Exercises: things engineers think about

1. If water contracts on freezing, what implications might this have for aquatic life?
2. At what temperature does water boil at the top of Mount McKinley, Alaska? In Death Valley, California?
3. Why do frozen water pipes tend to burst?
4. Why do many foods have high-altitude cooking instructions?
5. Can a substance that contracts on freezing exist as a solid when at a temperature greater than its triple-point temperature? Repeat for a substance that expands on freezing.
6. The specific internal energy is arbitrarily set to zero in Table A-2 for saturated liquid water at 0.01°C. If the reference value for $u$ at this reference state were specified differently, would there be any significant effect on thermodynamic analyses using $u$ and $h$?
7. For liquid water at 20°C and 1.0 MPa, what percent difference would there be if its specific enthalpy were evaluated using Eq. 3.14 instead of Eq. 3.13?
8. How do I measure the specific heat $c_p$ of liquid water at atmospheric pressure and room temperature?
9. If a block of iron and a block of tin having equal volumes each received the same energy input by heat transfer, which block would experience the greater temperature increase?
10. How many minutes do I have to exercise to burn the calories in a helping of my favorite dessert?
11. What is my annual contribution to the emission of CO$_2$ into the atmosphere?
12. How do I estimate the mass of air contained in a bicycle tire?
13. Specific internal energy and enthalpy data for water vapor are provided in two tables: Tables A-4 and A-23. When would Table A-23 be used?

Problems: developing engineering skills

Exploring Concepts: Phase and Pure Substance

3.1 A system consists of liquid water in equilibrium with a gaseous mixture of air and water vapor. How many phases are present? Does the system consist of a pure substance? Explain. Repeat for a system consisting of ice and liquid water in equilibrium with a gaseous mixture of air and water vapor.

3.2 A system consists of liquid oxygen in equilibrium with oxygen vapor. How many phases are present? The system undergoes a process during which some of the liquid is vaporized. Can the system be viewed as being a pure substance during the process? Explain.

3.3 A system consisting of liquid water undergoes a process. At the end of the process, some of the liquid water has frozen, and the system contains liquid water and ice. Can the system be viewed as being a pure substance during the process? Explain.

3.4 A dish of liquid water is placed on a table in a room. After a while, all of the water evaporates. Taking the water and the air in the room to be a closed system, can the system be regarded as a pure substance during the process? After the process is completed? Discuss.

Using $p$-$v$-$T$ Data

3.5 Determine the phase or phases in a system consisting of H$_2$O at the following conditions and sketch $p$-$v$ and $T$-$v$ diagrams showing the location of each state.

(a) $p = 80$ lbf/in.$^2$, $T = 312.07^\circ$F.
(b) $p = 80$ lbf/in.$^2$, $T = 400^\circ$F.
(c) $T = 400^\circ$F, $p = 360$ lbf/in.$^2$.
(d) $T = 320^\circ$F, $p = 70$ lbf/in.$^2$.
(e) $T = 10^\circ$F, $p = 14.7$ lbf/in.$^2$.

3.6 Determine the phase or phases in a system consisting of H$_2$O at the following conditions and sketch $p$-$v$ and $T$-$v$ diagrams showing the location of each state.

(a) $p = 5$ bar, $T = 151.9^\circ$C.
(b) $p = 5$ bar, $T = 200^\circ$C.
(c) $T = 200^\circ$C, $p = 2.5$ MPa.
(d) $T = 160^\circ$C, $p = 4.8$ bar.
(e) $T = -12^\circ$C, $p = 1$ bar.

3.7 The following table lists temperatures and specific volumes of water vapor at two pressures:

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>$v$ (m$^3$/kg)</th>
<th>$T$ (°C)</th>
<th>$v$ (m$^3$/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.2060</td>
<td>200</td>
<td>0.1325</td>
</tr>
<tr>
<td>240</td>
<td>0.2275</td>
<td>240</td>
<td>0.1483</td>
</tr>
<tr>
<td>280</td>
<td>0.2480</td>
<td>280</td>
<td>0.1627</td>
</tr>
</tbody>
</table>

Data encountered in solving problems often do not fall exactly on the grid of values provided by property tables, and linear interpolation between adjacent table entries becomes necessary. Using the data provided here, estimate
Chapter 3 Evaluating Properties

(a) the specific volume at \( T = 240^\circ C, \rho = 1.25 \text{ MPa}, \text{ in m}^3/\text{kg}. \)
(b) the temperature at \( p = 1.5 \text{ MPa}, \nu = 0.1555 \text{ m}^3/\text{kg}, \text{ in}^\circ C. \)
(c) the specific volume at \( T = 220^\circ C, \rho = 1.4 \text{ MPa}, \text{ in m}^3/\text{kg}. \)

3.8 The following table lists temperatures and specific volumes of ammonia vapor at two pressures:

<table>
<thead>
<tr>
<th>( p = 50 \text{ lb/in.}^2 )</th>
<th>( p = 60 \text{ lb/in.}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T(\circ F) )</td>
<td>( v(\text{ft}^3/\text{lb}) )</td>
</tr>
<tr>
<td>100</td>
<td>6.836</td>
</tr>
<tr>
<td>120</td>
<td>7.110</td>
</tr>
<tr>
<td>140</td>
<td>7.380</td>
</tr>
</tbody>
</table>

Data encountered in solving problems often do not fall exactly on the grid of values provided by property tables, and linear interpolation between adjacent table entries becomes necessary. Using the data provided here, estimate

(a) the specific volume at \( T = 120^\circ F, \rho = 54 \text{ lb/in.}^2, \text{ in ft}^3/\text{lb}. \)
(b) the temperature at \( p = 60 \text{ lb/in.}^2, \nu = 5.982 \text{ ft}^3/\text{lb}, \text{ in}^\circ F. \)
(c) the specific volume at \( T = 110^\circ F, \rho = 58 \text{ lb/in.}^2, \text{ in ft}^3/\text{lb}. \)

3.9 For H\(_2\)O, plot the following on a \( p-v \) diagram drawn to scale on log-log coordinates:

(a) the saturated liquid and saturated vapor lines from the triple point to the critical point, with pressure in MPa and specific volume in m\(^3\)/kg.
(b) lines of constant temperature at 100 and 300\(^\circ\)C.

3.10 For H\(_2\)O, determine the specified property at the indicated state. Locate the state on a sketch of the \( T-v \) diagram.

(a) \( p = 300 \text{ kPa}, \nu = 0.5 \text{ m}^3/\text{kg}. \) Find \( T \), in \(^\circ\)C.
(b) \( p = 28 \text{ MPa}, T = 200^\circ \text{C}. \) Find \( \nu \), in m\(^3\)/kg.
(c) \( p = 1 \text{ MPa}, T = 405^\circ \text{C}. \) Find \( \nu \), in m\(^3\)/kg.
(d) \( T = 100^\circ \text{C}, x = 60\%. \) Find \( \nu \), in m\(^3\)/kg.

3.11 For each case, determine the specific volume at the indicated state. Locate the state on a sketch of the \( T-v \) diagram.

(a) Water at \( p = 14.7 \text{ lb/in.}^2, T = 100^\circ \text{F}. \) Find \( \nu \), in ft\(^3\)/lb.
(b) Ammonia at \( T = -30^\circ \text{C}, x = 50\%. \) Find \( \nu \), in m\(^3\)/kg.
(c) Refrigerant 134a at \( p = 1.5 \text{ MPa}, T = 100^\circ \text{C}. \) Find \( \nu \), in m\(^3\)/kg.

3.12 For each case, determine the specified property at the indicated state. Locate the state on a sketch of the \( T-v \) diagram.

(a) Water at \( v = 0.5 \text{ m}^3/\text{kg}, p = 3 \text{ bar}, \) determine \( T \), in \(^\circ\)C.
(b) Ammonia at \( p = 11 \text{ lb/in.}^2, T = -20^\circ \text{F}, \) determine \( v \), in ft\(^3\)/lb.
(c) Propane at \( p = 1 \text{ MPa}, T = 85^\circ \text{C}, \) determine \( v \), in m\(^3\)/kg.

3.13 Determine the mass, in kg, of 0.1 m\(^3\) of Refrigerant 134a at 4 bar, 100\(^\circ\)C.

3.14 Determine the volume, in ft\(^3\), occupied by 2 lb of H\(_2\)O at a pressure of 1000 lb/in.\(^2\) and

(a) a temperature of 600\(^\circ\)F.
(b) a quality of 80\%.
(c) a temperature of 200\(^\circ\)F.

3.15 A closed vessel with a volume of 2 ft\(^3\) contains 5 lb of Refrigerant 134a. A pressure sensor in the tank wall reads 71.39 lb/in.\(^2\) (gage). If the atmospheric pressure is 14.4 lb/in.\(^2\), what is the temperature of the refrigerant, in \(^\circ\)F?

3.16 Two kg of a two-phase, liquid–vapor mixture of carbon dioxide (CO\(_2\)) exists at \(-40^\circ\)C in a 0.05 m\(^3\) tank. Determine the quality of the mixture, if the values of specific volume for saturated liquid and saturated vapor CO\(_2\) at \(-40^\circ\)C are \( v_l = 0.896 \times 10^{-2} \text{ m}^3/\text{kg} \) and \( v_v = 3.824 \times 10^{-2} \text{ m}^3/\text{kg} \), respectively.

3.17 Determine the quality of a two-phase liquid–vapor mixture of

(a) H\(_2\)O at 20\(^\circ\)C with a specific volume of 20 m\(^3\)/kg.
(b) Propane at 15 bar with a specific volume of 0.02997 m\(^3\)/kg.
(c) Refrigerant 134a at 60\(^\circ\)C with a specific volume of 0.001 m\(^3\)/kg.
(d) Ammonia at 1 MPa with a specific volume of 0.1 m\(^3\)/kg.

3.18 Determine the quality of a two-phase liquid–vapor mixture of

(a) H\(_2\)O at 14.696 lb/in.\(^2\) with a specific volume of 25 ft\(^3\)/lb.
(b) Propane at \(-80^\circ\)F with a specific volume of 0.02653 ft\(^3\)/lb.
(c) Refrigerant 134a at 50 lb/in.\(^2\) with a specific volume of 0.5 ft\(^3\)/lb.
(d) Ammonia at \(-40^\circ\)F with a specific volume of 20 ft\(^3\)/lb.

3.19 A two-phase liquid–vapor mixture of ammonia at 100\(^\circ\)F has a specific volume of 1.0 ft\(^3\)/lb. Determine the quality of a two-phase liquid–vapor mixture at 0\(^\circ\)F with the same specific volume.

3.20 A two-phase liquid–vapor mixture of a substance has a pressure of 150 bar and occupies a volume of 0.2 m\(^3\). The masses of saturated liquid and vapor present are 3.8 kg and 4.2 kg, respectively. Determine the specific volume of the mixture, in m\(^3\)/kg.

3.21 As shown in Fig. P3.21, a closed, rigid cylinder contains different volumes of saturated liquid water and saturated water vapor at a temperature of 150\(^\circ\)C. Determine the quality of the mixture, expressed as a percent.

![Fig. P3.21](image)

3.22 A closed system consists of a two-phase liquid–vapor mixture of H\(_2\)O in equilibrium at 300\(^\circ\)F. The quality of the mixture is 0.8 (80\%) and the mass of saturated vapor present is 2 lb. Determine the mass of saturated liquid present, in lb, and the total volume of the system, in ft\(^3\).

3.23 Ammonia, initially saturated vapor at \(-4^\circ\)C, undergoes a constant-specific volume process to 200 kPa. At the final state, determine the temperature, in \(^\circ\)C, and the quality. Locate each state on a sketch of the \( T-v \) diagram.

3.24 Water is contained in a closed, rigid, 0.2 m\(^3\) tank at an initial pressure of 5 bar and a quality of 50\%. Heat transfer
occurs until the tank contains only saturated vapor. Determine the final mass of vapor in the tank, in kg, and the final pressure, in bar.

3.25 A rigid tank contains 5 lb of a two-phase, liquid–vapor mixture of H₂O, initially at 260°F with a quality of 0.6. Heat transfer to the contents of the tank occurs until the temperature is 320°F. Show the process on a p–v diagram. Determine the mass of vapor, in lb, initially present in the tank and the final pressure, in lb/in.².

3.26 Two thousand kg of water, initially a saturated liquid at 150°C, is heated in a closed, rigid tank to a final state where the pressure is 2.5 MPa. Determine the final temperature, in °C, the volume of the tank, in m³, and sketch the process on T–v and p–v diagrams.

3.27 Steam is contained in a closed rigid container with a volume of 1 m³. Initially, the pressure and temperature of the steam are 7 bar and 500°C, respectively. The temperature drops as a result of heat transfer to the surroundings. Determine the temperature at which condensation first occurs, in °C, and the fraction of the total mass that has condensed when the pressure reaches 0.5 bar. What is the volume, in m³, occupied by saturated liquid at the final state?

3.28 Water vapor is heated in a closed, rigid tank from saturated vapor at 160°C to a final temperature of 400°C. Determine the initial and final pressures, in bar, and sketch the process on T–v and p–v diagrams.

3.29 Ammonia undergoes an isothermal process from an initial state at T₁ = 80°F and v₁ = 10 ft³/lb to saturated vapor. Determine the initial and final pressures, in lb/in.², and sketch the process on T–v and p–v diagrams.

3.30 One kilogram of water initially is at the critical point.

(a) If the water is cooled at constant-specific volume to a pressure of 30 bar, determine the quality at the final state.

(b) If the water undergoes a constant-temperature expansion to a pressure of 30 bar, determine the specific volume at the final state, in m³/kg.

Show each process on a sketch of the T–v diagram.

3.31 Three lb of saturated water vapor, contained in a closed rigid tank whose volume is 13.3 ft³, is heated to a final temperature of 400°F. Sketch the process on a T–v diagram. Determine the pressures at the initial and final states, each in lb/in.².

3.32 Two lb of water vapor is compressed at a constant pressure of 250 lb/in.² from a volume of 6.88 ft³ to a saturated vapor state. Determine the temperatures at the initial and final states, each in °F, and the work for the process, in Btu.

3.33 Seven lb of propane in a piston-cylinder assembly, initially at p₁ = 200 lb/in.² and T₁ = 200°F, undergoes a constant-pressure process to a final state. The work for the process is −88.84 Btu. At the final state, determine the temperature, in °F, if superheated, or the quality if saturated.

3.34 Ammonia in a piston-cylinder assembly undergoes a constant-pressure process at 2.5 bar from T₁ = 30°C to saturated vapor. Determine the work for the process, in kJ per kg of refrigerant.

3.35 Water vapor initially at 10 bar and 400°C is contained within a piston–cylinder assembly. The water is cooled at constant volume until its temperature is 150°C. The water is then condensed isothermally to saturated liquid. For the water as the system, evaluate the work, in kJ/kg.

3.36 Two kilograms of Refrigerant 22 undergo a process for which the pressure–volume relation is \( p v^{1.05} = \text{constant} \). The initial state of the refrigerant is fixed by \( p₁ = 2 \) bar, \( T₁ = −20°C \), and the final pressure is \( p₂ = 10 \) bar. Calculate the work for the process, in kJ.

3.37 Refrigerant 134a in a piston–cylinder assembly undergoes a process for which the pressure–volume relation is \( p v^{1.05} = \text{constant} \). At the initial state, \( p₁ = 200 \) kPa, \( T₁ = −10°C \). The final temperature is \( T₂ = 30°C \). Determine the final pressure, in kPa, and the work for the process, in kJ/kg of refrigerant.

3.38 A piston–cylinder assembly contains 0.04 lb of Refrigerant 134a. The refrigerant is compressed from an initial state where \( p₁ = 10 \) lb/in.² and \( T₁ = 20°F \) to a final state where \( p₂ = 160 \) lb/in.². During the process, the pressure and specific volume are related by \( p v = \text{constant} \). Determine the work, in Btu, for the refrigerant.

Using u–h Data

3.39 Determine the values of the specified properties at each of the following conditions.

(a) For Refrigerant 134a at \( T = 60°C \) and \( v = 0.072 \) m³/kg, determine \( p \) in kPa and \( h \) in kJ/kg.

(b) For ammonia at \( p = 8 \) bar and \( v = 0.005 \) m³/kg, determine \( T \) in °C and \( u \) in kJ/kg.

(c) For Refrigerant 22 at \( T = −10°C \) and \( u = 200 \) kJ/kg, determine \( p \) in bar and \( v \) in m³/kg.

3.40 Determine the values of the specified properties at each of the following conditions.

(a) For Refrigerant 134a at \( p = 140 \) lb/in.² and \( h = 100 \) Btu/lb, determine \( T \) in °F and \( v \) in ft³/lb.

(b) For ammonia at \( T = 0°F \) and \( v = 15 \) ft³/lb, determine \( p \) in lb/in.² and \( h \) in Btu/lb.

(c) For Refrigerant 22 at \( T = 30°F \) and \( v = 1.2 \) ft³/lb, determine \( p \) in lb/in.² and \( h \) in Btu/lb.

3.41 Using IT, determine the specified property data at the indicated states. Compare with results from the appropriate table.

(a) Cases (a), (b), and (c) of Problem 3.39.

(b) Cases (a), (b), and (c) of Problem 3.40.

3.42 Using the tables for water, determine the specified property data at the indicated states. In each case, locate the state by hand on sketches of the p–v and T–v diagrams.

(a) At \( p = 3 \) bar, \( T = 240°C \), find \( v \) in m³/kg and \( u \) in kJ/kg.

(b) At \( p = 3 \) bar, \( v = 0.5 \) m³/kg, find \( T \) in °C and \( u \) in kJ/kg.

(c) At \( T = 400°C \), \( p = 10 \) bar, find \( v \) in m³/kg and \( h \) in kJ/kg.

(d) At \( T = 320°C \), \( v = 0.03 \) m³/kg, find \( p \) in MPa and \( u \) in kJ/kg.

(e) At \( p = 28 \) MPa, \( T = 520°C \), find \( v \) in m³/kg and \( h \) in kJ/kg.

(f) At \( T = 100°C \), \( x = 60% \), find \( p \) in bar and \( v \) in m³/kg.
20 minutes of stirring, the refrigerant is at a pressure of 1.2 MPa. No overall changes in kinetic or potential energy occur. For the Refrigerant 22, determine

(a) the work, in kJ.
(b) the heat transfer, in kJ.
(c) Evaluate the constant K, in kW per minute.

3.58 A closed, rigid tank contains 2 kg of water initially at 80°C and a quality of 0.6. Heat transfer occurs until the tank contains only saturated vapor at a higher pressure. Kinetic and potential energy effects are negligible. For the water as the system, determine the amount of energy transfer by heat, in kJ.

3.59 As shown in Fig. 3.59, a rigid, closed tank having a volume of 20 ft³ and filled with 75 lb of Refrigerant 134a is exposed to the sun. At 9:00 AM, the refrigerant is at a pressure of 100 lb/in². By 3:00 PM, owing to solar radiation, the refrigerant is a saturated vapor at a pressure greater than 100 lb/in². For the refrigerant, determine (a) the initial temperature, in °F, (b) the final pressure, in lbf/in², and (c) the heat transfer, in Btu.

3.60 A rigid, insulated tank fitted with a paddle wheel is filled with water, initially a two-phase liquid–vapor mixture at 20 lbf/in², consisting of 0.07 lb of saturated liquid and 0.07 lb of saturated vapor. The tank contents are stirred by the paddle wheel until all of the water is saturated vapor at a pressure greater than 20 lbf/in². Kinetic and potential energy effects are negligible. For the water, determine the

(a) volume occupied, in ft³.
(b) initial temperature, in °F.
(c) final pressure, in lbf/in².
(d) work, in Btu.

3.61 If the hot plate of Example 3.2 transfers energy at a rate of 0.1 kW to the two-phase mixture, determine the time required, in h, to bring the mixture from (a) state 1 to state 2, (b) state 1 to state 3.

3.62 A rigid tank is filled with 5 lb of water, initially at \( T_1 = 260°F \) and \( v_1 = 7.07 \text{ ft}^3/\text{lb} \). The tank contents are heated until the temperature is \( T_2 = 350°F \). Kinetic and potential energy effects are negligible. For the water, determine (a) the initial and final pressure, each in lbf/in², and (b) the heat transfer, in Btu.

3.63 Saturated water vapor is contained in a closed rigid tank. The water is cooled to a temperature of 110°C. At this temperature the masses of saturated vapor and liquid are each 1000 kg. Determine the heat transfer for the process, in kJ.

3.64 A rigid, well-insulated tank contains a two-phase mixture consisting of 0.005 ft³ of saturated liquid water and 1.2 ft³ of saturated water vapor, initially at 14.7 lbf/in². A paddle wheel stirs the mixture until only saturated vapor at a higher pressure remains in the tank. Kinetic and potential energy effects are negligible. For the water, determine the amount of energy transfer by work, in Btu.

3.65 A two-phase liquid–vapor mixture of H₂O, initially at 1.0 MPa with a quality of 90%, is contained in a rigid, well-insulated tank. The mass of H₂O is 2 kg. An electric resistance heater in the tank transfers energy to the water at a constant rate of 60 W for 1.95 h. Determine the final temperature of the water in the tank, in °C, and the final pressure, in bar.

3.66 Two kilograms of Refrigerant 134a, initially at 2 bar and occupying a volume of 0.12 m³, undergoes a process at constant pressure until the volume has doubled. Kinetic and potential energy effects are negligible. Determine the work and heat transfer for the process, each in kJ.

3.67 Two lb of a two-phase liquid–vapor mixture of H₂O, initially at 100 lbf/in², are confined to one side of a rigid, well-insulated container by a partition. The other side of the container has a volume of 7 ft³ and is initially evacuated. The partition is removed and the water expands to fill the entire container. The pressure at the final equilibrium state is 40 lbf/in². Determine the quality of the mixture present initially and the overall volume of the container, in ft³.

3.68 One kilogram of saturated solid water at the triple point is heated to saturated liquid while the pressure is maintained constant. Determine the work and the heat transfer for the process, each in kJ. Show that the heat transfer equals the change in enthalpy of the water in this case.

3.69 A closed system initially contains a three-phase mixture consisting of 1 lb of saturated solid water (ice), 1 lb of saturated liquid water, and 0.2 lb of saturated water vapor at the triple point temperature and pressure. Heat transfer occurs while the pressure is maintained constant until only saturated vapor remains. Determine the amounts of energy transfer by work and heat, each in Btu.

3.70 A two-phase, liquid–vapor mixture of H₂O, initially at \( x = 30\% \) and a pressure of 100 kPa, is contained in a piston-cylinder assembly, as shown in Fig. P3.70. The mass of the piston is 10 kg, and its diameter is 15 cm. The pressure of the surroundings is 100 kPa. As the water is heated, the pressure inside the cylinder remains constant until the piston hits the stops. Heat transfer to the water continues at constant
volume until the pressure is 150 kPa. Friction between the piston and the cylinder wall and kinetic and potential energy effects are negligible. For the overall process of the water, determine the work and heat transfer, each in kJ.

**Fig. P3.70**

3.71 A piston-cylinder assembly contains 2 lb of water, initially at 300°F. The water undergoes two processes in series: constant-volume heating followed by a constant-pressure process. At the end of the constant-volume process, the pressure is 100 lbf/in.² and the water is a two-phase, liquid-vapor mixture with a quality of 80%. At the end of the constant-pressure process, the temperature is 400°F. Neglect kinetic and potential energy effects.

(a) Sketch T–v and p–v diagrams showing the key states and the processes.
(b) Determine the work and heat transfer for each of the two processes, all in Btu.

3.72 A system consisting of 2 lb of water vapor, initially at 300°F and occupying a volume of 20 ft³, is compressed isothermally to a volume of 9.05 ft³. The system is then heated at constant volume to a final pressure of 120 lbf/in.². During the isothermal compression there is energy transfer by work of magnitude 90.8 Btu into the system. Kinetic and potential energy effects are negligible. Determine the heat transfer, in Btu, for each process.

3.73 Ammonia in a piston-cylinder assembly undergoes two processes in series. At the initial state, \( p_1 = 120 \text{ lbf/in.}^2 \) and the quality is 100%. Process 1–2 occurs at constant volume until the temperature is 100°F. The second process, from state 2 to state 3, occurs at constant temperature, with \( Q_{23} = -98.9 \text{ Btu} \), until the quality is again 100%. Kinetic and potential energy effects are negligible. For 2.2 lb of ammonia, determine (a) the heat transfer for Process 1–2 and (b) the work for Process 2–3, each in Btu.

3.74 Three lb of water is contained in a piston-cylinder assembly, initially occupying a volume \( V_1 = 30 \text{ ft}^3 \) at \( T_1 = 300°F \). The water undergoes two processes in series:

**Process 1–2:** Constant-temperature compression to \( V_2 = 11.19 \text{ ft}^3 \), during which there is an energy transfer by heat from the water of 1275 Btu.

**Process 2–3:** Constant-volume heating to \( p_3 = 120 \text{ lbf/in.}^2 \). Sketch the two processes in series on a T–v diagram. Neglecting kinetic and potential energy effects, determine the work in Process 1–2 and the heat transfer in Process 2–3, each in Btu.

3.75 As shown in Fig. P3.75, a piston-cylinder assembly fitted with stops contains 0.1 kg of water, initially at 1 MPa, 500°C. The water undergoes two processes in series:

**Process 1–2:** Constant-pressure cooling until the piston face rests against the stops. The volume occupied by the water is then one-half its initial volume.

**Process 2–3:** With the piston face resting against the stops, the water cools to 25°C.

Sketch the two processes in series on a p–v diagram. Neglecting kinetic and potential energy effects, evaluate for each process the work and heat transfer, each in kJ.

**Fig. P3.75**

3.76 A system consisting of 2 kg of ammonia undergoes a cycle composed of the following processes:

**Process 1–2:** Constant volume from \( p_1 = 10 \text{ bar}, x_1 = 0.6 \) to saturated vapor.

**Process 2–3:** Constant temperature to \( p_3 = p_1, \ Q_{23} = +228 \text{ kJ} \).

**Process 3–4:** Constant pressure.

Sketch the cycle on p–v and T–v diagrams. Neglecting kinetic and potential energy effects, determine the net work for the cycle and the heat transfer for each process, all in kJ.

3.77 A system consisting of 1 kg of \( \text{H}_2\text{O} \) undergoes a power cycle composed of the following processes:

**Process 1–2:** Constant-pressure heating at 10 bar from saturated vapor.

**Process 2–3:** Constant-volume cooling to \( p_3 = 5 \text{ bar}, \ T_3 = 160°C \).

**Process 3–4:** Isothermal compression with \( Q_{34} = -815.8 \text{ kJ} \).

**Process 4–1:** Constant-volume heating.

Sketch the cycle on T–v and p–v diagrams. Neglecting kinetic and potential energy effects, determine the thermal efficiency.

3.78 A system consisting of 1 lb of Refrigerant 22 undergoes a cycle composed of the following processes:
contents of the tank. The tank and its contents come to equilibrium. What is the final temperature, in °C?

3.88 A 0.2 ft³ aluminum bar, initially at 200°F, is placed in an open tank together with 4 ft³ of liquid water, initially at 70°F. For the water and the bar as the system, determine the final equilibrium temperature, in °F, ignoring heat transfer between the tank and its surroundings.

3.89 A 50-lb iron casting with an initial temperature of 700°F is quenched in a tank filled with oil. The tank is 3 feet in diameter and 5 feet tall. The oil can be considered incompressible with a density of 60 lb/ft³ and an initial temperature of 80°F. The mass of the tank is negligible. If the specific heat of iron is 0.10 Btu/lb °F and that of oil is 0.45 Btu/lb °F, what is the equilibrium temperature of the iron and oil, in °F? Neglect heat transfer between the tank and its surroundings.

3.90 As shown in Fig. P3.90, a closed, insulated tank contains 0.15 kg of liquid water and has a 0.25-kg copper base. The thin walls of the container have negligible mass. Initially, the tank and its contents are all at 30°C. A heating element embedded in the copper base is energized with an electrical current of 10 amps at 12 volts for 100 seconds. Determine the final temperature, in °C, of the tank and its contents. Data for copper and liquid water are provided in Table A.19.

3.97 Five kg of butane (C₄H₁₀) in a piston-cylinder assembly undergo a process from p₁ = 5 MPa, T₁ = 500 K to p₂ = 3 MPa, T₂ = 450 K during which the relationship between pressure and specific volume is pv = constant. Determine the work, in kJ.

3.98 Five lbmol of carbon dioxide (CO₂), initially at 320 lb/lb², 660°F, is compressed at constant pressure in a piston–cylinder assembly. For the gas, W = −2000 Btu. Determine the final temperature, in °R.

3.99 For what ranges of pressure and temperature can air be considered an ideal gas? Explain your reasoning.

Working with the Ideal Gas Model

3.100 A tank contains 0.05 m³ of nitrogen (N₂) at −21°C and 10 MPa. Determine the mass of nitrogen, in kg, using
(a) the ideal gas model.
(b) data from the compressibility chart.
Comment on the applicability of the ideal gas model for nitrogen at this state.

3.101 Determine the percent error in using the ideal gas model to determine the specific volume of
(a) water vapor at 2000 lb/lb², 700°F.
(b) water vapor at 1 lb/lb², 200°F.
(c) ammonia at 60 lb/lb², 160°F.
(d) air at 1 atm, 2000°F.
(e) Refrigerant 22 at 300 lb/lb², 140°F.

3.102 Check the applicability of the ideal gas model
(a) for water at 700°F and pressures of 1600 lb/lb² and 160 lb/lb².
(b) for carbon dioxide at 865 K and pressures of 75 bar and 3 bar.

3.103 Determine the temperature, in K, of oxygen (O₂) at 250 bar and a specific volume of 0.003 m³/kg using generalized compressibility data and compare with the value obtained using the ideal gas model.

3.104 A closed, rigid tank is filled with a gas modeled as an ideal gas, initially at 27°C and a gage pressure of 300 kPa. If the gas is heated to 77°C, determine the final pressure, expressed as a gage pressure, in kPa. The local atmospheric pressure is 1 atm.

3.105 A tank contains 10 lb of air at 70°F with a pressure of 30 lb/lb². Determine the volume of the air, in ft³. Verify that ideal gas behavior can be assumed for air under these conditions.

3.106 Compare the densities, in kg/m³, of helium and argon, each at 300 K, 100 kPa. Assume ideal gas behavior.

3.107 Assuming the ideal gas model, determine the volume, in ft³, occupied by 1 lbmol of argon (Ar) gas at 100 lb/lb² and 550°F.

3.108 Show that the specific heat ratio of a monatomic ideal gas is equal to 5/3.

3.109 A balloon filled with helium, initially at 27°C, 1 bar, is released and rises in the atmosphere until the helium is at 17°C, 0.9 bar. Determine, as a percent, the change in volume of the helium from its initial volume.
3.110 By integrating $\bar{c}_p(T)$ obtained from Table A-21, determine the change in specific enthalpy, in kJ/kg, of methane (CH₄) from $T_1 = 320$ K, $p_1 = 2$ bar to $T_2 = 800$ K, $p_2 = 10$ bar. Check your result using IT.

3.111 Assuming ideal gas behavior for air, plot to scale the isotherms 300, 500, 1000, and 2000 K on a $p$-$v$ diagram.

3.112 Assuming ideal gas behavior for air, plot to scale the isotherms 500, 1000, 2000, and 4000°F on a $p$-$v$ diagram.

Using the Energy Balance with the Ideal Gas Model

3.113 As shown in Fig. P3.113, a piston-cylinder assembly fitted with a paddle wheel contains air, initially at $p_1 = 30$ lbf/in.², $T_1 = 540$°F, and $V_1 = 4$ ft³. The air undergoes a process to a final state where $p_2 = 20$ lbf/in.², $V_2 = 4.5$ ft³. During the process, the paddle wheel transfers work to the air by work in the amount 1 Btu, while the air transfers work by work to the piston in the amount 3.31 Btu. Assuming ideal gas behavior, determine for the air (a) the temperature at state 2, in °R, and (b) the heat transfer, in Btu.

![Fig. P3.113](image)

Initially, $p_1 = 30$ lbf/in.², $T_1 = 540$°F, $V_1 = 4$ ft³.

Finally, $p_2 = 20$ lbf/in.², $V_2 = 4.5$ ft³.

3.114 Ammonia is contained in a rigid, well-insulated container. The initial pressure is 20 lbf/in.², the mass is 0.12 lb, and the volume is 2 ft³. The gas is stirred by a paddle wheel, resulting in an energy transfer to the ammonia of magnitude 20 Btu. Assuming the ideal gas model, determine the final temperature of the ammonia, in °R. Neglect kinetic and potential energy effects.

3.115 One kilogram of nitrogen fills the cylinder of a piston-cylinder assembly, as shown in Fig. P3.115. There is no friction between the piston and the cylinder walls, and the surroundings are at 1 atm. The initial volume and pressure in the cylinder are 1 m³ and 1 atm, respectively. Heat transfer to the nitrogen occurs until the volume is doubled. Determine the heat transfer for the process, in kJ, assuming the specific heat ratio is constant, $k = 1.4$.

![Fig. P3.115](image)

3.116 A piston-cylinder assembly contains air at a pressure of 30 lbf/in.² and a volume of 0.75 ft³. The air is heated at constant pressure until its volume is doubled. Assuming the ideal gas model with constant specific heat ratio, $k = 1.4$, for the air, determine the work and heat transfer, each in Btu.

3.117 As shown in Fig. 3.117, a fan drawing electricity at a rate of 1.5 kW is located within a rigid enclosure, measuring 3 m x 4 m x 5 m. The enclosure is filled with air, initially at 27°C, 0.1 MPa. The fan operates steadily for 30 minutes. Assuming the ideal gas model, determine for the air (a) the mass, in kg, (b) the final temperature, in °C, and (c) the final pressure, in MPa. There is no heat transfer between the enclosure and the surroundings. Ignore the volume occupied by the fan itself and assume the fan stores no energy.

![Fig. P3.117](image)

3.118 A piston-cylinder assembly contains nitrogen (N₂), initially at 20 lbf/in.², 80°F and occupying a volume of 2 ft³. The nitrogen is compressed to a final state where the pressure is 160 lbf/in.² and the temperature is 300°F. During compression, heat transfer of magnitude 1.6 Btu occurs from the nitrogen to its surroundings. Assuming ideal gas behavior, determine for the nitrogen, (a) the mass in lb, and (b) the work, in Btu.

3.119 As shown in Fig. P3.119, a piston-cylinder assembly whose piston is resting on a set of stops contains 0.5 kg of helium gas, initially at 100 kPa and 25°C. The mass of the piston and the effect of the atmospheric pressure acting on the piston are such that a pressure of 500 kPa is required to raise it. How much energy must be transferred by heat to the helium, in kJ, before the piston starts rising? Assume ideal gas behavior for the helium.

![Fig. P3.119](image)

3.120 As shown in Fig. P3.120, a tank fitted with an electrical resistor of negligible mass holds 2 kg of nitrogen (N₂), initially at 27°C, 0.1 MPa. Over a period of 10 minutes, electricity is
the amount of energy transfer by heat, in Btu, and the final pressure, in lb/in.$^2$.

3.126 Two kilograms of a gas with molecular weight 28 are contained in a closed, rigid tank fitted with an electric resistor. The resistor draws a constant current of 10 amps at a voltage of 12 V for 10 minutes. Measurements indicate that when equilibrium is reached, the temperature of the gas has increased by 40.3°C. Heat transfer to the surroundings is estimated to occur at a constant rate of 20 W. Assuming ideal gas behavior, determine an average value of the specific heat $c_p$, in kJ/kg · K, of the gas in this temperature interval based on the measured data.

3.127 As shown in Fig. P3.127, a rigid tank initially contains 3 kg of carbon dioxide (CO$_2$) at 500 kPa. The tank is connected by a valve to a piston-cylinder assembly located vertically above, initially containing 0.05 m$^3$ of CO$_2$. Although the valve is closed, a slow leak allows CO$_2$ to flow into the cylinder from the tank until the tank pressure falls to 200 kPa. The weight of the piston and the pressure of the atmosphere maintain a constant pressure of 200 kPa in the cylinder. Owing to heat transfer, the temperature of the CO$_2$ throughout the tank and cylinder stays constant at 290 K. Assuming ideal gas behavior, determine for the CO$_2$ the work and heat transfer, each in kJ.

3.128 A rigid tank, with a volume of 2 ft$^3$, contains air initially at 20 lb/in.$^2$, 500°F. If the tank receives a heat transfer of magnitude 6 Btu, determine the final temperature, in °R, and the final pressure, in lb/in.$^2$ Assume ideal gas behavior, and use

(a) a constant specific heat value from Table A-20E.
(b) a specific heat function from Table A-21E.
(c) data from Table A-22E.

3.129 Air is compressed adiabatically from $p_1 = 1$ bar, $T_1 = 300$ K to $p_2 = 15$ bar, $V_2 = 0.1227$ m$^3$/kg. The air is then cooled at constant volume to $T_2 = 300$ K. Assuming ideal gas behavior, and ignoring kinetic and potential energy effects, calculate the work for the first process and the heat transfer for the second process, each in kJ per kg of air. Solve the problem each of two ways:

(a) using data from Table A-22.
(b) using a constant specific heat evaluated at 300 K.

3.130 Air is compressed in a piston-cylinder assembly from $p_1 = 10$ lb/in.$^2$, $T_1 = 500°F$ to a final volume of $V_f = 1$ ft$^3$ in a process described by $pv^{1.25} = constant$. The mass of air is 0.5 lb. Assuming ideal gas behavior and neglecting kinetic and potential energy effects, determine the work and the heat transfer, each in Btu, using (a) constant specific heats evaluated at 500°F, and (b) data from Table A-22E. Compare the results and discuss.

3.131 Helium (He) gas initially at 2 bar, 200 K undergoes a polytropic process, with $n = k$, to a final pressure of 14 bar. Determine the work and heat transfer for the process, each in kJ per kg of helium. Assume ideal gas behavior.

3.132 A piston-cylinder assembly contains carbon monoxide modeled as an ideal gas with constant specific heat ratio, $k = 1.4$. The carbon monoxide undergoes a polytropic expansion with $n = k$ from an initial state, where $T_1 = 200°F$ and $p_1 = 40$ lb/in.$^2$, to a final state, where the volume is twice the initial volume. Determine (a) the final temperature, in °F, and final pressure, in lb/in.$^2$, and (b) the work and heat transfer, each in Btu/lb.

3.133 Two-tenths mol of nitrogen (N$_2$) in a piston-cylinder assembly undergoes two processes in series as follows:

**Process 1-2:** Constant pressure at 5 bar from $V_1 = 1.33$ m$^3$ to $V_2 = 1$ m$^3$.

**Process 2-3:** Constant volume to $p_3 = 4$ bar.

Assuming ideal gas behavior and neglecting kinetic and potential energy effects, determine the work and heat transfer for each process, in kJ.

3.134 One kilogram of air in a piston-cylinder assembly undergoes two processes in series from an initial state where $p_1 = 0.5$ MPa, $T_1 = 227°C$.

**Process 1-2:** Constant-temperature expansion until the volume is twice the initial volume.

**Process 2-3:** Constant-volume heating until the pressure is again 0.5 MPa.

Sketch the two processes in series on a $p$-$v$ diagram. Assuming ideal gas behavior, determine (a) the pressure at state 2, in MPa, (b) the temperature at state 3, in °C, and for each of the processes (c) the work and heat transfer, each in kJ.

3.135 A piston-cylinder assembly contains air modeled as an ideal gas with a constant specific heat ratio, $k = 1.4$. The air undergoes a power cycle consisting of four processes in series:

**Process 1-2:** Constant-temperature expansion at 600 K from $p_1 = 0.5$ MPa to $p_2 = 0.4$ MPa.

**Process 2-3:** Polytropic expansion with $n = k$ to $p_3 = 0.3$ MPa.

**Process 3-4:** Constant-pressure compression to $V_4 = V_1$.

**Process 4-1:** Constant-volume heating.

Sketch the cycle on a $p$-$v$ diagram. Determine (a) the work and heat transfer for each process, in kJ/kg, and (d) the thermal efficiency.