CARNOT CYCLE: CALCULATION EXAMPLE

A mass \( m = 1 \text{ kg} \) of water executes a Carnot cycle. The high temperature isothermal expansion is from \( P_1 = 15 \text{ bar} \) to \( x_2 = 0.25 \) to the saturated vapor state. The adiabatic expansion is to \( P_4 = 1 \text{ bar} \).

Calculate the properties of the working fluid at each state and calculate the thermal efficiency of the cycle.

**Diagram representations**

![Pressure-Volume and Temperature-Entropy Diagrams]

**State 2 characterization**

Given:

- Temperature determination:

  **Saturated water—Temperature table**

<table>
<thead>
<tr>
<th>Temp., press., T °C</th>
<th>Sat. liquid, ( v_l )</th>
<th>Sat. vapor, ( v_g )</th>
<th>Sat. liquid, ( u_l )</th>
<th>Sat. vapor, ( u_g )</th>
<th>Sat. liquid, ( h_l )</th>
<th>Sat. vapor, ( h_g )</th>
<th>Sat. liquid, ( s_l )</th>
<th>Sat. vapor, ( s_g )</th>
</tr>
</thead>
<tbody>
<tr>
<td>175</td>
<td>0.001121</td>
<td>0.21659</td>
<td>740.02</td>
<td>1839.4</td>
<td>2579.4</td>
<td>2579.4</td>
<td>2.0906</td>
<td>6.6242</td>
</tr>
<tr>
<td>180</td>
<td>0.001127</td>
<td>0.19384</td>
<td>761.92</td>
<td>1820.9</td>
<td>2582.8</td>
<td>2582.8</td>
<td>2.1392</td>
<td>6.5841</td>
</tr>
<tr>
<td>185</td>
<td>0.001134</td>
<td>0.17390</td>
<td>783.91</td>
<td>1802.1</td>
<td>2586.0</td>
<td>2586.0</td>
<td>2.1875</td>
<td>6.5447</td>
</tr>
<tr>
<td>190</td>
<td>0.001141</td>
<td>0.15636</td>
<td>806.00</td>
<td>1783.0</td>
<td>2589.0</td>
<td>2589.0</td>
<td>2.2355</td>
<td>6.5059</td>
</tr>
<tr>
<td>195</td>
<td>0.001149</td>
<td>0.14089</td>
<td>828.18</td>
<td>1763.6</td>
<td>2591.7</td>
<td>2591.7</td>
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<td>6.4678</td>
</tr>
<tr>
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<td>0.12721</td>
<td>850.46</td>
<td>1743.7</td>
<td>2594.2</td>
<td>2594.2</td>
<td>2.3305</td>
<td>6.4302</td>
</tr>
</tbody>
</table>

  **Interpolation procedure:**

  \[ \Rightarrow \]
• Specific internal energy, volume and entropy calculations:

\[ u_2 = \quad \quad u_2 = \quad \quad s_2 = \]

where:

Numerical applications:

\[ \underbrace{u_2 =}_{u_2 = \quad \quad u_2 = \quad \quad s_2 =} \]

State 3 characterization

Given:

• Specific internal energy, volume and entropy calculations:

Superheated water (Continued)

<table>
<thead>
<tr>
<th>°C</th>
<th>v</th>
<th>u</th>
<th>h</th>
<th>s</th>
<th>( P = 1.00 \text{ MPa} ) (179.88°C)</th>
<th>v</th>
<th>u</th>
<th>h</th>
<th>s</th>
<th>( P = 1.40 \text{ MPa} ) (195.04°C)</th>
<th>v</th>
<th>u</th>
<th>h</th>
<th>s</th>
<th>( P = 1.60 \text{ MPa} ) (201.37°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>0.3222</td>
<td>332.0</td>
<td>210.0</td>
<td>1.064</td>
<td>2.393</td>
<td>312.5</td>
<td>210.0</td>
<td>1.064</td>
<td>2.393</td>
<td>312.5</td>
<td>210.0</td>
<td>1.064</td>
<td>2.393</td>
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<td></td>
</tr>
<tr>
<td>120</td>
<td>0.3707</td>
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<td>235.2</td>
<td>1.082</td>
<td>2.406</td>
<td>359.7</td>
<td>235.2</td>
<td>1.082</td>
<td>2.406</td>
<td>359.7</td>
<td>235.2</td>
<td>1.082</td>
<td>2.406</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>0.4387</td>
<td>387.3</td>
<td>260.4</td>
<td>1.099</td>
<td>2.419</td>
<td>387.3</td>
<td>260.4</td>
<td>1.099</td>
<td>2.419</td>
<td>387.3</td>
<td>260.4</td>
<td>1.099</td>
<td>2.419</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.5276</td>
<td>415.0</td>
<td>285.6</td>
<td>1.115</td>
<td>2.432</td>
<td>415.0</td>
<td>285.6</td>
<td>1.115</td>
<td>2.432</td>
<td>415.0</td>
<td>285.6</td>
<td>1.115</td>
<td>2.432</td>
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<td>0.6374</td>
<td>442.6</td>
<td>310.8</td>
<td>1.131</td>
<td>2.445</td>
<td>442.6</td>
<td>310.8</td>
<td>1.131</td>
<td>2.445</td>
<td>442.6</td>
<td>310.8</td>
<td>1.131</td>
<td>2.445</td>
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</tr>
<tr>
<td>-40</td>
<td>0.7680</td>
<td>470.2</td>
<td>336.0</td>
<td>1.146</td>
<td>2.458</td>
<td>470.2</td>
<td>336.0</td>
<td>1.146</td>
<td>2.458</td>
<td>470.2</td>
<td>336.0</td>
<td>1.146</td>
<td>2.458</td>
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<tr>
<td>-80</td>
<td>0.9199</td>
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<td>361.2</td>
<td>1.161</td>
<td>2.471</td>
<td>497.8</td>
<td>361.2</td>
<td>1.161</td>
<td>2.471</td>
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<td>361.2</td>
<td>1.161</td>
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<tr>
<td>-120</td>
<td>1.093</td>
<td>525.4</td>
<td>386.4</td>
<td>1.175</td>
<td>2.484</td>
<td>525.4</td>
<td>386.4</td>
<td>1.175</td>
<td>2.484</td>
<td>525.4</td>
<td>386.4</td>
<td>1.175</td>
<td>2.484</td>
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<td></td>
</tr>
</tbody>
</table>

Interpolation procedure:

Numerical applications:

\[ \underbrace{u_3 =}_{u_3 = \quad \quad u_3 = \quad \quad s_3 =} \]
State 4 characterization

Given:

- Temperature determination:

  **Saturated water—Temperature table**

<table>
<thead>
<tr>
<th>Temp. T °C</th>
<th>Sat. press. P sat kPa</th>
<th>Sat. liquid, specific internal energy u_f, kJ/kg</th>
<th>Sat. vapor, specific internal energy u_v, kJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>38.597</td>
<td>0.001026</td>
<td>4.1291</td>
</tr>
<tr>
<td>80</td>
<td>47.416</td>
<td>0.001029</td>
<td>3.4053</td>
</tr>
<tr>
<td>85</td>
<td>57.868</td>
<td>0.001032</td>
<td>2.8261</td>
</tr>
<tr>
<td>90</td>
<td>70.183</td>
<td>0.001036</td>
<td>2.3593</td>
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<tr>
<td>95</td>
<td>84.609</td>
<td>0.001040</td>
<td>1.9808</td>
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<tr>
<td>100</td>
<td>101.42</td>
<td>0.001043</td>
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<td>105</td>
<td>120.90</td>
<td>0.001047</td>
<td>1.4186</td>
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<tr>
<td>110</td>
<td>143.38</td>
<td>0.001052</td>
<td>1.2094</td>
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<tr>
<td>115</td>
<td>169.18</td>
<td>0.001056</td>
<td>1.0350</td>
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<tr>
<td>120</td>
<td>198.67</td>
<td>0.001060</td>
<td>0.89133</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sat. liquid, volume v_f, m^3/kg</th>
<th>Sat. vapor, volume v_v, m^3/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>313.99</td>
<td>2161.3</td>
</tr>
<tr>
<td>334.97</td>
<td>2146.6</td>
</tr>
<tr>
<td>355.96</td>
<td>2131.9</td>
</tr>
<tr>
<td>376.97</td>
<td>2117.0</td>
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<tr>
<td>398.00</td>
<td>2102.0</td>
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<td>419.06</td>
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<td>2071.8</td>
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<td>461.27</td>
<td>2056.4</td>
</tr>
<tr>
<td>482.42</td>
<td>2040.9</td>
</tr>
<tr>
<td>503.60</td>
<td>2025.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sat. liquid, entropy s_f, kJ/kg·K</th>
<th>Sat. vapor, entropy s_v, kJ/kg·K</th>
</tr>
</thead>
<tbody>
<tr>
<td>314.03</td>
<td>2320.6</td>
</tr>
<tr>
<td>335.02</td>
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<tr>
<td>356.02</td>
<td>2295.3</td>
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<td>377.04</td>
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<td>398.09</td>
<td>2269.6</td>
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<td>419.17</td>
<td>2256.4</td>
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<td>2243.1</td>
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<td>461.42</td>
<td>2229.7</td>
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<tr>
<td>482.59</td>
<td>2216.0</td>
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<tr>
<td>503.81</td>
<td>2202.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sat. liquid, quality x_f</th>
<th>Sat. vapor, quality x_v</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0158</td>
<td>6.6655</td>
</tr>
<tr>
<td>1.0756</td>
<td>6.5355</td>
</tr>
<tr>
<td>1.1346</td>
<td>6.4089</td>
</tr>
<tr>
<td>1.1929</td>
<td>6.2853</td>
</tr>
<tr>
<td>1.2504</td>
<td>6.1647</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sat. liquid, quality x_f</th>
<th>Sat. vapor, quality x_v</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1072</td>
<td>1.3072</td>
</tr>
<tr>
<td>1.3634</td>
<td>5.9319</td>
</tr>
<tr>
<td>1.4188</td>
<td>5.8193</td>
</tr>
<tr>
<td>1.4737</td>
<td>5.7092</td>
</tr>
<tr>
<td>1.5279</td>
<td>5.6013</td>
</tr>
</tbody>
</table>

Interpolation procedure:

- Saturated liquid/saturated vapor specific internal energy, volume and entropy (interpolation):

Numerical applications:

- Quality calculation:
• Specific internal energy and specific volume calculations:

Numerical applications: 
\[ v_1 = \quad u_1 = \]

**State 1 characterization**

Given: 

\[ \Rightarrow \quad \text{Numerical application:} \quad x_1 = \]

• Quality calculation:

\[ \Rightarrow \quad \text{Numerical application:} \quad x_1 = \]

• Specific internal energy and specific volume calculations:

Numerical applications: 
\[ v_1 = \quad u_1 = \]

**Thermal efficiency**

• Thermal efficiency definition:

• 1→2 Energy conservation

\[ 1^{\text{st law:}} \Rightarrow \]

Numerical application:
• 2→3 Energy conservation

1\textsuperscript{st} law: 

Numerical application:

• 3→4 Energy conservation

1\textsuperscript{st} law: 

Numerical application:

• 4→1 Energy conservation

1\textsuperscript{st} law: 

Numerical application:

• Net work: 

• Net heat transfer: 

• Thermal efficiency: 

• Carnot theory prediction: