Chapter 7

Problems

7.1. Air expands adiabatically through a nozzle from a negligible initial velocity to a final velocity of 325 $m{\cdot}s^{-1}$. What is the temperature drop of the air, if air is assumed to be an ideal gas for which $C_P = (7/2)R$?

7.2. In Ex. 7.5 an expression is found for the Joule/Thomson coefficient, $\mu = (\partial T/\partial P)_H$, that relates it to a heat capacity and equation-of-state information. Develop similar expressions for the derivatives:

(*a*) $(\partial T/\partial P)_S$ (*b*) $(\partial T/\partial V)_U$

What can you say about the *signs* of these derivatives? For what types of processes might these derivatives be important characterizing quantities?

7.3. The thermodynamic sound speed c is defined in Sec. 7.1. Prove that:

$$c = \sqrt{\frac{VC_P}{\mathscr{M}C_V\kappa}}$$

where V is molar volume and $\mathscr{M}$ is molar mass. To what does this general result reduce for: (*a*) an ideal gas? (*b*) an incompressible liquid? What do these results suggest qualitatively about the speed of sound in liquids relative to gases?

7.4. Steam enters a nozzle at 800 kPa and 280°C at negligible velocity and discharges at a pressure of 525 kPa. Assuming isentropic expansion of the steam in the nozzle, what is the exit velocity and what is the cross-sectional area at the nozzle exit for a flow rate of 0.75 $kg{\cdot}s^{-1}$?

7.5. Steam enters a converging nozzle at 800 kPa and 280°C with negligible velocity. If expansion is isentropic, what is the minimum pressure that can be reached in such a nozzle, and what is the cross-sectional area at the nozzle throat at this pressure for a flow rate of 0.75 $kg{\cdot}s^{-1}$?

7.6. A gas enters a converging nozzle at pressure P_1 with negligible velocity, expands isentropically in the nozzle, and discharges into a chamber at pressure P_2. Sketch graphs showing the velocity at the throat and the mass flow rate as functions of the pressure ratio P_2/P_1.

7.7. For isentropic expansion in a converging/diverging nozzle with negligible entrance velocity, sketch graphs of mass flow rate $\dot{m}$, velocity u, and area ratio A/A_1 versus the pressure ratio P/P_1. Here, A is the cross-sectional area of the nozzle at the point in the nozzle where the pressure is P, and subscript 1 denotes the nozzle entrance.

7.8. An ideal gas with constant heat capacities enters a converging/diverging nozzle with negligible velocity. If it expands isentropically within the nozzle, show that the throat velocity is given by:

$$u_{\text{throat}}^2 = \frac{\gamma R T_1}{\mathcal{M}} \left(\frac{2}{\gamma + 1}\right)$$

where T_1 is the temperature of the gas entering the nozzle, $\mathcal{M}$ is the molar mass, and R is the molar gas constant.

7.9. Steam expands isentropically in a converging/diverging nozzle from inlet conditions of 1400 kPa, 325°C, and negligible velocity to a discharge pressure of 140 kPa. At the throat, the cross-sectional area is 6 cm^2. Determine the mass flow rate of the steam and the state of the steam at the exit of the nozzle.

7.10. Steam expands adiabatically in a nozzle from inlet conditions of 130(psia), 420(°F), and a velocity of 230(ft)$(s)^{-1}$ to a discharge pressure of 35(psia) where its velocity is 2000(ft)$(s)^{-1}$. What is the state of the steam at the nozzle exit, and what is $\dot{S}_G$ for the process?

7.11. Air discharges from an adiabatic nozzle at 15°C with a velocity of 580 $m{\cdot}s^{-1}$. What is the temperature at the entrance of the nozzle if the entrance velocity is negligible? Assume air to be an ideal gas for which $C_P = (7/2)R$.

7.12. Cool water at 15°C is throttled from 5(atm) to 1(atm), as in a kitchen faucet. What is the temperature change of the water? What is the lost work per kilogram of water for this everyday household happening? At 15°C and 1(atm), the volume expansivity β for liquid water is about 1.5×10^{-4} K^{-1}. The surroundings temperature T_σ is 20°C. State carefully any assumptions you make. The steam tables are a source of data.

7.13. For a pressure-explicit equation of state, prove that the Joule/Thomson inversion curve is the locus of states for which:

$$T\left(\frac{\partial Z}{\partial T}\right)_\rho = \rho\left(\frac{\partial Z}{\partial \rho}\right)_T$$

Apply this equation to (*a*) the van der Waals equation; (*b*) the Redlich/Kwong equation. Discuss the results.

7.14. Two nonconducting tanks of negligible heat capacity and of equal volume initially contain equal quantities of the same ideal gas at the same T and P. Tank A discharges to the atmosphere through a small turbine in which the gas expands isentropically; tank B discharges to the atmosphere through a porous plug. Both devices operate until discharge ceases.

(*a*) When discharge ceases, is the temperature in tank A less than, equal to, or greater than the temperature in tank B?

(*b*) When the pressures in both tanks have fallen to half the initial pressure, is the temperature of the gas discharging from the turbine less than, equal to, or greater than the temperature of the gas discharging from the porous plug?

(*c*) During the discharge process, is the temperature of the gas leaving the turbine less than, equal to, or greater than the temperature of the gas leaving tank *A* at the same instant?

(*d*) During the discharge process, is the temperature of the gas leaving the porous plug less than, equal to, or greater than the temperature of the gas leaving tank *B* at the same instant?

(*e*) When discharge ceases, is the mass of gas remaining in tank *A* less than, equal to, or greater than the mass of gas remaining in tank *B*?

7.15. A steam turbine operates adiabatically at a power level of 3500 kW. Steam enters the turbine at 2400 kPa and 500°C and exhausts from the turbine as saturated vapor at 20 kPa. What is the steam rate through the turbine, and what is the turbine efficiency?

7.16. A turbine operates adiabatically with superheated steam entering at T_1 and P_1 with a mass flow rate $\dot{m}$. The exhaust pressure is P_2 and the turbine efficiency is η. For one of the following sets of operating conditions, determine the power output of the turbine and the enthalpy and entropy of the exhaust steam.

(*a*) $T_1 = 450°\text{C}$, $P_1 = 8000$ kPa, $\dot{m} = 80$ kg·s^{-1}, $P_2 = 30$ kPa, $\eta = 0.80$
(*b*) $T_1 = 550°\text{C}$, $P_1 = 9000$ kPa, $\dot{m} = 90$ kg·s^{-1}, $P_2 = 20$ kPa, $\eta = 0.77$
(*c*) $T_1 = 600°\text{C}$, $P_1 = 8600$ kPa, $\dot{m} = 70$ kg·s^{-1}, $P_2 = 10$ kPa, $\eta = 0.82$
(*d*) $T_1 = 400°\text{C}$, $P_1 = 7000$ kPa, $\dot{m} = 65$ kg·s^{-1}, $P_2 = 50$ kPa, $\eta = 0.75$
(*e*) $T_1 = 200°\text{C}$, $P_1 = 1400$ kPa, $\dot{m} = 50$ kg·s^{-1}, $P_2 = 200$ kPa, $\eta = 0.75$
(*f*) $T_1 = 900(°\text{F})$, $P_1 = 1100$(psia), $\dot{m} = 150(\text{lb}_\text{m})(\text{s})^{-1}$, $P_2 = 2$(psia), $\eta = 0.80$
(*g*) $T_1 = 800(°\text{F})$, $P_1 = 1000$(psia), $\dot{m} = 100(\text{lb}_\text{m})(\text{s})^{-1}$, $P_2 = 4$(psia), $\eta = 0.75$

7.17. Nitrogen gas initially at 8.5 bar expands isentropically to 1 bar and 150°C. Assuming nitrogen to be an ideal gas, calculate the *initial* temperature and the work produced per mole of nitrogen.

7.18. Combustion products from a burner enter a gas turbine at 10 bar and 950°C and discharge at 1.5 bar. The turbine operates adiabatically with an efficiency of 77%. Assuming the combustion products to be an ideal-gas mixture with a heat capacity of 32 J·mol^{-1}·K^{-1}, what is the work output of the turbine per mole of gas, and what is the temperature of the gases discharging from the turbine?

7.19. Isobutane expands adiabatically in a turbine from 5000 kPa and 250°C to 500 kPa at a rate of 0.7 kg mol·s^{-1}. If the turbine efficiency is 0.80, what is the power output of the turbine and what is the temperature of the isobutane leaving the turbine?

7.20. The steam rate to a turbine for variable output is controlled by a throttle valve in the inlet line. Steam is supplied to the throttle valve at 1700 kPa and 225°C. During a test run, the pressure at the turbine inlet is 1000 kPa, the exhaust steam at 10 kPa has a quality of 0.95, the steam flow rate is 0.5 kg·s^{-1}, and the power output of the turbine is 180 kW.

(*a*) What are the heat losses from the turbine?

(*b*) What would be the power output if the steam supplied to the throttle valve were expanded isentropically to the final pressure?

7.21. Carbon dioxide gas enters an adiabatic expander at 8 bar and 400°C and discharges at 1 bar. If the turbine efficiency is 0.75, what is the discharge temperature and what is the work output per mole of CO_2? Assume CO_2 to be an ideal gas at these conditions.

7.22. Tests on an adiabatic gas turbine (expander) yield values for inlet conditions (T_1, P_1) and outlet conditions (T_2, P_2). Assuming ideal gases with constant heat capacities, determine the turbine efficiency for one of the following:

(*a*) $T_1 = 500$ K, $P_1 = 6$ bar, $T_2 = 371$ K, $P_2 = 1.2$ bar, $C_P/R = 7/2$
(*b*) $T_1 = 450$ K, $P_1 = 5$ bar, $T_2 = 376$ K, $P_2 = 2$ bar, $C_P/R = 4$
(*c*) $T_1 = 525$ K, $P_1 = 10$ bar, $T_2 = 458$ K, $P_2 = 3$ bar, $C_P/R = 11/2$
(*d*) $T_1 = 475$ K, $P_1 = 7$ bar, $T_2 = 372$ K, $P_2 = 1.5$ bar, $C_P/R = 9/2$
(*e*) $T_1 = 550$ K, $P_1 = 4$ bar, $T_2 = 403$ K, $P_2 = 1.2$ bar, $C_P/R = 5/2$

7.23. The efficiency of a particular series of adiabatic gas turbines (expanders) correlates with power output according to the empirical expression: $\eta = 0.065 + 0.080 \ln |\dot{W}|$. Here, $|\dot{W}|$ is the absolute value of the *actual* power output in kW. Nitrogen gas is to be expanded from inlet conditions of 550 K and 6 bar to an outlet pressure of 1.2 bar. For a molar flow rate of 175 mol·s^{-1}, what is the delivered power in kW? What is the efficiency of the turbine? What is the rate of entropy generation $\dot{S}_G$? Assume nitrogen to be an ideal gas with $C_P = (7/2)R$.

7.24. A turbine operates adiabatically with superheated steam entering at 45 bar and 400°C. If the exhaust steam must be "dry," what is the minimum allowable exhaust pressure for a turbine efficiency, $\eta = 0.75$? Suppose the efficiency were 0.80. Would the minimum exhaust pressure be lower or higher? Why?

7.25. Turbines can be used to recover energy from high-pressure liquid streams. However, they are not used when the high-pressure stream is a *saturated* liquid. Why? Illustrate by determining the downstream state for isentropic expansion of saturated liquid water at 5 bar to a final pressure of 1 bar.

7.26. Liquid water enters an adiabatic hydroturbine at 5(atm) and 15°C, and exhausts at 1(atm). Estimate the power output of the turbine in J·kg^{-1} of water if its efficiency is $\eta = 0.55$. What is the outlet temperature of the water? Assume water to be an incompressible liquid.

7.27. An expander operates adiabatically with nitrogen entering at T_1 and P_1 with a molar flow rate $\dot{n}$. The exhaust pressure is P_2, and the expander efficiency is η. Estimate the power output of the expander and the temperature of the exhaust stream for one of the following sets of operating conditions.

(*a*) $T_1 = 480$°C, $P_1 = 6$ bar, $\dot{n} = 200$ mol·s^{-1}, $P_2 = 1$ bar, $\eta = 0.80$
(*b*) $T_1 = 400$°C, $P_1 = 5$ bar, $\dot{n} = 150$ mol·s^{-1}, $P_2 = 1$ bar, $\eta = 0.75$
(*c*) $T_1 = 500$°C, $P_1 = 7$ bar, $\dot{n} = 175$ mol·s^{-1}, $P_2 = 1$ bar, $\eta = 0.78$
(*d*) $T_1 = 450$°C, $P_1 = 8$ bar, $\dot{n} = 100$ mol·s^{-1}, $P_2 = 2$ bar, $\eta = 0.85$
(*e*) $T_1 = 900$(°F), $P_1 = 95$(psia), $\dot{n} = 0.5$(lb mol)(s)$^{-1}$, $P_2 = 15$(psia), $\eta = 0.80$

7.28. What is the ideal-work rate for the expansion process of Ex. 7.6? What is the thermodynamic efficiency of the process? What is the rate of entropy generation $\dot{S}_G$? What is $\dot{W}_{\text{lost}}$? Take $T_\sigma = 300$ K.

7.29. Exhaust gas at 400°C and 1 bar from internal-combustion engines flows at the rate of 125 mol·s^{-1} into a waste-heat boiler where saturated steam is generated at a pressure of 1200 kPa. Water enters the boiler at 20°C (T_σ), and the exhaust gases are cooled to within 10°C of the steam temperature. The heat capacity of the exhaust gases is $C_P/R = 3.34 + 1.12 \times 10^{-3}\ T/K$. The steam flows into an adiabatic turbine and exhausts at a pressure of 25 kPa. If the turbine efficiency η is 72%,

(*a*) What is $\dot{W}_S$, the power output of the turbine?
(*b*) What is the thermodynamic efficiency of the boiler/turbine combination?
(*c*) Determine $\dot{S}_G$ for the boiler and for the turbine.
(*d*) Express $\dot{W}_{\text{lost}}$ (boiler) and $\dot{W}_{\text{lost}}$ (turbine) as fractions of $|\dot{W}_{\text{ideal}}|$, the ideal work of the process.

7.30. A small adiabatic air compressor is used to pump air into a 20 m^3 insulated tank. The tank initially contains air at 25°C and 101.33 kPa, exactly the conditions at which air enters the compressor. The pumping process continues until the pressure in the tank reaches 1000 kPa. If the process is adiabatic and if compression is isentropic, what is the shaft work of the compressor? Assume air to be an ideal gas for which $C_P = (7/2)R$ and $C_V = (5/2)R$.

7.31. Saturated steam at 125 kPa is compressed adiabatically in a centrifugal compressor to 700 kPa at the rate of 2.5 kg·s^{-1}. The compressor efficiency is 78%. What is the power requirement of the compressor and what are the enthalpy and entropy of the steam in its final state?

7.32. A compressor operates adiabatically with air entering at T_1 and P_1 with a molar flow rate $\dot{n}$. The discharge pressure is P_2 and the compressor efficiency is η. Estimate the power requirement of the compressor and the temperature of the discharge stream for one of the following sets of operating conditions.

(*a*) $T_1 = 25$°C, $P_1 = 101.33$ kPa, $\dot{n} = 100$ mol·s^{-1}, $P_2 = 375$ kPa, $\eta = 0.75$
(*b*) $T_1 = 80$°C, $P_1 = 375$ kPa, $\dot{n} = 100$ mol·s^{-1}, $P_2 = 1000$ kPa, $\eta = 0.70$
(*c*) $T_1 = 30$°C, $P_1 = 100$ kPa, $\dot{n} = 150$ mol·s^{-1}, $P_2 = 500$ kPa, $\eta = 0.80$
(*d*) $T_1 = 100$°C, $P_1 = 500$ kPa, $\dot{n} = 50$ mol·s^{-1}, $P_2 = 1300$ kPa, $\eta = 0.75$
(*e*) $T_1 = 80$(°F), $P_1 = 14.7$(psia), $\dot{n} = 0.5$(lb mol)(s)$^{-1}$, $P_2 = 55$(psia), $\eta = 0.75$
(*f*) $T_1 = 150$(°F), $P_1 = 55$(psia), $\dot{n} = 0.5$(lb mol)(s)$^{-1}$, $P_2 = 135$(psia), $\eta = 0.70$

7.33. Ammonia gas is compressed from 21°C and 200 kPa to 1000 kPa in an adiabatic compressor with an efficiency of 0.82. Estimate the final temperature, the work required, and the entropy change of the ammonia.

7.34. Propylene is compressed adiabatically from 11.5 bar and 30°C to 18 bar at a rate of 1 kg mol·s^{-1}. If the compressor efficiency is 0.8, what is the power requirement of the compressor, and what is the discharge temperature of the propylene?

7.35. Methane is compressed adiabatically in a pipeline pumping station from 3500 kPa and 35°C to 5500 kPa at a rate of 1.5 kg mol·s^{-1}. If the compressor efficiency is 0.78, what is the power requirement of the compressor and what is the discharge temperature of the methane?

7.36. What is the ideal work for the compression process of Ex. 7.9? What is the thermodynamic efficiency of the process? What are S_G and W_{lost}? Take $T_\sigma = 293.15$ K.

7.37. A *fan* is (in effect) a gas compressor which moves large volumes of air at low pressure across small (1 to 15 kPa) pressure differences. The usual design equation is:

$$\dot{W} = \dot{n}\,\frac{RT_1}{\eta P_1}\,\Delta P$$

where subscript 1 denotes inlet conditions and η is the efficiency with respect to isentropic operation. Develop this equation. Show also how it follows from the usual equation for compression of an ideal gas with constant heat capacities.

7.38. For an adiabatic gas compressor, the efficiency with respect to isentropic operation η is a measure of internal irreversibilities; so is the dimensionless rate of entropy generation $S_G/R \equiv \dot{S}_G/(\dot{n}R)$. Assuming that the gas is ideal with constant heat capacities, show that η and S_G/R are related through the expression:

$$\frac{S_G}{R} = \frac{C_P}{R}\ln\left(\frac{\eta + \pi - 1}{\eta\pi}\right)$$

where

$$\pi \equiv (P_2/P_1)^{R/C_P}$$

7.39. Air at 1(atm) and 35°C is compressed in a staged reciprocating compressor (with intercooling) to a final pressure of 50(atm). For each stage, the inlet gas temperature is 35°C and the maximum allowable outlet temperature is 200°C. Mechanical power is the same for all stages, and isentropic efficiency is 65% for each stage. The volumetric flow rate of air is 0.5 m^3·s^{-1} at the inlet to the first stage.

(*a*) How many stages are required?
(*b*) What is the mechanical-power requirement per stage?
(*c*) What is the heat duty for each intercooler?
(*d*) Water is the coolant for the intercoolers. It enters at 25°C and leaves at 45°C. What is the cooling-water rate per intercooler?

Assume air is an ideal gas with $C_P = (7/2)R$.

7.40. Demonstrate that the power requirement for compressing a gas is smaller the more complex the gas. Assume fixed values of $\dot{n}$, η, T_1, P_1, and P_2, and that the gas is ideal with constant heat capacities.

7.41. Tests on an adiabatic gas compressor yield values for inlet conditions (T_1, P_1) and outlet conditions (T_2, P_2). Assuming ideal gases with constant heat capacities, determine the compressor efficiency for one of the following:

(*a*) $T_1 = 300$ K, $P_1 = 2$ bar, $T_2 = 464$ K, $P_2 = 6$ bar, $C_P/R = 7/2$
(*b*) $T_1 = 290$ K, $P_1 = 1.5$ bar, $T_2 = 547$ K, $P_2 = 5$ bar, $C_P/R = 5/2$
(*c*) $T_1 = 295$ K, $P_1 = 1.2$ bar, $T_2 = 455$ K, $P_2 = 6$ bar, $C_P/R = 9/2$
(*d*) $T_1 = 300$ K, $P_1 = 1.1$ bar, $T_2 = 505$ K, $P_2 = 8$ bar, $C_P/R = 11/2$
(*e*) $T_1 = 305$ K, $P_1 = 1.5$ bar, $T_2 = 496$ K, $P_2 = 7$ bar, $C_P/R = 4$

7.42. Air is compressed in a steady-flow compressor, entering at 1.2 bar and 300 K and leaving at 5 bar and 500 K. Operation is *non*adiabatic, with heat transfer to the surroundings at 295 K. For the same change in state of the air, is the mechanical-power requirement per mole of air greater or less for nonadiabatic than for adiabatic operation? Why?

7.43. A boiler house produces a large excess of low-pressure [50(psig), 5(°F)-superheat] steam. An upgrade is proposed that would first run the low-pressure steam through an adiabatic steady-flow compressor, producing medium-pressure [150(psig)] steam. A young engineer expresses concern that compression could result in the formation of liquid water, damaging the compressor. Is there cause for concern? *Suggestion:* Refer to the Mollier diagram of Fig. F.3 of App. F.

7.44. A pump operates adiabatically with liquid water entering at T_1 and P_1 with a mass flow rate $\dot{m}$. The discharge pressure is P_2, and the pump efficiency is η. For one of the following sets of operating conditions, determine the power requirement of the pump and the temperature of the water discharged from the pump.

(*a*) $T_1 = 25°C$, $P_1 = 100$ kPa, $\dot{m} = 20\ \text{kg·s}^{-1}$, $P_2 = 2000$ kPa, $\eta = 0.75$,
$\beta = 257.2 \times 10^{-6}\ \text{K}^{-1}$
(*b*) $T_1 = 90°C$, $P_1 = 200$ kPa, $\dot{m} = 30\ \text{kg·s}^{-1}$, $P_2 = 5000$ kPa, $\eta = 0.70$,
$\beta = 696.2 \times 10^{-6}\ \text{K}^{-1}$
(*c*) $T_1 = 60°C$, $P_1 = 20$ kPa, $\dot{m} = 15\ \text{kg·s}^{-1}$, $P_2 = 5000$ kPa, $\eta = 0.75$,
$\beta = 523.1 \times 10^{-6}\ \text{K}^{-1}$
(*d*) $T_1 = 70(°\text{F})$, $P_1 = 1(\text{atm})$, $\dot{m} = 50(\text{lb}_\text{m})(\text{s})^{-1}$, $P_2 = 20(\text{atm})$, $\eta = 0.70$,
$\beta = 217.3 \times 10^{-6}\ \text{K}^{-1}$
(*e*) $T_1 = 200(°\text{F})$, $P_1 = 15(\text{psia})$, $\dot{m} = 80(\text{lb}_\text{m})(\text{s})^{-1}$, $P_2 = 1500(\text{psia})$, $\eta = 0.75$,
$\beta = 714.3 \times 10^{-6}\ \text{K}^{-1}$

7.45. What is the ideal work for the pumping process of Ex. 7.10? What is the thermodynamic efficiency of the process? What is S_G? What is W_{lost}? Take $T_\sigma = 300$ K.

7.46. Show that the points on the Joule/Thomson inversion curve [for which $\mu = (\partial T/\partial P)_H = 0$] are also characterized by each of the following:

(*a*) $\left(\dfrac{\partial Z}{\partial T}\right)_P = 0$; (*b*) $\left(\dfrac{\partial H}{\partial P}\right)_T = 0$; (*c*) $\left(\dfrac{\partial V}{\partial T}\right)_P = \dfrac{V}{T}$; (*d*) $\left(\dfrac{\partial Z}{\partial V}\right)_P = 0$;

(*e*) $V\left(\dfrac{\partial P}{\partial V}\right)_T + T\left(\dfrac{\partial P}{\partial T}\right)_V = 0$

7.47. According to Prob. 7.3, the thermodynamic sound speed c depends on the PVT equation of state. Show how isothermal sound-speed measurements can be used to estimate the second virial coefficient B of a gas. Assume that Eq. (3.36) applies, and that the ratio C_P/C_V is given by its ideal-gas value.

7.48. Real-gas behavior for turbomachinery is sometimes empirically accommodated through the expression $\dot{W} = \langle Z \rangle \dot{W}^{ig}$, where $\dot{W}^{ig}$ is the ideal-gas mechanical power and $\langle Z \rangle$ is some suitably defined average value of the compressibility factor.

(*a*) Rationalize this expression.
(*b*) Devise a turbine example incorporating real-gas behavior via residual properties, and determine a numerical value of $\langle Z \rangle$ for the example.

7.49. Operating data are taken on an air turbine. For a particular run, $P_1 = 8$ bar, $T_1 = 600$ K, and $P_2 = 1.2$ bar. However, the recorded outlet temperature is only partially legible; it could be $T_2 = 318$, 348, or 398 K. Which must it be? For the given conditions, assume air to be an ideal gas with constant $C_P = (7/2)R$.

7.50. Liquid benzene at 25°C and 1.2 bar is converted to vapor at 200°C and 5 bar in a two-step steady-flow process: compression by a pump to 5 bar, followed by vaporization in a counterflow heat exchanger. Determine the power requirement of the pump and the duty of the exchanger in kJ·mol^{-1}. Assume a pump efficiency of 70%, and treat benzene vapor as an ideal gas with constant $C_P = 105$ J·mol^{-1}·K^{-1}.

7.51. Liquid benzene at 25°C and 1.2 bar is converted to vapor at 200°C and 5 bar in a two-step steady-flow process: vaporization in a counterflow heat exchanger at 1.2 bar, followed by compression as a gas to 5 bar. Determine the duty of the exchanger and the power requirement of the compressor in kJ·mol^{-1}. Assume a compressor efficiency of 75%, and treat benzene vapor as an ideal gas with constant $C_P = 105$ J·mol^{-1}·K^{-1}.

7.52. Of the processes proposed in Probs. 7.50 and 7.51, which would you recommend? Why?

7.53. Liquids (identified below) at 25°C are completely vaporized at 1(atm) in a countercurrent heat exchanger. Saturated steam is the heating medium, available at four pressures: 4.5, 9, 17, and 33 bar. Which variety of steam is most appropriate for each case? Assume a minimum approach ΔT of 10°C for heat exchange.

(*a*) Benzene
(*b*) *n*-Decane
(*c*) Ethylene glycol
(*d*) *o*-Xylene

7.54. One hundred (100) kmol·h^{-1} of ethylene is compressed from 1.2 bar and 300 K to 6 bar by an electric-motor-driven compressor. Determine the capital cost C of the unit. Treat ethylene as an ideal gas with constant $C_P = 50.6$ J·mol^{-1}·K^{-1}.

Data: η(compressor) = 0.70

C(compressor)/\$ = $3040(\dot{W}_S/\text{kW})^{0.952}$
where $\dot{W}_S \equiv$ *isentropic* power requirement for the compressor.

C(motor)/\$ = $380(|\dot{W}_e|/\text{kW})^{0.855}$
where $\dot{W}_e \equiv$ *delivered* shaft power of motor.

7.55. Four different types of drivers for gas compressors are: electric motors, gas expanders, steam turbines, and internal-combustion engines. Suggest when each might be appropriate. How would you estimate operating costs for each of these drivers? Ignore such add-ons as maintenance, operating labor, and overhead.

7.56. Two schemes are proposed for the reduction in pressure of ethylene gas at 375 K and 18 bar to 1.2 bar in a steady-flow process:

(*a*) Pass it through a throttle valve.
(*b*) Send it through an adiabatic expander of 70% efficiency.

For each proposal, determine the downstream temperature, and the rate of entropy generation in J·mol^{-1}·K^{-1}. What is the power output for proposal (*b*) in kJ·mol^{-1}? Discuss the pros and cons of the two proposals. Do not assume ideal gases.

7.57. A stream of hydrocarbon gas at 500°C is cooled by continuously combining it with a stream of light oil in an adiabatic tower. The light oil enters as a liquid at 25°C; the combined stream leaves as a gas at 200°C.

(*a*) Draw a carefully labeled flow diagram for the process.
(*b*) Let F and D denote respectively the molar flow rates of hot hydrocarbon gas and light oil. Use data given below to determine a numerical value for the oil-to-gas ratio D/F. Explain your analysis.
(*c*) What is the advantage to quenching the hydrocarbon gas with a *liquid* rather than with another (cooler) gas? Explain.

Data: C_P^v(ave) = 150 J·mol^{-1}·K^{-1} for the hydrocarbon gas.

C_P^v(ave) = 200 J·mol^{-1}·K^{-1} for the oil vapor.

ΔH^{lv}(oil) = 35,000 J·mol^{-1} at 25°C.