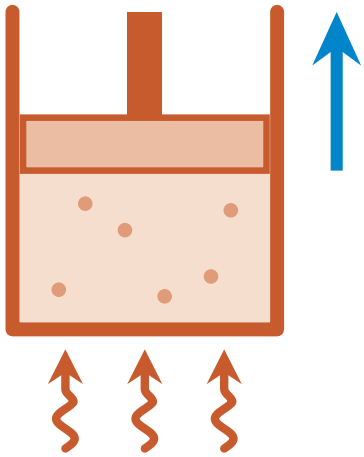
THERMODYNAMICS 1

PROBLEM BOOK

SAMPLE PAGES

8 chapters · 154 problems · step-by-step solutions



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How to use this book

- Each chapter opens with a reminder box summarizing the definitions and formulas the problems rely on.
- Difficulty: ★☆☆ basic ★★☆ intermediate ★★★ advanced. Each chapter has a few multiple-choice concept questions; its last problem is an exam-style mixed problem combining several topics.
- The dotted area below each problem is for your own work. Solve first; if stuck, go back to the reminder box and the lecture notes, and look at the solution last.
- All solutions are at the end of the book. The Solution → link next to a problem takes you to its solution, and ← Problem takes you back. Short answers are in the **ANSWER** box.
- **Property tables:** The problems are solved with the *Appendix: Property Tables* at the end of the book; values not listed directly in a table are found by linear interpolation.
- **Shared chapters:** Chapters 7–8 (entropy, exergy) also appear in *Thermodynamics 2*, for schools whose second course begins with these topics.
- **Midterm and final:** The midterm usually covers basic concepts, energy analysis, properties of pure substances, and closed systems (Chapters 1–4); the final adds control volumes, the second law, and entropy (Chapters 5–7). At some schools the first course ends with exergy (Chapter 8). The order and scope of topics vary from school to school; choose the chapters to study according to your own course syllabus.

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CHAPTER 3

PROPERTIES OF PURE SUBSTANCES

absolute pressure $P = P_{\text{gage}} + P_{\text{atm}}$

quality $x = \dfrac{m_g}{m_f + m_g}$

saturated mixture (y: v, u, h, s)

$y = y_f + x\, y_{fg}, \quad y_{fg} = y_g - y_f$

linear interpolation $y = y_1 + (y_2 - y_1)\dfrac{x - x_1}{x_2 - x_1}$

compressed liquid (no table)

$v \approx v_f(T), \quad h \approx h_f(T) + v_f(T)[P - P_{\text{sat}}(T)]$

ideal gas (P, T absolute) $Pv = RT, \quad PV = mRT$

gas constant $R = \dfrac{R_u}{M}, \quad R_u = 8.314\ \text{kJ/(kmol·K)}$

ideal gas, fixed mass $\dfrac{P_1V_1}{T_1} = \dfrac{P_2V_2}{T_2}$

compressibility factor $Z = \dfrac{Pv}{RT} = \dfrac{v_{\text{a}}}{v_{\text{ideal}}}$

reduced properties

$P_R = \dfrac{P}{P_{\text{cr}}}, \quad T_R = \dfrac{T}{T_{\text{cr}}}, \quad v_R = \dfrac{v}{RT_{\text{cr}}/P_{\text{cr}}}$

In this chapter and the following chapters, properties are read only from the Appendix tables at the end of the book: Tables T-2–T-6 for water, T-7–T-9 for R-134a, T-1 for the molar mass, gas constant and critical-point properties of gases, T-10 for ideal-gas specific heats, and the T-12 chart for the compressibility factor. Values not found in a table are obtained by linear interpolation, and the interpolation is shown in the solution. Pressures are absolute unless stated otherwise; gage pressure is stated explicitly. In the ideal-gas (perfect-gas) relation the temperature is in kelvins: $T\,[\text{K}] = T\,[^\circ\text{C}] + 273.15$. A saturated liquid–vapor mixture (wet vapor) is defined only in the region between the saturation lines; the quality x is not used in other regions. A value of Z read from the chart is given to two significant figures. In the figures the process is drawn in blue, lines of constant pressure and constant temperature in dashed gray, and heat transfer with a red arrow.

Phase change and property diagrams

3.2 ★☆☆ Solution →

Which of the following states of water is superheated vapor?

A) $P = 200$ kPa, $T = 110\ ^\circ$C

B) $P = 1$ MPa, $v = 0.15\ \text{m}^3/\text{kg}$

C) $T = 150\ ^\circ$C, $v = 0.3\ \text{m}^3/\text{kg}$

D) $P = 300$ kPa, $T = 140\ ^\circ$C

E) $T = 80\ ^\circ$C, $P = 50$ kPa

3.4 ★☆☆ Solution →

In Erzurum the atmospheric pressure is about 81 kPa. The valve of a pressure cooker opens when the gage pressure reaches 70 kPa and keeps the pressure at this value by releasing steam.

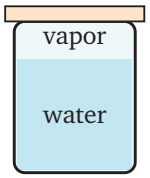
a. At what temperature does the food cook inside the cooker?

b. If the same food were cooked in Erzurum in a pot with the lid open, at what temperature would the water boil? By how much does the pressure cooker raise the cooking temperature?

c. If a cooking temperature of 120 °C is desired in Erzurum, to what gage pressure should the valve be set?

Mixed problems

3.18 ★★★ Solution →



For hydrothermal synthesis in a chemistry laboratory, 75% of the volume of a rigid 250 mL hydrothermal reactor is filled with liquid water at 25 °C, the air is evacuated from the remaining space, and the reactor is sealed and heated.

a. At 180 °C, find the pressure in the reactor, the quality, and the fraction of the reactor volume occupied by the liquid.

b. If heating continues, at what temperature does the reactor become completely filled with liquid? What happens beyond this temperature?

c. The liner of the reactor can withstand at most 250 °C. What is the maximum percentage to which the reactor can be filled at 25 °C so that it does not become completely filled with liquid up to this temperature?

CHAPTER 5

MASS AND ENERGY ANALYSIS OF CONTROL VOLUMES

mass flow rate $\dot{m} = \rho VA = \dfrac{VA}{v}, \quad \dot{V} = VA$

mass in steady flow $\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}}$

flow work; energy of a flowing fluid

$w_{\text{flow}} = Pv, \quad \theta = h + \dfrac{V^2}{2} + gz$

steady flow, single inlet and exit

$q_{\text{net,in}} - w_{\text{net,out}} = h_2 - h_1 + \dfrac{V_2^2 - V_1^2}{2} + g\,(z_2 - z_1)$

steady flow, general

$\dot{Q}_{\text{net,in}} - \dot{W}_{\text{net,out}} = \sum \dot{m}_{\text{out}}\,\theta_{\text{out}} - \sum \dot{m}_{\text{in}}\,\theta_{\text{in}}$

throttling valve $h_{\text{out}} \approx h_{\text{in}}$

incompressible fluid (pump) $\Delta h = c\,\Delta T + v\,\Delta P$

unsteady flow (uniform) $Q_{\text{net,in}} - W_{\text{net,out}} = \sum m_{\text{out}}\theta_{\text{out}} - \sum m_{\text{in}}\theta_{\text{in}} + (m_2 u_2 - m_1 u_1)$

A control volume (open system) is a region of space through whose boundary mass crosses. Sign convention: the energy balance is written with the incoming and outgoing energy flows; the difference $\dot{E}_{\text{in}} - \dot{E}_{\text{out}}$ equals the rate of change of the energy in the control volume; in steady flow this difference is zero. Heat and work whose direction is known are given as positive quantities with an in/out subscript ($\dot{Q}_{\text{in}}$, $\dot{W}_{\text{out}}$ …); if the direction is not known in advance, a net quantity ($\dot{Q}_{\text{net,in}}$, $\dot{W}_{\text{net,out}}$) is used, and if it comes out negative its direction is stated in words. Unless stated otherwise, the flow is steady; potential energy changes are neglected; kinetic energy is taken into account in nozzles and diffusers and is neglected in other devices if the velocities are not given. With velocity in meters per second, $V^2/2$ comes out in joules per kilogram; it is divided by 1000 to be added to enthalpy. Properties of water and R-134a are read from Tables T-2–T-9, the gas constant from Table T-1; for ideal gases, constant specific heats (Table T-10(a)) or the temperature-dependent enthalpy of air (Table T-11) are used. If a compressed liquid lies outside the table, $h \approx h_f(T)$ is taken. In the schematics, mass flow is shown with black arrows, heat with red and work with blue.

Nozzles and diffusers

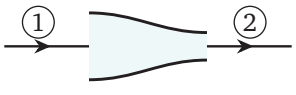
5.5 ★★☆ Solution →

In a steam ejector that evacuates a vacuum distillation column, saturated vapor at 700 kPa enters the nozzle with a velocity of 30 m/s. At the nozzle exit the pressure is 20 kPa and the quality of the steam is 0.85. The steam flow rate through the nozzle is 0.25 kg/s; the nozzle is adiabatic.

a. Find the steam velocity at the nozzle exit.

b. Find the inlet and exit cross-sectional areas of the nozzle.

c. What is the role of the high exit velocity in the ejector?

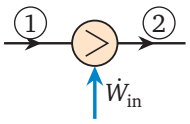


nozzle

Turbines, compressors, and pumps

5.7

★☆☆ Solution →



In the district cooling (chilled water) distribution loop of an airport terminal, a pump raises the pressure of 55 kg/s of water at 10 °C by 350 kPa; the pump receives 26 kW of power through its shaft. The pump is adiabatic; the inlet and outlet pipes have the same diameters and elevations.

a. Find the work supplied per unit mass and the part of it that goes into the pressure rise ($v\,\Delta P$).

b. Find the temperature rise of the water in the pump.

Mixing chambers and heat exchangers

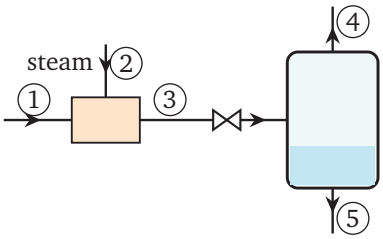
5.18

★★★ Solution →

In the UHT (ultra-high-temperature, short-time heat treatment) line of a dairy plant, the product is heated by direct steam injection: saturated steam at 600 kPa is injected into 0.5 kg/s of product at 75 °C, and the mixture is heated under pressure to 140 °C. After a short holding time, the mixture is throttled into a vacuum chamber (flash vessel); there part of it turns into vapor by flash evaporation, and the vapor is separated. The product is taken to have the properties of water; $h \approx h_f(T)$ for liquids; the injector and the flash vessel are adiabatic.

a. Find the required steam flow rate and the percentage of water added to the product by mass.

b. The mass of vapor separated in the flash vessel must equal that of the injected steam (so that the product is not diluted). What must the temperature and pressure of the flash vessel be? (Saturated liquid and saturated vapor leave the flash vessel.)



CHAPTER 7

ENTROPY

entropy (internally reversible) $$dS = \left(\frac{\delta Q}{T}\right)_{\text{int rev}}$$

Clausius inequality $$\oint \frac{\delta Q}{T} \le 0$$

closed-system entropy balance
$$S_2 - S_1 = \sum \frac{Q_k}{T_k} + S_{\text{gen}}$$

steady-flow entropy balance
$$\sum \dot{m} s_{\text{out}} - \sum \dot{m} s_{\text{in}} = \sum \frac{\dot{Q}_k}{T_k} + \dot{S}_{\text{gen}}$$

increase of entropy principle $$S_{\text{gen}} \ge 0$$

closed-system energy balance
$$Q_{\text{in}} - W_{\text{out}} = m\,(u_2 - u_1)$$

steady-flow energy balance
$$\dot{Q}_{\text{in}} - \dot{W}_{\text{out}} = \dot{m}\,(h_{\text{out}} - h_{\text{in}})$$

Carnot efficiency $$\eta_{\text{Carnot}} = 1 - \frac{T_L}{T_H}$$

saturated mixture $$y = y_f + x\,y_{fg} \quad (y : v, u, h, s)$$

Gibbs equations ($T\,ds$ relations)
$$T\,ds = du + P\,dv = dh - v\,dP$$

incompressible substance $$s_2 - s_1 = c \ln \frac{T_2}{T_1}$$

ideal gas $$Pv = RT, \quad \Delta u = c_v\,\Delta T, \quad \Delta h = c_p\,\Delta T$$

ideal gas, constant c_p $$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

ideal gas, air table $$s_2 - s_1 = s_2^\circ - s_1^\circ - R \ln \frac{P_2}{P_1}$$

isentropic, air table $$\frac{P_{r2}}{P_{r1}} = \frac{P_2}{P_1}, \quad \frac{v_{r2}}{v_{r1}} = \frac{v_2}{v_1}$$

isentropic, constant k
$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k}$$

reversible steady-flow work (input)
$$w_{\text{in}} = \int_1^2 v\,dP$$

isentropic efficiencies
$$\eta_{\text{T}} = \frac{h_1 - h_{2a}}{h_1 - h_{2s}}, \quad \eta_{\text{C}} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

The energy balance for closed systems and control volumes (open systems), the ideal-gas relations and the Carnot efficiency are given in the reminder box. In energy balances the quantities are written as positive, and the direction is shown by the subscripts "in" and "out". In the entropy balance, however, Q_k is the heat crossing the part of the boundary at temperature T_k and is algebraic: heat into the system is positive and heat out of the system is negative. Temperatures in the balances are in kelvins: $T\,[\text{K}] = T\,[^\circ\text{C}] + 273.15$. Properties are read from the Appendix tables: Tables T-2–T-5 for water, T-7–T-9 for R-134a, T-1 for the gas constant, T-10 (300 K) for constant specific heats and k, and T-11 for the temperature-dependent properties of air (h, u, s°, P_r, v_r). For ideal gases, the problem states whether constant specific heats or the air table is used. For liquid water, $v \approx v_f(T)$, $h \approx h_f(T)$, $s \approx s_f(T)$ (saturated-liquid approximation). Kinetic and potential energy changes are neglected. The subscript s denotes the isentropic exit state and a the actual exit state. On T-s diagrams an isentropic process is drawn as a vertical line and an irreversible process as a dashed line.

Entropy and the increase of entropy principle

7.3 ★★☆ Solution →

A patent application states that a cyclic device receives 500 kJ of heat from a source at 600 K and 200 kJ from a second source at 400 K in each cycle, and rejects heat to the surroundings at 300 K. The applicant describes two operating modes: in mode A the device produces 250 kJ of work per cycle, in mode B 330 kJ.

a. Find the heat rejected to the surroundings in each mode, and determine with the Clausius inequality whether the modes are possible.

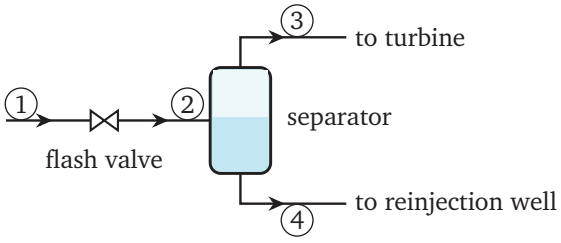
b. What is the maximum work that can be produced in one cycle with these heat sources?

c. How much entropy is generated per cycle in mode A?

Entropy balance

7.21 ★★☆ Solution →

In a single-flash geothermal power plant, 120 kg/s of geothermal water arriving from the well as saturated liquid at 220 °C (1) is throttled to 400 kPa in a flash valve (2); the resulting mixture is separated in a separator into saturated vapor (3) and saturated liquid (4). The vapor is sent to the turbine and the liquid is reinjected underground. The valve and the separator are adiabatic.



a. Find the quality of the mixture leaving the valve and the mass flow rate of the vapor going to the turbine.

b. Find the rate of entropy generation in the valve.

c. Show with an entropy balance that no entropy is generated in an ideal separator.

SOLUTIONS

3 PROPERTIES OF PURE SUBSTANCES

3.2

← Problem

If the pressure is given, T is compared with $T_{\text{sat}}(P)$; if the temperature is given, P is compared with $P_{\text{sat}}(T)$, or v with v_f and v_g.

(D): From Table T-3, $T_{\text{sat}}(300\ \text{kPa}) = 133.52\ ^\circ\text{C}$. Since $T = 140\ ^\circ\text{C} > T_{\text{sat}}$, the water is superheated vapor. **D** is true.

- (A): From Table T-3, $T_{\text{sat}}(200\ \text{kPa}) = 120.21\ ^\circ\text{C}$; $T < T_{\text{sat}}$: compressed liquid.
- (B): From Table T-3, at 1 MPa, $v_f = 0.001127$, $v_g = 0.19436\ \text{m}^3/\text{kg}$; $v_f < v < v_g$: saturated mixture.
- (C): From Table T-2, at 150 °C, $v_f = 0.001091$, $v_g = 0.39245\ \text{m}^3/\text{kg}$; $v_f < v < v_g$: saturated mixture.
- (E): From Table T-2, $P_{\text{sat}}(80\ ^\circ\text{C}) = 47.414$ kPa; $P > P_{\text{sat}}$: compressed liquid. Even though the pressure is only slightly above the saturation pressure, the water does not boil.

ANSWER D

3.4

← Problem

In the cooker, water and steam coexist (saturated mixture); the temperature is the saturation temperature at the *absolute* pressure inside the cooker.

a. $P = 70 + 81 = 151$ kPa. In Table T-3, 111.35 °C at 150 kPa and 116.04 °C at 175 kPa:

$$T = 111.35 + (116.04 - 111.35)\frac{151 - 150}{175 - 150}$$
$$= 111.54 \approx 111.5\ ^\circ\text{C}.$$

b. In the open pot $P = 81$ kPa. In Table T-3, 93.49 °C at 80 kPa and 96.69 °C at 90 kPa:

$$T = 93.49 + (96.69 - 93.49)\frac{81 - 80}{90 - 80}$$
$$= 93.81 \approx 93.8\ ^\circ\text{C}.$$

The pressure cooker raises the cooking temperature by $111.54 - 93.81 = 17.7$ K. At high altitudes water boils below 100 °C, which slows cooking; the pressure cooker overcomes this.

c. From Table T-2, $P_{\text{sat}}(120\ ^\circ\text{C}) = 198.67$ kPa. The gage pressure is

$$P_{\text{gage}} = 198.67 - 81 = 117.67 \approx 118\ \text{kPa}.$$

ANSWER a. 111.5 °C b. 93.8 °C; 17.7 K higher c. 118 kPa (gage)

3.18

← Problem

The reactor is rigid and sealed: the mass and the specific volume are constant throughout the heating. From Table T-2, $v_f(25\ ^\circ\text{C}) = 0.001003\ \text{m}^3/\text{kg}$:

$$m = \frac{0.75(250 \times 10^{-6})}{0.001003} = 0.18694\ \text{kg},$$

$$v = \frac{250 \times 10^{-6}}{0.18694} = 0.0013373\ \text{m}^3/\text{kg}.$$

a. From Table T-2 (180 °C): $P_{\text{sat}} = 1002.8$ kPa, $v_f = 0.001127$, $v_g = 0.19384\ \text{m}^3/\text{kg}$. Since $v_f < v < v_g$, the state is a saturated mixture: $P = 1002.8 \approx 1003$ kPa.

$$x = \frac{0.0013373 - 0.001127}{0.19384 - 0.001127} = 0.001091.$$

Liquid volume:

$$V_f = m(1-x)v_f = 0.18694(0.998909)(0.001127)$$
$$= 2.1045 \times 10^{-4}\ \text{m}^3;$$

the liquid fills 84.2% of the reactor. The heated liquid expands, while the mass that evaporates is very small.

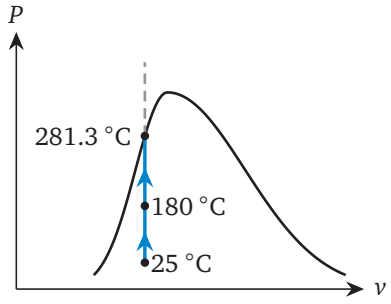
b. The reactor becomes completely filled with liquid when the specific volume of the saturated liquid equals that of the reactor, at $v_f(T) = 0.0013373\ \text{m}^3/\text{kg}$. In Table T-2, $v_f = 0.001333$ at 280 °C and $0.001366\ \text{m}^3/\text{kg}$ at 290 °C:

$$T = 280 + 10\frac{0.0013373 - 0.001333}{0.001366 - 0.001333} = 281.3\ ^\circ\text{C}.$$

Beyond this point the state leaves the saturation line and moves into the compressed liquid region. Since

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the volume of the liquid changes very little with pressure, if heating continues the pressure rises rapidly far above the saturation pressure (≈ 6.6 MPa), and the reactor may burst.



c. To avoid filling up to 250 °C, we need $v \geq v_f(250\ ^\circ\text{C}) = 0.001252\ \text{m}^3/\text{kg}$ (Table T-2). Since the fill ratio is $V_\text{w}/V = m\,v_f(25\ ^\circ\text{C})/(mv) = v_f(25\ ^\circ\text{C})/v$,

$$\frac{V_\text{w}}{V} \leq \frac{0.001003}{0.001252} = 0.801.$$

The reactor can be filled to at most 80.1% at 25 °C; the 75% fill is below this limit. In laboratories, lower ratios are used to provide a safety margin.

ANSWER a. 1003 kPa, $x = 0.001091$, 84.2%
b. 281.3 °C; the pressure rises rapidly c. 80.1%

5 MASS AND ENERGY ANALYSIS OF CONTROL VOLUMES

5.5

← Problem

Assumptions: steady flow; adiabatic; no work; no potential energy change.

The control volume is the nozzle.

State 1: from Table T-3 (700 kPa, saturated vapor) $h_1 = 2762.8\ \text{kJ/kg}$, $v_1 = 0.27277\ \text{m}^3/\text{kg}$. State 2: from Table T-3 (20 kPa) $h_f = 251.42$, $h_{fg} = 2357.5\ \text{kJ/kg}$, $v_f = 0.001017$, $v_g = 7.648\ \text{m}^3/\text{kg}$:

$$h_2 = 251.42 + 0.85(2357.5) = 2255.3\ \text{kJ/kg},$$

$$v_2 = 0.001017 + 0.85(7.6470) = 6.5010\ \text{m}^3/\text{kg}.$$

a. Energy balance ($h_1 - h_2 = 507.5\ \text{kJ/kg}$):

$$V_2 = \sqrt{2(507.5 \times 1000) + 30^2} = 1007.9 \approx 1008\ \text{m/s}.$$

b. $A = \dot{m}v/V$:

$$A_1 = \frac{0.25(0.27277)}{30} = 2.273 \times 10^{-3} \approx 2.27 \times 10^{-3}\ \text{m}^2,$$

$$A_2 = \frac{0.25(6.5010)}{1007.9} = 1.6125 \times 10^{-3} \approx 1.61 \times 10^{-3}\ \text{m}^2.$$

While the specific volume increases 24-fold, the velocity increases 34-fold; the exit area is smaller than the inlet area (diameters of about 53.8 and 45.3 mm).

c. The nozzle converts the enthalpy of the steam into kinetic energy. The fast, low-pressure jet entrains and draws in the gas from the column; the mixture then slows down in a diffuser and its pressure rises. The result is a vacuum pump with no moving parts.

ANSWER a. 1008 m/s b. $A_1 = 2.27 \times 10^{-3}\ \text{m}^2$, $A_2 = 1.61 \times 10^{-3}\ \text{m}^2$

5.7

← Problem

Assumptions: steady flow; adiabatic; no kinetic or potential energy change; liquid water is incompressible.

The control volume is the pump.

a. The pump receives $\dot{W}_\text{in} = 26\ \text{kW}$ of power; per unit mass, $w_\text{in} = 26/55 = 0.4727\ \text{kJ/kg}$. Energy balance $w_\text{in} = h_2 - h_1 = \Delta u + v\,\Delta P$. From Table T-2,

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$v_f(10\,^\circ\text{C}) = 0.001000\ \text{m}^3/\text{kg}$:

$$v\,\Delta P = 0.001000(350) = 0.350\ \text{kJ/kg};$$

Of the work supplied, $0.350/0.4727 = 74\%$ goes into the pressure rise.

b. The rest passes into the internal energy of the water through friction:

$$\Delta u = 0.4727 - 0.350 = 0.1227\ \text{kJ/kg}.$$

From Table T-2, $u_f(10\,^\circ\text{C}) = 42.02$, $u_f(15\,^\circ\text{C}) = 62.98$ kJ/kg; in this range $c = 20.96/5 = 4.192$ kJ/(kg·K):

$$\Delta T = \frac{0.1227}{4.192} = 0.0293\ \text{K}.$$

The rise is too small to measure, but it is a heat load of $55(0.1227) = 6.75$ kW; the chiller must remove this load as well.

ANSWER a. 0.4727 kJ/kg; $v\,\Delta P = 0.350$ kJ/kg (74%) b. 0.0293 K

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5.18 ← Problem

Assumptions: steady flow; adiabatic; no work; no kinetic or potential energy change.

States: 1 product (75 °C), 2 steam, 3 heated mixture (140 °C), 4 flash vapor, 5 product (flash vessel exit).

From Table T-2, $h_1 = h_f(75\,^\circ\text{C}) = 314.03$, $h_3 = h_f(140\,^\circ\text{C}) = 589.16$ kJ/kg (the pressure of the mixture is kept above $P_{\text{sat}}(140\,^\circ\text{C}) = 361.54$ kPa, so the mixture is liquid). From Table T-3, $h_2 = h_g(600\ \text{kPa}) = 2756.1$ kJ/kg.

a. Injector: $\dot m_1 h_1 + \dot m_2 h_2 = (\dot m_1 + \dot m_2) h_3$:

$$\dot m_2 = 0.5\,\frac{589.16 - 314.03}{2756.1 - 589.16} = 0.06348 \approx 0.0635\ \text{kg/s}.$$

The water added to the product is $0.06348/0.5 = 12.7\%$ by mass.

b. Flash vessel (h_3 does not change in throttling): $\dot m_4 = \dot m_2$ and $\dot m_5 = \dot m_1$ are required. Energy balance, with vessel temperature T:

$$0.5\,h_f(T) + 0.06348\,h_g(T) = 0.56348(589.16) = 331.98\ \text{kW}.$$

The left side is evaluated at two rows of Table T-2:

$$75\,^\circ\text{C}:\ 0.5(314.03) + 0.06348(2634.6) = 324.27\ \text{kW} \quad (\text{diff.} -7.71),$$

$$80\,^\circ\text{C}:\ 0.5(335.01) + 0.06348(2643.0) = 335.29\ \text{kW} \quad (\text{diff.} +3.31).$$

Interpolating so that the difference is zero:

$$T = 75 + 5\,\frac{7.71}{7.71 + 3.31} = 78.50 \approx 78.5\,^\circ\text{C}.$$

The pressure is the saturation pressure at this temperature; in Table T-2, 38.595 at 75 °C and 47.414 kPa at 80 °C, ratio 0.6997:

$$P = 38.595 + 0.6997(8.819) = 44.77 \approx 44.8\ \text{kPa}.$$

The product leaves the flash vessel at 78.5 °C with its inlet water content. The exit temperature is slightly higher than 75 °C because the enthalpy of the injected steam (at 600 kPa) is greater than that of the separated vapor. Flash evaporation cools the product within seconds and also removes volatile odors that spoil its taste.

ANSWER a. 0.0635 kg/s; 12.7% b. 78.5 °C; 44.8 kPa

7 ENTROPY

7.3

← Problem

Assumptions: the reservoirs are at constant temperature; heat is transferred at the reservoir temperatures.

a. The energy balance of the cycle is $Q_L = 500 + 200 - W_{\text{net,out}}$: $Q_L = 450$ kJ in mode A and $Q_L = 370$ kJ in mode B. Heat is transferred at the reservoir temperatures:

$$\oint \frac{\delta Q}{T} = \frac{500}{600} + \frac{200}{400} - \frac{450}{300}$$
$$= 0.8333 + 0.5 - 1.5 = -0.1667 \text{ kJ/K}.$$

A: the integral is negative; the cycle is possible (irreversible).

$$\oint \frac{\delta Q}{T} = 0.8333 + 0.5 - \frac{370}{300} = +0.1 \text{ kJ/K}.$$

B: the integral is positive; the Clausius inequality is violated and the cycle is impossible.

b. The maximum work is obtained in a reversible cycle, when $\oint \delta Q/T = 0$:

$$Q_{L,\min} = 300(0.8333 + 0.5) = 400 \text{ kJ},$$

$$W_{\max} = 700 - 400 = 300 \text{ kJ}.$$

The claim of 330 kJ in mode B exceeds this limit.

c. If the device and the reservoirs are considered together, the entropy of the fluid does not change over the cycle; the sum of the entropy changes of the reservoirs is the entropy generated:

$$S_{\text{gen}} = -\oint \frac{\delta Q}{T} = 0.1667 \text{ kJ/K}.$$

ANSWER a. A: 450 kJ, possible; B: 370 kJ, impossible b. 300 kJ c. 0.1667 kJ/K

7.21

← Problem

Assumptions: steady flow; adiabatic.

From Table T-2 (220 °C): $h_1 = h_f = 943.58$ kJ/kg, $s_1 = s_f = 2.5177$ kJ/(kg·K). From Table T-3 (400 kPa): $h_f = 604.65$, $h_{fg} = 2133.4$ kJ/kg; $s_f = 1.7765$, $s_{fg} = 5.1190$ kJ/(kg·K).

a. In the valve $h_2 = h_1$:

$$x_2 = \frac{943.58 - 604.65}{2133.4} = 0.1589,$$

$$\dot{m}_3 = 0.1589(120) = 19.06 \text{ kg/s}.$$

b. Entropy:

$$s_2 = 1.7765 + 0.1589(5.1190) = 2.5898 \text{ kJ/(kg·K)},$$

$$\dot{S}_{\text{gen}} = 120(2.5898 - 2.5177) = 8.65 \text{ kW/K}.$$

c. In the separator $\dot{m}_3 = x_2\,\dot{m}$, $\dot{m}_4 = (1-x_2)\,\dot{m}$; $s_3 = s_g$, $s_4 = s_f$:

$$\dot{S}_{\text{gen}} = \dot{m}_3 s_g + \dot{m}_4 s_f - \dot{m} s_2$$
$$= \dot{m}\,[x_2 s_g + (1-x_2)s_f - (s_f + x_2 s_{fg})] = 0.$$

The separator only separates the two phases from each other; it does not change the state of the mixture.

ANSWER a. $x_2 = 0.1589$; 19.06 kg/s b. 8.65 kW/K c. $\dot{S}_{\text{gen}} = 0$

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APPENDIX: PROPERTY TABLES

The values in this appendix are computed from reference equations of state (IAPWS-95 for water, the international standard equation for R-134a) and from ideal-gas specific heats; units are SI. States not in a table are found by **linear interpolation**: if $x_1 < x < x_2$, then $y = y_1 + (y_2 - y_1)(x - x_1)/(x_2 - x_1)$. In the superheated vapor and compressed liquid tables, when both temperature and pressure fall between entries, interpolate first in temperature at the two pressures and then in pressure (double interpolation). The numerical answers of the problems are computed with the values in these tables and with this rule.

This sample includes only the Appendix tables used by the selected problems (T-1, T-2, T-3). The Appendix of the full book has 12 tables on 17 pages: water, ice, R-134a, ideal gases, air, and the compressibility chart.

Table T-1 Molar mass, gas constant, and critical-point properties

Substance	Formula	M kg/kmol	R kJ/(kg·K)	T_{cr} K	P_{cr} MPa	v_{cr} m³/kmol	Z_{cr}
Hydrogen	H_2	2.016	4.124	33.1	1.296	0.0645	0.303
Helium	He	4.003	2.077	5.2	0.2283	0.0575	0.304
Methane	CH_4	16.043	0.5183	190.6	4.599	0.0986	0.286
Ammonia	NH_3	17.031	0.4882	405.6	11.36	0.0730	0.246
Water	H_2O	18.015	0.4615	647.1	22.06	0.0559	0.229
Neon	Ne	20.180	0.4120	44.4	2.662	0.0415	0.299
Ethylene	C_2H_4	28.054	0.2964	282.4	5.042	0.1309	0.281
Nitrogen	N_2	28.014	0.2968	126.2	3.396	0.0894	0.289
Carbon monoxide	CO	28.010	0.2968	132.9	3.498	0.0922	0.292
Air	—	28.97	0.2870	132.5	3.786	0.0845	0.290
Ethane	C_2H_6	30.070	0.2765	305.3	4.872	0.1458	0.280
Oxygen	O_2	31.998	0.2598	154.6	5.046	0.0750	0.294
Methanol	CH_3OH	32.042	0.2595	513.4	8.216	0.1138	0.219
Argon	Ar	39.950	0.2081	150.7	4.863	0.0746	0.290
Propylene	C_3H_6	42.081	0.1976	364.2	4.555	0.1833	0.276
Carbon dioxide	CO_2	44.009	0.1889	304.1	7.377	0.0941	0.275
Nitrous oxide	N_2O	44.013	0.1889	309.5	7.245	0.0972	0.274
Propane	C_3H_8	44.097	0.1885	369.9	4.251	0.2000	0.276
Ethanol	C_2H_5OH	46.069	0.1805	514.7	6.268	0.1686	0.247
Butane (*n*-)	C_4H_{10}	58.124	0.1430	425.1	3.796	0.2549	0.274
Sulfur dioxide	SO_2	64.058	0.1298	430.6	7.887	0.1238	0.273
Chlorine	Cl_2	70.900	0.1173	416.9	7.642	0.1258	0.277
Benzene	C_6H_6	78.114	0.1064	562.0	4.906	0.2563	0.269
Krypton	Kr	83.798	0.09922	209.5	5.525	0.0922	0.292
R-134a	CH_2FCF_3	102.030	0.08149	374.2	4.059	0.1993	0.260
Xenon	Xe	131.290	0.06333	289.7	5.842	0.1190	0.289

$R = R_u/M$, $R_u = 8.31446$ kJ/(kmol·K). Molar masses from the IUPAC standard atomic weights; the molar mass of air is the conventional value. $Z_{cr} = P_{cr} v_{cr}/(R_u T_{cr})$; the critical point of air is that of the pseudo-pure fluid model. Substances are listed by molar mass.

Table T-2 Saturated water: temperature table

		Specific volume m^3/kg		Internal energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/(kg·K)		
T, °C	P_{sat}, kPa	v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
0.01	0.6117	0.001000	205.99	0.000	2374.9	0.001	2500.9	2500.9	0.0000	9.1555	9.1555
5	0.8726	0.001000	147.01	21.019	2381.8	21.020	2489.0	2510.1	0.0763	8.9486	9.0248
10	1.2282	0.001000	106.30	42.020	2388.6	42.021	2477.2	2519.2	0.1511	8.7487	8.8998
15	1.7058	0.001001	77.875	62.980	2395.5	62.981	2465.4	2528.3	0.2245	8.5558	8.7803
20	2.3393	0.001002	57.757	83.912	2402.3	83.914	2453.5	2537.4	0.2965	8.3695	8.6660
25	3.1699	0.001003	43.337	104.83	2409.1	104.83	2441.7	2546.5	0.3672	8.1894	8.5566
30	4.2470	0.001004	32.878	125.73	2415.9	125.73	2429.8	2555.5	0.4368	8.0152	8.4520
35	5.6290	0.001006	25.205	146.63	2422.7	146.63	2417.9	2564.5	0.5051	7.8466	8.3517
40	7.3849	0.001008	19.515	167.53	2429.4	167.53	2406.0	2573.5	0.5724	7.6831	8.2555
45	9.5950	0.001010	15.252	188.43	2436.1	188.43	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.027	209.33	2442.7	209.34	2381.9	2591.3	0.7038	7.3710	8.0748
55	15.762	0.001015	9.5643	230.24	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.946	0.001017	7.6672	251.16	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9081
65	25.042	0.001020	6.1935	272.09	2462.4	272.12	2345.4	2617.5	0.8937	6.9359	7.8296
70	31.201	0.001023	5.0395	293.03	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.595	0.001026	4.1289	313.99	2475.2	314.03	2320.6	2634.6	1.0158	6.6654	7.6812
80	47.414	0.001029	3.4052	334.96	2481.6	335.01	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.867	0.001032	2.8258	355.95	2487.8	356.01	2295.3	2651.3	1.1346	6.4088	7.5434
90	70.182	0.001036	2.3591	376.97	2494.0	377.04	2282.5	2659.5	1.1929	6.2853	7.4781
95	84.608	0.001040	1.9806	398.00	2500.0	398.09	2269.5	2667.6	1.2504	6.1647	7.4151
100	101.42	0.001043	1.6718	419.06	2506.0	419.17	2256.4	2675.6	1.3072	6.0469	7.3541
110	143.38	0.001052	1.2093	461.26	2517.7	461.42	2229.6	2691.1	1.4188	5.8193	7.2381
120	198.67	0.001060	0.89121	503.60	2528.9	503.81	2202.1	2705.9	1.5279	5.6012	7.1291
130	270.28	0.001070	0.66800	546.09	2539.5	546.38	2173.7	2720.1	1.6346	5.3918	7.0264
140	361.54	0.001080	0.50845	588.77	2549.6	589.16	2144.3	2733.4	1.7392	5.1901	6.9293
150	476.16	0.001091	0.39245	631.66	2559.1	632.18	2113.7	2745.9	1.8418	4.9953	6.8371
160	618.23	0.001102	0.30678	674.79	2567.8	675.47	2082.0	2757.4	1.9426	4.8066	6.7491
170	792.19	0.001114	0.24259	718.20	2575.7	719.08	2048.8	2767.9	2.0417	4.6233	6.6650
180	1002.8	0.001127	0.19384	761.92	2582.8	763.05	2014.2	2777.2	2.1392	4.4448	6.5840
190	1255.2	0.001141	0.15636	806.00	2589.0	807.43	1977.9	2785.3	2.2355	4.2704	6.5059
200	1554.9	0.001157	0.12721	850.47	2594.2	852.27	1939.7	2792.0	2.3305	4.0996	6.4302
210	1907.7	0.001173	0.10429	895.39	2598.3	897.63	1899.6	2797.3	2.4245	3.9318	6.3563
220	2319.6	0.001190	0.086092	940.82	2601.2	943.58	1857.4	2800.9	2.5177	3.7663	6.2840
230	2797.1	0.001209	0.071503	986.81	2602.9	990.19	1812.7	2802.9	2.6101	3.6027	6.2128
240	3346.9	0.001229	0.059705	1033.4	2603.1	1037.6	1765.4	2803.0	2.7020	3.4403	6.1423
250	3976.2	0.001252	0.050083	1080.8	2601.8	1085.8	1715.2	2800.9	2.7935	3.2785	6.0721
260	4692.3	0.001276	0.042173	1129.0	2598.7	1135.0	1661.6	2796.6	2.8849	3.1167	6.0016
270	5503.0	0.001303	0.035621	1178.1	2593.7	1185.3	1604.4	2789.7	2.9765	2.9539	5.9304
280	6416.6	0.001333	0.030153	1228.3	2586.4	1236.9	1543.0	2779.9	3.0685	2.7894	5.8579
290	7441.8	0.001366	0.025555	1279.9	2576.5	1290.0	1476.7	2766.7	3.1612	2.6222	5.7834
300	8587.9	0.001404	0.021660	1332.9	2563.6	1345.0	1404.6	2749.6	3.2552	2.4507	5.7059
310	9865.1	0.001448	0.018335	1387.9	2547.1	1402.2	1325.7	2727.9	3.3510	2.2734	5.6244
320	11284	0.001499	0.015471	1445.3	2526.0	1462.2	1238.4	2700.6	3.4494	2.0878	5.5372
330	12858	0.001561	0.012979	1505.8	2499.2	1525.9	1140.2	2666.0	3.5518	1.8903	5.4422
340	14601	0.001638	0.010781	1570.6	2464.4	1594.5	1027.3	2621.8	3.6601	1.6755	5.3356
350	16529	0.001740	0.008802	1642.1	2418.1	1670.9	892.75	2563.6	3.7784	1.4326	5.2110
360	18666	0.001895	0.006949	1726.3	2351.8	1761.7	719.83	2481.5	3.9167	1.1369	5.0536
370	21044	0.002215	0.004954	1844.1	2230.3	1890.7	443.83	2334.5	4.1112	0.6901	4.8012
373.95	22064	0.003106	0.003106	2015.7	2015.7	2084.3	0.000	2084.3	4.4070	0.0000	4.4070

Reference: the internal energy and entropy of saturated liquid water at the triple point (0.01 °C) are zero. Values are computed from the IAPWS-95 equation of state. f: saturated liquid, g: saturated vapor, $h_{fg} = h_g - h_f$, $s_{fg} = s_g - s_f$, $u_{fg} = u_g - u_f$.

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Table T-3 Saturated water: pressure table

		Specific volume m^3/kg		Internal energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/(kg·K)		
P, kPa	T_{sat}, °C	v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
1	6.97	0.001000	129.18	29.298	2384.5	29.299	2484.4	2513.7	0.1059	8.8690	8.9749
2	17.49	0.001001	66.987	73.426	2398.9	73.428	2459.4	2532.9	0.2606	8.4620	8.7226
3	24.08	0.001003	45.653	100.97	2407.9	100.98	2443.9	2544.8	0.3543	8.2221	8.5764
4	28.96	0.001004	34.791	121.38	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5	32.87	0.001005	28.185	137.74	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.80	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6480	251.40	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9072
25	64.96	0.001020	6.2032	271.93	2462.4	271.96	2345.5	2617.4	0.8932	6.9370	7.8302
30	69.10	0.001022	5.2284	289.24	2467.7	289.27	2335.3	2624.5	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9930	317.58	2476.3	317.62	2318.4	2636.1	1.0261	6.6429	7.6690
50	81.32	0.001030	3.2400	340.49	2483.2	340.54	2304.7	2645.2	1.0912	6.5018	7.5930
60	85.93	0.001033	2.7317	359.84	2489.0	359.91	2292.9	2652.9	1.1454	6.3857	7.5311
70	89.93	0.001036	2.3648	376.68	2493.9	376.75	2282.7	2659.4	1.1921	6.2869	7.4790
75	91.76	0.001037	2.2170	384.36	2496.1	384.44	2277.9	2662.4	1.2132	6.2425	7.4557
80	93.49	0.001039	2.0871	391.63	2498.2	391.71	2273.5	2665.2	1.2330	6.2009	7.4339
90	96.69	0.001041	1.8694	405.10	2502.1	405.20	2265.1	2670.3	1.2696	6.1246	7.3943
100	99.61	0.001043	1.6939	417.40	2505.6	417.50	2257.4	2674.9	1.3028	6.0561	7.3588
101.325	99.97	0.001043	1.6732	418.95	2506.0	419.06	2256.5	2675.5	1.3069	6.0475	7.3544
125	105.97	0.001048	1.3749	444.22	2513.0	444.35	2240.5	2684.9	1.3741	5.9099	7.2840
150	111.35	0.001053	1.1593	466.97	2519.2	467.13	2226.0	2693.1	1.4337	5.7893	7.2230
175	116.04	0.001057	1.0036	486.82	2524.5	487.00	2213.1	2700.1	1.4850	5.6865	7.1715
200	120.21	0.001061	0.88568	504.49	2529.1	504.70	2201.5	2706.2	1.5302	5.5967	7.1269
250	127.41	0.001067	0.71866	535.08	2536.8	535.34	2181.1	2716.5	1.6072	5.4452	7.0524
300	133.52	0.001073	0.60576	561.10	2543.2	561.43	2163.5	2724.9	1.6717	5.3199	6.9916
350	138.86	0.001079	0.52418	583.88	2548.5	584.26	2147.7	2732.0	1.7274	5.2128	6.9401
400	143.61	0.001084	0.46238	604.22	2553.1	604.65	2133.4	2738.1	1.7765	5.1190	6.8955
450	147.90	0.001088	0.41390	622.65	2557.1	623.14	2120.2	2743.4	1.8205	5.0356	6.8560
500	151.83	0.001093	0.37481	639.54	2560.7	640.09	2108.0	2748.1	1.8604	4.9603	6.8207
600	158.83	0.001101	0.31558	669.72	2566.8	670.38	2085.8	2756.1	1.9308	4.8284	6.7592
700	164.95	0.001108	0.27277	696.23	2571.8	697.00	2065.8	2762.8	1.9918	4.7153	6.7071
800	170.41	0.001115	0.24034	719.97	2576.0	720.86	2047.4	2768.3	2.0457	4.6160	6.6616
900	175.35	0.001121	0.21489	741.55	2579.6	742.56	2030.5	2773.0	2.0940	4.5272	6.6213
1000	179.88	0.001127	0.19436	761.39	2582.7	762.52	2014.6	2777.1	2.1381	4.4470	6.5850
1200	187.96	0.001139	0.16326	796.96	2587.8	798.33	1985.4	2783.7	2.2159	4.3058	6.5217
1400	195.04	0.001149	0.14078	828.36	2591.8	829.97	1958.9	2788.8	2.2835	4.1839	6.4675
1600	201.37	0.001159	0.12374	856.60	2594.8	858.46	1934.4	2792.8	2.3435	4.0765	6.4199
1800	207.11	0.001168	0.11037	882.37	2597.2	884.47	1911.4	2795.9	2.3975	3.9800	6.3775
2000	212.38	0.001177	0.099585	906.14	2599.1	908.50	1889.8	2798.3	2.4468	3.8923	6.3390
2500	223.95	0.001197	0.079949	958.91	2602.1	961.91	1840.0	2801.9	2.5543	3.7015	6.2558
3000	233.85	0.001217	0.066664	1004.7	2603.2	1008.3	1794.8	2803.2	2.6455	3.5400	6.1856
3500	242.56	0.001235	0.057058	1045.5	2602.9	1049.8	1752.8	2802.6	2.7254	3.3989	6.1243
4000	250.35	0.001253	0.049776	1082.5	2601.7	1087.5	1713.3	2800.8	2.7968	3.2728	6.0696
5000	263.94	0.001286	0.039446	1148.2	2597.0	1154.6	1639.6	2794.2	2.9210	3.0527	5.9737
6000	275.58	0.001319	0.032448	1206.0	2589.9	1213.9	1570.7	2784.6	3.0278	2.8623	5.8901
7000	285.83	0.001352	0.027378	1258.2	2581.0	1267.7	1505.0	2772.6	3.1224	2.6924	5.8148
8000	295.01	0.001385	0.023526	1306.2	2570.5	1317.3	1441.4	2758.7	3.2081	2.5369	5.7450
9000	303.34	0.001418	0.020490	1351.1	2558.5	1363.9	1379.1	2742.9	3.2870	2.3922	5.6791
10000	311.00	0.001453	0.018030	1393.5	2545.2	1408.1	1317.4	2725.5	3.3606	2.2553	5.6160
11000	318.08	0.001489	0.015990	1434.1	2530.5	1450.4	1255.9	2706.3	3.4303	2.1242	5.5545
12000	324.68	0.001526	0.014264	1473.1	2514.3	1491.5	1194.0	2685.4	3.4967	1.9972	5.4939
13000	330.85	0.001566	0.012780	1511.1	2496.5	1531.5	1131.2	2662.7	3.5608	1.8728	5.4336
14000	336.67	0.001610	0.011485	1548.4	2477.1	1571.0	1066.9	2637.9	3.6232	1.7495	5.3727
15000	342.16	0.001657	0.010338	1585.3	2455.6	1610.2	1000.5	2610.7	3.6846	1.6260	5.3106
16000	347.35	0.001709	0.009309	1622.3	2431.8	1649.7	931.10	2580.8	3.7457	1.5006	5.2463
17000	352.29	0.001769	0.008371	1659.9	2405.2	1690.0	857.47	2547.5	3.8077	1.3710	5.1787
18000	356.99	0.001840	0.007502	1699.0	2374.8	1732.1	777.74	2509.8	3.8718	1.2342	5.1061
19000	361.47	0.001927	0.006677	1740.5	2339.1	1777.2	688.85	2466.0	3.9401	1.0855	5.0256
20000	365.75	0.002040	0.005865	1786.4	2295.0	1827.2	585.13	2412.3	4.0156	0.9158	4.9314
21000	369.83	0.002206	0.004996	1841.2	2233.7	1887.6	451.04	2338.6	4.1064	0.7015	4.8079
22000	373.71	0.002704	0.003647	1951.8	2092.8	2011.3	161.75	2173.1	4.2945	0.2501	4.5446
22064	373.95	0.003106	0.003106	2015.7	2015.7	2084.3	0.000	2084.3	4.4070	0.0000	4.4070

Reference, source and symbols as in Table T-2.

IN THE FULL BOOK

- 8 chapters and 154 problems, all with step-by-step solutions.
- A reminder box at the start of each chapter, summarizing the relations the problems rely on.
- Basic, intermediate and advanced problems, each with a dotted area for your own work.
- One-click links from each problem to its solution and back.
- Twelve property tables at the end of the book (17 pages): saturated and superheated steam, compressed liquid, ice, R-134a, ideal-gas specific heats, the air table, and the generalized compressibility chart.

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