2-30 Steam Tables

**Given:** Property table for H₂O

**Find:** Complete the table.

**Solution:**

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>P (kPa)</th>
<th>h (kJ/kg)</th>
<th>x</th>
<th>phase description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) 120.23</td>
<td>200</td>
<td>2046.03</td>
<td>0.7</td>
<td>saturated mixture</td>
</tr>
<tr>
<td>b) 140</td>
<td>361.3</td>
<td>1800</td>
<td>0.564</td>
<td>saturated mixture</td>
</tr>
<tr>
<td>c) 177.69</td>
<td>950</td>
<td>753.02</td>
<td>0.0</td>
<td>saturated liquid</td>
</tr>
<tr>
<td>d) 80</td>
<td>500</td>
<td>334.91</td>
<td>n/a</td>
<td>compressed liquid</td>
</tr>
<tr>
<td>e) 350</td>
<td>800</td>
<td>3161.7</td>
<td>n/a</td>
<td>superheated vapor</td>
</tr>
</tbody>
</table>

a) Since we know that the quality is 0.7, we know that the water is a saturated mixture. We go to Table A-5 and look for 200 kPa (0.2 MPa). We find that the temperature is T<sub>sat</sub> = 120.23 °C. To find h, we read off h<sub>f</sub> = 504.70 kJ/kg and h<sub>fg</sub> = 2201.9 kJ/kg. h = h<sub>f</sub> + x h<sub>fg</sub> = 2046.03 kJ/kg.

b) First, we need to find out what phase this water is in. We go to Table A-4, and see that at 140 °C, the value for h given falls between h<sub>f</sub> and h<sub>g</sub>. Therefore, the water is a saturated mixture. Pressure is P<sub>sat</sub> at 140 °C, or 361.3 kPa. To find the quality, we read off h<sub>f</sub> = 589.13 kJ/kg and h<sub>fg</sub> = 2144.7 kJ/kg. x = (h – h<sub>f</sub>) / h<sub>fg</sub> = 0.564.

c) When quality is given as 0.0, we know that the state is a saturated liquid. Go to Table A-5, and from 950 kPa (0.95 MPa), we read T<sub>sat</sub> = 177.69 °C and h = h<sub>f</sub> = 753.02 kJ/kg.

d) To find the state for this problem, we can either start with Table A-4 or A-5. I will choose A-4, and see that P<sub>sat</sub> for water at 80 °C is 47.39 kPa, which is considerably lower than 500 kPa. Therefore, we know that this water is a compressed liquid. Going to the compressed liquid table (A-7), we find that there is no entry for 500 kPa - that is because at this pressure and temperature, the property of water does not change significantly from properties of water at saturated liquid state. We will go back to Table A-4, and use the values for saturated liquid at 80 °C: h<sub>f</sub> = 334.91 kJ/kg. The quality is non-applicable in this case.

e) Since we are given the pressure, we will start in Table A-5. At 800 kPa, the value for h given is greater than h<sub>f</sub>; therefore, we have a superheated vapor. Turning to Table A-6, at 800 kPa, the value for h given corresponds to 350 °C. Quality is non-applicable.
2-32 Steam Tables

Given: Property table for R-134a

Find: Complete the table.

Solution:

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>P (kPa)</th>
<th>u (kJ/kg)</th>
<th>phase description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) 20</td>
<td>571.6</td>
<td>95</td>
<td>saturated mixture</td>
</tr>
<tr>
<td>b) -12</td>
<td>185.4</td>
<td>34.25</td>
<td>saturated liquid</td>
</tr>
<tr>
<td>c) 86.88</td>
<td>400</td>
<td>300</td>
<td>superheated vapor</td>
</tr>
<tr>
<td>d) 8</td>
<td>600</td>
<td>60.43</td>
<td>compressed liquid</td>
</tr>
</tbody>
</table>

a) First, we will go to Table A-11 to find out what phase we have. At 20 °C, \( u = 95 \text{ kJ/kg} \) falls between \( u_f \) and \( u_g \); therefore, we have a saturated mixture. The pressure is the saturation pressure, 571.6 kPa.

b) Since we know that this is a saturated liquid, we go straight to Table A-11 and look up the saturation pressure at -12 °C, which is 185.4 kPa. The internal energy is equal to \( u_f \) at the same temperature, 34.25 kJ/kg.

c) Because we are given pressure instead of temperature, we go to Table A-12. At 400 kPa, \( u_g = 231.97 \text{ kJ/kg} \), which is less than the value that we are given. Therefore, we have a superheated vapor. Turning to Table A-13, \( u = 300 \text{ kJ/kg} \) falls between 80 °C (\( u = 293.73 \text{ kJ/kg} \)) and 90 °C (\( u = 302.84 \text{ kJ/kg} \)). Interpolating between these values, we find \( T = 86.88 \text{ °C} \).

d) From Table A-11, we see that at 8 °C, the saturation pressure is 387.56 kPa, which is less than the pressure that we are given; therefore, we have a compressed liquid. However, because the pressure is not very high, we can use \( u_f \) at 8 °C to estimate: \( u = 60.43 \text{ kJ/kg} \).

2-52 Steam Tables

Given: A 0.5 m³ vessel containing 10 kg of R-134a at -20 °C

Find: a) pressure, b) total internal energy, and c) volume occupied by the liquid phase.

Solution:

a) From the mass and the volume of the refrigerant, we can find the specific volume:
\[
\nu = \frac{V}{m} = \frac{0.5}{10} = 0.05 \text{ m}^3/\text{kg}.
\]
From Table A-11, at -20 °C, this value for \( \nu \) falls between \( \nu_f \) and \( \nu_g \); therefore, we have a saturated mixture. For -20 °C, \( \nu_f = 0.0007361 \text{ m}^3/\text{kg} \), \( \nu_g = 0.1464 \text{ m}^3/\text{kg} \), \( u_f = 24.17 \text{ kJ/kg} \), and \( u_g = 215.84 \text{ kJ/kg} \). The pressure is \( P_{\text{sat}} \), equal to 132.99 kPa.

b) To find the internal energy, we first need to know the quality of the saturated mixture.
\[
x = \frac{\nu - \nu_f}{\nu_g - \nu_f} = \frac{(0.05 - 0.0007361)/(0.1464 - 0.0007361)}{0.3382}.
\]
The internal energy is:
\[
u = u_f + x(u_g - u_f) = 24.17 + 0.3382(215.84 - 24.17) = 88.99 \text{ kJ/kg}.
\]
The total internal energy of the vessel is:
\[
u = m\nu = 10 \times 88.99 = 889.9 \text{ kJ}.
\]

c) The volume occupied by the liquid phase is (mass of the liquid phase)\( \times \) (specific volume of the liquid phase) = (1 - \( x \))\( m \nu_f = (1 - 0.3382)(10)(0.0007361) = 0.00487 \text{ m}^3.\]
**2-75 Ideal Gases**

**Given:** 1 m³ tank containing air at 25 °C and 500 kPa, connected through a closed valve to another tank with 5 kg of air at 35 °C and 200 kPa. The valve is opened, and the entire system reaches thermal equilibrium with the surroundings, which are at 20 °C.

**Find:** a) volume of the second tank, and b) final pressure of air.

**Solution:**

a) To find the volume of the second tank, we apply the ideal gas equation to the second tank: \( PV = mRT \). From Table A-1, we find \( R \) of air to be 0.2870 kJ/kgK.

\[
V = \frac{mRT}{P} = \frac{5(0.2870)(35+273)}{200} = 2.2099 \text{ m}^3
\]

b) The final pressure of the air can be found by applying the ideal gas equation to the total system. To do this, we first need to find the total mass and volume of the system.

The mass in the first tank is found by: \( m = \frac{PV}{RT} = \frac{500 \times 1}{(0.2870)(298)} = 5.846 \text{ kg} \).

The total mass is 5 + 5.846 = 10.846 kg. The total volume the tanks are 3.2099 m³.

\[
P = \frac{mRT}{V} = \frac{(10.866)(0.2870)(273+20)}{3.2099} = 284.14 \text{ kPa}
\]

**2-121 Steam Tables**

**Given:** A 4-L rigid tank with 2 kg of saturated water mixture at 50 °C. The water is heated slowly until it is in single phase.

**Find:** a) the phase of the water at final state; b) the phase of the water at final state if the volume of the tank were 400 L.

**Solution:**

a) The volume of the tank is 4-L, or 0.004 m³. The specific volume of the contents of the tank is:

\[
v = \frac{V}{m} = \frac{0.004}{2} = 0.002 \text{ m}^3/\text{kg}
\]

We can locate this on Table A-4 at 50 °C to see that we have a saturated mixture.

As this mixture heats up, the specific volume remains constant because the mass and volume of the content does not change. The temperature and pressure of the tank, however, will increase. Staying on Table A-4, we can read down the table from 50 °C to see at what temperature \( v = 0.002 \text{ m}^3/\text{kg} \) equals \( v_L \) or \( v_g \). This happens for the first time at ~365 °C, when \( v = v_L \). This means that the single-phase will be a **saturated liquid**.

b) In the second case, the volume of the tank is now 400-L or 0.4 m³, and the specific volume of the water in the tank is 0.2 m³/kg. Repeating the same process, we find that this becomes single-phase at ~178 °C as **saturated vapor**.
2-125 Ideal Gases

Given: A 20 m³ tank containing nitrogen at 25 °C and 800 kPa. Some nitrogen escapes until the pressure drops to 600 kPa. The temperature at this point is 20 °C.

Find: the amount of nitrogen that has escaped.

Solution:
Since nitrogen is an ideal gas, we go to Table A-1 to find the ideal gas constant: R = 0.2968 kJ/kgK.

According to the ideal gas equation, \( PV = mRT \). We will solve for the mass at state 1:

\[ m_1 = \frac{P_1 V_1}{RT_1} = \frac{800 \times 20}{0.2968 \times 298K} = 180.90 \text{ kg.} \] (make sure \( T \) is in Kelvins)

At state 2, \( V_2 = V_1 \), and the new mass is:

\[ m_2 = \frac{P_2 V_2}{RT_2} = \frac{600 \times 20}{0.2968 \times 293K} = 137.99 \text{ kg.} \]

The change in mass is the amount that has escaped: \( m_1 - m_2 = 180.90 - 137.99 = 42.9 \text{ kg.} \)

3-18 Work: PV = constant

Given: 2.4 kg of air at 150 kPa and 12 °C in a frictionless piston-cylinder device. The air is compressed until pressure reaches 600 kPa, while the temperature remains constant.

Find: Work input during the process.

Solution:
The ideal gas constant for air is 0.2870 kJ/kgK (from Table A-1).

In an ideal gas undergoing isothermal process, \( PV \) remains constant. The work for \( PV=\text{constant} \) case is:

\[ W_2 = mP_1 V_1 \ln\left(\frac{V_2}{V_1}\right) \]

Rewriting this expression for ideal gas, we get:

\[ W_2 = mRT \ln\left(\frac{P_1}{P_2}\right) = (2.4)(0.2870)(285)\ln(150/600) = -272.14 \]

The negative sign means that the system had work done on it; the work input is \( 272.14 \text{ kJ} \).

3-24 Work: \( PV^n = \text{constant} \)

Given: Frictionless piston-cylinder device with 2 kg of nirogen at 100 kPa and 300 K. Nitrogen is compressed slowly according to the relation \( PV^{1.4} = \text{constant} \) until it reaches 360 K.

Find: Work input during the process.

Solution:
The ideal gas constant for nitrogen is 0.2968 kJ/kgK (from Table A-1).

For \( PV^n = \text{ct} \) process with an ideal gas, the work is calculated by:

\[ W_2 = mR(T_2 - T_1)/(1 - n) = (2)(0.2968)(360 - 300)/(1 - 1.4) = -89.04 \]

The negative sign means that the system had work done on it; the work input is \( 89.04 \text{ kJ} \).
3-29 Work: Spring

**Given:** A piston-cylinder device with 50 kg of water at 150 kPa and 25 °C. The cross-sectional area of the piston is 0.1 m$^2$. Heat is transferred to the water, causing it to expand. When the volume reaches 0.2 m$^3$, the piston reaches a linear spring with a spring constant of 100 kN/m. Heat is added to the water until piston rises 20 cm more.

**Find:** a) final pressure and temperature, and b) work done during the process. c) Show the process on a P-V diagram.

**Solution:**

a) First, we must notice that this is a two-step process with three states: state 1 is the initial state; state 2 is when the piston just hits the spring; state 3 is the final state. Process 1→2 is an constant pressure process.

The final pressure at state 3 can be found from the spring constant:

\[ P_3 = P_2 + \frac{F_{\text{spring}}}{A_{\text{piston}}} = 150 \text{ kPa} + \frac{100 \text{ kN/m} \times 0.2 \text{ m}}{0.1 \text{ m}^2} = 150 + 200 = 350 \text{ kPa}. \]

The final volume is $V_2$ plus the volume that is equivalent to 20 cm height in the piston:

\[ V_3 = V_2 + (20 \text{ cm} \times 0.1 \text{ m}^2) = 0.2 \text{ m}^3 + 0.02 \text{ m}^3 = 0.22 \text{ m}^3. \]

The specific volume of the water at this point is:

\[ v_3 = \frac{V_3}{m} = \frac{0.22}{50} = 0.0044 \text{ m}^3/\text{kg}. \]

Going to Table A-6, we see that at 350 kPa, this falls $v_f$ and $v_g$; therefore, we have a saturated mixture. $T_3$ is the saturation temperature at $P_3$, equal to 138.88 °C.

b) We will find work in two steps. First, work from state 1 to 2 can be found using the constant pressure case:

\[ W_{21} = P_1(V_2 - V_1). \]

Initially, the water is at 150 kPa and 25 °C, which is a compressed liquid with specific volume approximately equal to $v_2$ at 25 °C: $v_2 = 0.001003 \text{ m}^3/\text{kg}$. The volume of the water is:

\[ V_1 = mv_1 = 50 \times 0.001003 = 0.05015 \text{ m}^3. \]

\[ W_{21} = P_1(V_2 - V_1) = 150(0.2 - 0.05015) = 22.4775 \text{ kJ}. \]

The work from state 2 to 3 is found by the following expression:

\[ W_{32} = P_2(V_3 - V_2) + \frac{1}{2}(P_3 - P_2)(V_3 - V_2) = 150(0.22 - 0.2) + \frac{1}{2}(350 - 150)(0.22 - 0.2) = 5 \text{ kJ}. \]

The total work done is:

\[ W = W_{21} + W_{32} = 22.4775 + 5 = 27.48 \text{ kJ}. \]

c) The P-V diagram is shown on the right (not to scale). Some points to notice are:

- Process 1→2 is constant pressure: $P_2 = P_1$
- State 1 is compressed liquid
- State 3 is saturated mixture.
- Pressure rises linearly between states 2 and 3.
- Work is given by the area under line 1-2-3.
3-88 Work: Constant P

Given: 5 kg of saturated liquid-vapor mixture in a piston-cylinder device at 100 kPa. Initially, 2 kg of the mixture is in liquid phase. Heat is transferred to the water until the piston, which is initially resting on a set of stops, begins to move at 200 kPa. Heat transfer continues until the total volume increases by 20 percent.

Find: a) initial and final temperatures, b) mass of the liquid phase when the piston first begins to move, and c) work done during the process. d) Show the process on a P-v diagram.

Solution:

First, we must understand what is going on in this two-step process. There are three states, illustrated to the right. Process 1→2 is a constant volume process; Process 2→3 is a constant pressure process.

a) At state 1, we have 2 kg of the total 5 kg water in liquid phase. We therefore have a saturated mixture, with \( x = \frac{3}{5} = 0.6 \).

The temperature at state 1 is the saturation temperature at 100 kPa, equal to 99.63 °C.

The volume at state 1 can be found from specific volume: \( \nu = \nu_f + x(\nu_g - \nu_f) \). At 100 kPa, \( \nu_f = 0.001043 \text{ m}^3/\text{kg} \) and \( \nu_g = 1.6940 \text{ m}^3/\text{kg} \), so:

\[
\nu_1 = 0.001043 + 0.6(1.6940 - 0.001043) = 1.0168 \text{ m}^3/\text{kg}.
\]

At state 2, we are given the pressure of 200 kPa. We also know that the volume and specific volume are same as in state 1.

At state 3, pressure is the same as in state 2, so \( P_3 = 200 \text{ kPa} \). The volume is 20 percent greater than \( V_2 \) (which is equal to \( V_1 \)), so \( V_3 = 1.2V_1 = 6.101 \text{ m}^3 \). Similarly, \( \nu_3 = 1.2\nu_1 = 1.2202 \text{ m}^3/\text{kg} \). At 200 kPa, this is greater than \( \nu_g \), so we have a superheated vapor.

Turning to Table A-6, we find that \( \nu_3 \) falls somewhere between 250 °C (\( \nu = 1.1988 \text{ m}^3/\text{kg} \)) and 300 °C (\( \nu = 1.3162 \text{ m}^3/\text{kg} \)). We interpolate between these values to find \( T_3 \):

\[
T_3 = (v_3 - v_{250})\times(300 - 250)/(v_{300} - v_{250}) + 250 = (1.2202 - 1.1988)(50)/(1.3162 - 1.1988) + 250 = 259.1 \text{ °C}.
\]

b) When the piston begins to move (state 2), the pressure is 200 kPa and the specific volume is the same as in state 1 (1.0168 m³/kg).

From Table A-5, we see that \( v_2 \) is greater than \( v_g \) at 200 kPa; therefore we have a superheated vapor. The mass of the liquid phase is zero (there is no liquid in the cylinder).

c) The work done during the process can be found by breaking the process down into two steps. Process 1→2 has no work because there is no change in volume. Process 2→3 is treated as a constant pressure case.

\[
W_3 = P_2(V_3 - V_2) = 200(6.101 - 5.084) = 203.4 \text{ kJ}.
\]

d) The P-v diagram is shown on the right.

- 1→2 is a vertical line; 2→3 is a horizontal line.
- state 1 is saturated mixture; states 2 & 3 are superheated vapor.