.99 Referring to the turbojet in Problem 9.79 and the modified turbojet in Problem 9.81, calculate the thrust developed by each engine, in lbf. Discuss.

9.100 Air enters the diffuser of a turbojet engine at 18 kPa, 216 K, with a volumetric flow rate of 230 m$^3$/s and a velocity of 265 m/s. The compressor pressure ratio is 15, and its isentropic efficiency is 87%. Air enters the turbine at 1360 K and the same pressure as at the exit of the compressor. The turbine isentropic efficiency is 89%, and the nozzle isentropic efficiency is 97%. The pressure at the nozzle exit is 18 kPa. On the basis of an air-standard analysis, calculate the thrust, in kN.

9.101 Calculate the ratio of the thrust developed to the mass flow rate of air, in N per kg/s, for the ramjet engine in Problem 9.83.

9.102 Air flows at steady state through a horizontal, well-insulated, constant-area duct of diameter 0.25 m. At the inlet, $p_1 = 2.4$ bar, $T_1 = 430$ K. The temperature of the air leaving the duct is 370 K. The mass flow rate is 600 kg/min. Determine the magnitude, in N, of the net horizontal force exerted by the duct walls on the air. In which direction does the force act?

9.103 Liquid water at 70°F flows at steady state through a 2-in.-diameter horizontal pipe. The mass flow rate is 25 lb/s. The pressure decrease by 2 lbf/in.$^2$ from inlet to exit of the pipe. Determine the magnitude, in lb, and direction of the horizontal force required to hold the pipe in place.

9.104 Air enters a horizontal, well-insulated nozzle operating at steady state at 12 bar, 500K, with a velocity of 50 m/s and exits at 7 bar, 440 K. The mass flow rate is 1 kg/s. Determine the net force, in N, exerted by the air on the duct in the direction of flow.

9.105 Using the ideal gas model, determine the sonic velocity of

(a) air at 60°F.
(b) oxygen (O$_2$) at 900°R.
(c) argon at 540°R.

9.106 A flash of lightning is sighted and 3 seconds later thunder is heard. Approximately how far away was the lightning strike?

9.107 Using data from Table A-4, estimate the sonic velocity, in m/s, of steam of 60 bar, 360°C. Compare the result with the value predicted by the ideal gas model.

9.108 Plot the Mach number of carbon dioxide at 1 bar, 460 m/s, as a function of temperature in the range 250 to 1000 K.

9.109 An ideal gas flows through a duct. At a particular location, the temperature, pressure, and velocity are known. Determine the Mach number, stagnation temperature, in °R, and the stagnation pressure, in lbf/in.$^2$, for

(a) air at 310°F, 100 lbf/in.$^2$, and a velocity of 1400 ft/s.
(b) helium at 520°R, 20 lbf/in.$^2$, and a velocity of 900 ft/s.
(c) nitrogen at 600°R, 50 lbf/in.$^2$, and a velocity of 500 ft/s.

9.110 For Problem 9.104, determine the values of the Mach number, the stagnation temperature, in K, and the stagnation pressure, in bar, at the inlet and exit of the duct, respectively.

9.111 Using the Mollier diagram, Fig. A-3E, determine for water vapor at 500 lbf/in.$^2$, 600°F, and 1000 ft/s

(a) the stagnation enthalpy, in Btu/lb.
(b) the stagnation temperature, in °F.
(c) the stagnation pressure, in lbf/in.$^2$.

9.112 Steam flows through a passageway, and at a particular location the pressure is 3 bar, the temperature is 281.4°C, and the velocity is 688.8 m/s. Determine the corresponding specific stagnation enthalpy, in kJ/kg, and stagnation temperature, in °C, if the stagnation pressure is 7 bar.

9.113 For the isentropic flow of an ideal gas with constant specific heat ratio $k$, the ratio of the temperature $T_n$ to the stagnation temperature $T_o$ is $T_n/T_o = 2/(k + 1)$. Develop this relationship.

9.114 A gas expands isentropically through a converging nozzle from a large tank at 8 bar, 500 K. Assuming ideal gas behavior, determine the critical pressure $p_*$, in bar, and the corresponding temperature, in K, if the gas is

(a) air.
(b) carbon dioxide (CO$_2$).
(c) water vapor.

9.115 Carbon dioxide is contained in a large tank, initially at 100 lbf/in.$^2$, 800°R. The gas discharges through a converging nozzle to the surroundings, which are at 14.7 lbf/in.$^2$, and the pressure in the tank drops. Estimate the pressure in the tank, in lbf/in.$^2$, when the first time ceases to be choked.

9.116 Steam expands isentropically through a converging nozzle operating at steady state from a large tank at 1.83 bar, 280°C. The mass flow rate is 2 kg/s, the flow is choked, and the exit plane pressure is 1 bar. Determine the diameter of the nozzle, in cm, at locations where the pressure is 1.5 bar, and 1 bar, respectively.

9.117 An ideal gas mixture with $k = 1.31$ and a molecular weight of 23 is supplied to a converging nozzle at $p_o = 5$ bar, $T_o = 700$ K, which discharges into a region where the pressure is 1 bar. The exit area is 30 cm$^2$. For steady isentropic flow through the nozzle, determine

(a) the exit temperature of the gas, in K.
(b) the exit velocity of the gas, in m/s.
(c) the mass flow rate, in kg/s.

9.118 An ideal gas expands isentropically through a converging nozzle from a large tank at 120 lbf/in.$^2$, 600°R, and discharges into a region at 60 lbf/in.$^2$. Determine the mass flow rate, in lb/s, for an exit flow area of 1 in.$^2$, if the gas is

(a) air, with $k = 1.4$.
(b) carbon dioxide, with $k = 1.26$.
(c) argon, with $k = 1.667$.

9.119 Air at $p_o = 1.4$ bar, $T_o = 280$ K expands isentropically through a converging nozzle and discharges to the atmosphere at 1 bar. The exit plane area is 0.0013 m$^2$.

(a) Determine the mass flow rate, in kg/s.
(b) If the supply region pressure, $p_o$, were increased to 2 bar, what would be the mass flow rate, in kg/s?
9.120 Air enters a nozzle operating at steady state at 45 lbf/in.$^2$, 800°F, with a velocity of 400 ft/s and expands isentropically to an exit velocity of 1500 ft/s. Determine
(a) the exit pressure, in lbf/in.$^2$
(b) the ratio of the exit area to the inlet area.
(c) whether the nozzle is diverging only, converging only, or converging-diverging in cross section.

9.121 Air as an ideal gas with $k = 1.4$ enters a converging-diverging nozzle operating at steady state and expands isentropically as shown in Fig. P9.121. Using data from the figure and from Table 9.2 as needed, determine
(a) the stagnation pressure, in lbf/in.$^2$, and the stagnation temperature, in °R.
(b) the throat area, in in.$^2$
(c) the exit area, in in.$^2$

![Fig. P9.121](image)

9.122 Air as an ideal gas with $k = 1.4$ enters a diffuser operating at steady state at 4 bar, 290 K, with a velocity of 512 m/s. Assuming isentropic flow, plot the velocity, in m/s, the Mach number, and the area ratio $A/A_0$ for locations in the flow corresponding to pressures ranging from 4 to 14 bar.

9.123 A converging-diverging nozzle operating at steady state has a throat area of 3 cm$^2$ and an exit area of 6 cm$^2$. Air as an ideal gas with $k = 1.4$ enters the nozzle at 8 bar, 400 K, and a Mach number of 0.2, and flows isentropically throughout. If the nozzle is choked, and the diverging portion acts as a supersonic nozzle, determine the mass flow rate, in kg/s, and the Mach number, pressure, and temperature, in K, at the exit. If the diverging portion acts as a supersonic diffuser.

9.124 For the nozzle in Problem 9.123, determine the back pressure, in bar, for which a normal shock would stand at the exit plane.

9.125 For the nozzle in Problem 9.123, a normal shock stands in the diverging section at a location where the pressure is 2 bar. The flow is isentropic, except where the shock stands. Determine the back pressure, in bar.

9.126 Air as an ideal gas with $k = 1.4$ enters a converging-diverging duct with a Mach number of 2. At the inlet, the pressure is 26 lbf/in.$^2$, and the temperature is 445°F. A normal shock stands at a location in the converging section of the duct, with $M_s = 1.5$. At the exit of the duct, the pressure is 150 lbf/in.$^2$. The flow is isentropic everywhere except in the immediate vicinity of the shock. Determine temperature, in °R, and the Mach number at the exit.

9.127 Air as an ideal gas with $k = 1.4$ undergoes a normal shock. The upstream conditions are $p_s = 0.5$ bar, $T_s = 280$ K, and $M_s = 1.8$. Determine
(a) the pressure $p_e$, in bar.
(b) the stagnation pressure $p_{es}$, in bar.
(c) the stagnation temperature $T_{es}$, in K.
(d) the change in specific entropy across the shock, in kJ/kg · °R.
(e) Plot the quantities of parts (a)–(d) versus $M_e$ ranging from 1.0 to 2.0. All other upstream conditions remain the same.

9.128 A converging-diverging nozzle operates at steady state with a mass flow rate of 0.7 lbm/s. Air as an ideal gas with $k = 1.4$ flows through the nozzle, discharging to the atmosphere at 14.7 lbf/in.$^2$ and 540°F. A normal shock stands at the exit plane with $M_s = 2$. Up to the shock, the flow is isentropic. Determine
(a) the stagnation pressure $p_{es}$, in lbf/in.$^2$.
(b) the stagnation temperature $T_{es}$, in °R.
(c) the nozzle exit area, in in.$^2$

9.129 For the nozzle in Problem 9.128, calculate the throat area, in in.$^2$, and the entropy produced, in Btu/°R per lb of air flowing.

9.130 Air at 3.4 bar, 530 K, and a Mach number of 0.4 enters a converging-diverging nozzle operating at steady state. A normal shock stands in the diverging section at a location where the Mach number is $M_s = 1.8$. The flow is isentropic, except where the shock stands. If the air behaves as an ideal gas with $k = 1.4$, determine
(a) the stagnation temperature $T_{es}$, in K.
(b) the stagnation pressure $p_{es}$, in bar.
(c) the pressure $p_e$, in bar.
(d) the pressure $p_s$ in bar.
(e) the stagnation pressure $p_{es}$, in bar.
(f) the stagnation temperature $T_{es}$, in K.

If the throat area is $7.6 \times 10^{-4}$ m$^2$, and the exit plane pressure is 2.4 bar, determine the mass flow rate, in kg/s, and the exit area, in m$^2$.

9.131 Air as an ideal gas with $k = 1.4$ enters a converging-diverging channel at a Mach number of 1.6. A normal shock stands at the inlet to the channel. Downstream of the shock the flow is isentropic; the Mach number is unity at the throat; and the air exits at 20 lbf/in.$^2$, 700°F, with negligible velocity. If the mass flow rate is 45 lbm/s, determine the inlet and throat areas, in ft$^2$.

9.132 Derive the following expressions: (a) Eq. 9.55, (b) Eq. 9.56, (c) Eq. 9.57.

9.133 Using Interactive Thermodynamics: IT, generate tables of the same isentropic flow functions as in Table 9.2 for specific heat ratios of 1.2, 1.3, 1.4, and 1.67 and Mach numbers ranging from 0 to 5.

9.134 Using Interactive Thermodynamics: IT, generate tables of the same normal shock functions as in Table 9.3 for specific heat ratios of 1.2, 1.3, 1.4, and 1.67 and Mach numbers ranging from 1 to 5.