Given $T$ and $P$

Super Heat Region if,
- $P < P_{\text{sat}}$
- $T > T_{\text{sat}}$

Compressed Liquid Region if,
- $P > P_{\text{sat}}$
- $T < T_{\text{sat}}$
T-s diagram for water. [Source: Joseph H. Keenan, Frederick G. Keyes, Philip G. Hill, and Joan G. Moore, *Steam Tables* (New York: John Wiley & Sons, 1969).]
STEAM PRESSURE AND TEMPERATURE TABLES

### TABLE A-5

**Saturated water—Pressure table**

<table>
<thead>
<tr>
<th>$P$ (kPa)</th>
<th>$T_{sat}$ (°C)</th>
<th>$v_r$</th>
<th>$v_g$</th>
<th>$u_r$</th>
<th>$u_g$</th>
<th>$h_r$</th>
<th>$h_g$</th>
<th>$s_r$</th>
<th>$s_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6113</td>
<td>0.01</td>
<td>0.001000</td>
<td>206.14</td>
<td>0.00</td>
<td>2375.3</td>
<td>2375.3</td>
<td>0.01</td>
<td>2501.3</td>
<td>2501.4</td>
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<tr>
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<td>6.98</td>
<td>0.001000</td>
<td>129.21</td>
<td>29.30</td>
<td>2365.7</td>
<td>2385.0</td>
<td>29.30</td>
<td>2484.9</td>
<td>2514.2</td>
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<tr>
<td>1.5</td>
<td>13.03</td>
<td>0.001001</td>
<td>87.98</td>
<td>54.71</td>
<td>2338.6</td>
<td>2393.3</td>
<td>54.71</td>
<td>2470.6</td>
<td>2525.3</td>
</tr>
<tr>
<td>2.0</td>
<td>17.50</td>
<td>0.001001</td>
<td>67.00</td>
<td>73.48</td>
<td>2326.0</td>
<td>2399.5</td>
<td>73.48</td>
<td>2460.0</td>
<td>2533.5</td>
</tr>
<tr>
<td>2.5</td>
<td>21.08</td>
<td>0.001002</td>
<td>54.25</td>
<td>88.48</td>
<td>2315.9</td>
<td>2404.4</td>
<td>88.48</td>
<td>2451.6</td>
<td>2540.0</td>
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<tr>
<td>3.0</td>
<td>24.08</td>
<td>0.001003</td>
<td>45.67</td>
<td>101.04</td>
<td>2307.5</td>
<td>2408.5</td>
<td>101.04</td>
<td>2444.5</td>
<td>2545.5</td>
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<tr>
<td>4.0</td>
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<td>0.001004</td>
<td>34.80</td>
<td>121.45</td>
<td>2293.7</td>
<td>2415.2</td>
<td>121.45</td>
<td>2432.9</td>
<td>2554.4</td>
</tr>
</tbody>
</table>

### TABLE A-4

**Saturated water—Temperature table**

<table>
<thead>
<tr>
<th>Temp. ($^\circ$C)</th>
<th>$P_{sat}$ (kPa)</th>
<th>$T_{sat}$</th>
<th>$v_r$</th>
<th>$v_g$</th>
<th>$u_r$</th>
<th>$u_g$</th>
<th>$h_r$</th>
<th>$h_g$</th>
<th>$s_r$</th>
<th>$s_g$</th>
</tr>
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<tbody>
<tr>
<td>0.01</td>
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<td>0.00</td>
<td>2375.3</td>
<td>2375.3</td>
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<td>2501.4</td>
<td>0.0000</td>
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<tr>
<td>5</td>
<td>0.8721</td>
<td>0.001000</td>
<td>147.12</td>
<td>0.97</td>
<td>2307.3</td>
<td>2315.9</td>
<td>0.97</td>
<td>2458.6</td>
<td>2484.9</td>
<td>0.1059</td>
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<td>4.00</td>
<td>2347.2</td>
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<td>4.00</td>
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<tr>
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<td>62.99</td>
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<td>2396.1</td>
<td>62.99</td>
<td>2465.9</td>
<td>2528.9</td>
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<td>57.79</td>
<td>83.95</td>
<td>2319.0</td>
<td>2402.9</td>
<td>83.95</td>
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<td>2538.1</td>
<td>0.3120</td>
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<tr>
<td>25</td>
<td>3.169</td>
<td>0.001003</td>
<td>43.36</td>
<td>104.88</td>
<td>2304.9</td>
<td>2409.8</td>
<td>104.88</td>
<td>2442.3</td>
<td>2547.2</td>
<td>0.3545</td>
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<tr>
<td>30</td>
<td>4.246</td>
<td>0.001004</td>
<td>32.89</td>
<td>125.78</td>
<td>2290.8</td>
<td>2416.6</td>
<td>125.78</td>
<td>2430.5</td>
<td>2556.3</td>
<td>0.4226</td>
</tr>
</tbody>
</table>

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832 THERMODYNAMICS

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830 THERMODYNAMICS
Three Tables
- Temperature Table at spaced T’s
- Pressure Table at spaced P’s
- Superheat Table at spaced T and P

6 Properties
- Temperature
- Pressure
- Volume
- Internal Energy
- Enthalpy
- Entropy

T-s diagram for water. [Source: Joseph H. Keenan, Frederick G. Keyes, Philip G. Hill, and Joan G. Moore, Steam Tables (New York: John Wiley & Sons, 1969).]
Solid-Liquid-Gas Phase Diagram
Saturation liquid internal energy at 0 C       0. Table Base
Saturated liquid enthalpy at 25 C                 104.89 kJ/kg
Saturated vapor entropy at 25 C                   8.558 kJ/kg K

Enthalpy at 20 C, 300 kPa

assume saturated liquid enthalpy at 20 C         83.96 kJ/kg

Temperature of saturated vapor with an internal energy of 2396.1 kJ/kg

Enthalpy of vaporization at 10 C                 2477.7 kJ/kg
Table A-4 Metric T,p
Table A-5 Metric T
Table A-6 Metric T,p
Table A-6E English T,p
Table A-7 Metric T,p
Table A-7E English T,p

Pressures at various temperatures are listed in Table A-4, Table A-5, Table A-6, and Table A-7, which cover the temperature and pressure ranges for compressed liquid, saturated liquid-vapor, and superheated vapor regions. The critical point is marked, and the lines indicate the transitions between phases. The diagram illustrates the thermodynamic properties of a substance, with the x-axis representing pressure (p) and the y-axis representing temperature (T).
Two Phase Real Gas Properties

\[ V = V_f + V_g \]
\[ m_v = m_f v_f + m_g v_g \]
\[ x = \frac{m_g}{m} \text{ Quality} \]
\[ v = (1 - x) v_f + x v_g \]
\[ v = v_f + x \times v_{fg} \]
\[ x = \frac{v - v_f}{v_{fg}} \]
\[ h = h_f + x \times h_{fg} \]
\[ u = u_f + x \times u_{fg} \]
\[ v = v_f + x \times v_{fg} \]
Quality, \( x = \frac{v - v_f}{v_g - v_f} \)

\[
x = \frac{300 - 0.0161}{467.7 - 0.0161} = 0.64 \ (64\%)
\]

\( u = u_f + x \times (u_f - u_g) \)

\( u = u_f + x \times u_{fg} \)

\( u = 58.07 + 0.64 \times 982.2 \)

\( u = 686.7 \ BTU/lb \)

\( h = h_f + x \times h_{fg} \)

\( h = 58.07 + 0.64 \times 1042.7 \)

\( h = 725.4 \ BTU/lb \)

\( s = s_f + x \times s_{fg} \)

\( s = 0.1296 + 0.64 \times 1.8526 \)

\( s = 1.315 \ BTU/lb^\circ R \)

Find the properties of water at 90\( ^\circ \)F, \( v = 300 \ ft^3/lb \).

\[ \begin{align*}
\text{Temperature} \\
\text{Table A-4E} \\
\text{page 880}
\end{align*} \]
10 MPa saturated steam has an enthalpy of 2010 kJ/kg. What is its internal energy?

\[ h = h_f + x \ h_{fg} \]

2010 kJ/kg = 1407.56 + x 1317.1

\[ x = .4574 \]

\[ u = u_f + x \ u_{fg} \]

\[ u = 1393.04 + .4574 \times 1151.4 \]

\[ u = 1919.69 \text{ kJ/kg} \]

**EES Program**

\[ x = \text{quality(steam, P = 10000., h = 2010)} \]

\[ x = .4576 \]

\[ u = \text{intenergy(steam, P = 10000., h = 2010)} \]

\[ h = 1919.65 \text{ kJ/kg} \]
Steam at 20 C has an enthalpy of 1800 kJ/kg. What is the internal energy?

\[ h = h_f + x \ h_{fg} \]

\[ 1800 \text{ kJ/kg} = 83.96 + x \times 2454.1 \]

\[ x = 0.7 \]

\[ u = u_f + x \ u_{fg} \]

\[ u = 83.95 + 0.7 \times 2319.0 \]

\[ u = 1707.25 \text{ kJ/kg} \]
# STEAM SUPERHEAT TABLE

## TABLE A–6

### Superheated water

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>v (m³/kg)</th>
<th>u (kJ/kg)</th>
<th>h (kJ/kg)</th>
<th>s (kJ/kg·K)</th>
<th>v (m³/kg)</th>
<th>u (kJ/kg)</th>
<th>h (kJ/kg)</th>
<th>s (kJ/kg·K)</th>
<th>v (m³/kg)</th>
<th>u (kJ/kg)</th>
<th>h (kJ/kg)</th>
<th>s (kJ/kg·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sat.¹</td>
<td>14.674</td>
<td>2437.9</td>
<td>2584.7</td>
<td>8.1502</td>
<td>3.240</td>
<td>2483.9</td>
<td>2645.9</td>
<td>7.5939</td>
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<td>3.418</td>
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<td>2682.5</td>
<td>7.6947</td>
<td>1.6958</td>
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<td>2676.2</td>
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<td>3.889</td>
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<td>2780.1</td>
<td>7.9401</td>
<td>1.9364</td>
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<td>2776.4</td>
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<td>2879.5</td>
<td>8.9038</td>
<td>4.820</td>
<td>2735.0</td>
<td>2976.0</td>
<td>8.3556</td>
<td>2.406</td>
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<td>8.0333</td>
</tr>
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<td>250</td>
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<td>2977.3</td>
<td>9.1002</td>
<td>5.284</td>
<td>2811.3</td>
<td>3075.5</td>
<td>8.5373</td>
<td>2.639</td>
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<td>3076.5</td>
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<td>6.209</td>
<td>2968.5</td>
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<td>3279.6</td>
<td>9.6077</td>
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<td>10.8396</td>
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<td>4640.5</td>
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<td>4891.1</td>
<td>10.4859</td>
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<td>4891.2</td>
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<td>13.597</td>
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<td>10.6662</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

* *P = 0.01 MPa (45.81°C)*

* *P = 0.05 MPa (81.33°C)*

* *P = 0.10 MPa (99.63°C)*
Enthalpy at 700 C and .10 Mpa  
3928.2 kJ/kg

Temperature at entropy of 8.8642 and .05 Mpa  
400 C

Enthalpy at .05 MPa and entropy of 10.6662 kJ/kg·C  
5147.7 kJ/kg
Steam initially at a temperature of 1100°C and a pressure of .10 MPa undergoes a process during which its entropy remains constant to a pressure of .01 MPa. What is the enthalpy and temperature of the steam at the end of the process?

Entropy at 1100°C, .1 MPa: 10.1659 kJ/kg K
Enthalpy at .01 MPa, entropy 10.1659: 3705.4 kJ/kg
Temperature at .01 MPa, entropy 10.1659: 600°C
Engineering Equation Solver - EES
Fluid Property Information - 69 fluids available
Thermophysical Functions - 25 properties calculated

Equations Window

\[ h = \text{enthalpy}(\text{steam}, T=200., P=200) \]  superheated vapor
\[ h = \text{enthalpy}(\text{steam}, T=200., X=1) \]  saturated vapor
\[ u = \text{intenergy}(\text{steam}, T=200., X=0.) \]  saturated liquid
\[ p = \text{pressure}(\text{steam}, T=200., X=0.) \]  saturation pressure

Thermophysical Functions
- entropy
- intenergy
- pressure
- quality
- density
- enthalpy
- isidealgas
- temperature
- volume

Function Arguments
- H specific enthalpy
- P pressure
- S specific entropy
- T temperature
- U specific internal energy
- V specific volume
- X quality
## Fluid Property Information

EES provided built-in property data for the fluids listed below. Click on a fluid name to access additional information for that fluid. All names in EES are case-insensitive. Additional fluid property data can be added by the user.

<table>
<thead>
<tr>
<th>Ideal Gas</th>
<th>Real Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>Oxygen*</td>
</tr>
<tr>
<td>AirH2O</td>
<td>n-Butane*</td>
</tr>
<tr>
<td>CH4</td>
<td>n-HEXANE*</td>
</tr>
<tr>
<td>C2H2</td>
<td>n-Pentane*</td>
</tr>
<tr>
<td>C2H4</td>
<td>Neon*</td>
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<tr>
<td>C2H6</td>
<td>Nitrogen*</td>
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<tr>
<td>C3H8</td>
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</tr>
<tr>
<td>C4H10</td>
<td>R22 ha*</td>
</tr>
<tr>
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<td>R11</td>
</tr>
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<td>R13</td>
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<tr>
<td>N2</td>
<td>R14</td>
</tr>
<tr>
<td>NO</td>
<td>R22</td>
</tr>
<tr>
<td>NO2</td>
<td>R500</td>
</tr>
<tr>
<td>O2</td>
<td>R502</td>
</tr>
<tr>
<td>SO2</td>
<td>R507C</td>
</tr>
</tbody>
</table>

### Thermophysical Functions

The built-in thermophysical property functions are listed below in alphabetical order:

- CONDUCTIVITY
- CV
- DEWPOINT
- DENSITY
- ENTHALPY
- ENTROPY
- HUMRAT
- INTENERGY
- ISIDEALGAS
- MOLARMASS
- PRANDTL
- PRESSURE
- P CRIT
- QUALITY
- RELHUM
- SOUNDSPEED
- SPECHEAT
- SURFACETENSION
- TEMPERATURE
- T CRIT
- V CRIT
- WETBULB
- VOLUME
- VISCOITY
### Table

#### Pressure Table

- **Saturation internal energy at 4 kPa**
  - \( u_1 = 121.45 \text{kJ/kg} \)
  - \( u_g = 2415.2 \text{kJ/kg} \)

#### Superheat Table

- **Enthalpy and volume of water at 150 kPa and 30 °C**
  - \( h_1 = h \text{ saturated liquid @ 30°C} = 125.75 \text{kJ/kg} \)
  - \( v_1 = v \text{ saturated liquid@30°C} = 0.001004 \text{m}^3/\text{kg} \)

#### Temperature Table

- **Internal energy of water at 20 MPa and 300 °C**
  - \( u_1 = u \text{ saturated liquid @ 300°C} = 1332.0 \text{kJ/kg} \)

### EES Program

- \( u_1 = \text{intenergy(steam, P = 4., X = 0)} \)
- \( u_g = \text{intenergy(steam, P = 4., X = 1.)} \)
- \( u_g = 2414.29 \)
- \( h_1 = \text{enthalpy(steam, T = 30., p = 500.)} \)
- \( h_1 = 125.67 \text{kJ/kg} \)
- \( v_1 = \text{volume(steam, T = 30., p = 500.)} \)
- \( v_1 = 0.001004 \text{m}^3/\text{kg} \)
- \( u_1 = \text{intenergy(steam, T = 300., p = 20000.)} \)
- \( u_1 = 1333.446 \text{kJ/kg} \)
Linear Interpolation with 2 Variables

\[ h @ (T = 450 \text{ C}, p = 27 \text{ MPa}) \quad \text{Steam Superheat Table} \]

\[ \begin{align*}
  p &= 25 \text{ mPa} & p &= 27 \text{ MPa} & p &= 30 \text{ MPa} \\
  T &= 450 & h &= 2949.7 & h &= 2898.4 & h &= 2821.4 \\
\end{align*} \]

For the pressure table entry, \( \frac{27 - 25}{30 - 25} = .4 \)

The desired pressure, 27 kPa, is 40 % of the difference between table values. All the other properties at 27 kPa must be at the same difference.

EES

\[ h = \text{enthalpy(steam, } T = 450.\text{, } p = 27000) \]

\[ h = 2901.7 \text{ kJ/kg} \quad .22\% \text{ difference, table and interpolation} \]
Linear Interpolation with 2 Variables

\[ h\@ (T = 450 \, \text{C}, \, p = 27 \, \text{MPa}) \quad \text{Steam Superheat Table} \]

<table>
<thead>
<tr>
<th></th>
<th>p = 25 mPa</th>
<th>p = 27 MPa</th>
<th>p = 30 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>T = 450</td>
<td>h = 2949.7</td>
<td>h = 2898.4</td>
<td>h = 2821.4</td>
</tr>
</tbody>
</table>

\[ h = m x + b = \left( \frac{A}{C} \right) B + h@ (p=25) \]

\[ h = \frac{(2821.4 - 2949.7)}{(30 - 25)} (27 - 25) + 2947.7 \]
\[ h = -51.32 + 2947.7 \]
\[ h = 2898.4 \, \text{kJ/kg} \]

EES
\[ h = \text{enthalpy(steam, T = 450., p = 27000)} \]
\[ h = 2901.7 \, \text{kJ/kg} \quad 0.22\% \quad \text{difference, table and interpolation} \]
3 kg vapor and 1 kg liquid R-134a is contained in a rigid tank at 20 C.
What is the volume of the tank? If the tank is heated until the pressure
reaches .6 MPa? What is the quality, and enthalpy of the mixture of
liquid and vapor?

\[ V_1 = V_f + V_g \]
\[ V_1 = m_f \times v_f @ 20 \text{ C} + m_g \times v_g @ 20 \text{ C} \]
\[ V_1 = 1 \text{ kg} \times .0008157 + 3 \text{ kg} \times .0358 \]
\[ V_1 = .1082 \text{ m}^3 \]
\[ v_1 = \frac{V_1}{m} = \frac{.1082 \text{ m}^3}{4 \text{ kg}} = .027 \text{ m}^3/\text{kg} \]

After heating,
\[ V = \text{constant}, m = \text{constant} \Rightarrow v = \text{constant} \]
\[ v_2 = v_1 = v_f @ .6 \text{ MPa} + x \times v_{fg} @ .6 \text{ MPa} \]
\[ x_2 = \frac{.027 - .00008196}{.0341 - .0008196} = .787(78.7\%) \]
\[ h_2 = h_f + x \times h_{fg} \]
\[ h_2 = 79.84 + .787 \times 179.71 = 211.27 \text{ kJ/kg} \]
3 kg of vapor and 2 kg of liquid R-134a is contained in a piston cylinder device. The volume of the vapor is .1074 cubic meters. What is the temperature and pressure? If the cylinder and its contents are heated until volume is .15 cubic meters what is the quality?

\[ v_{gl} = \frac{V_{gl}}{m_{gl}} = \frac{.1074 \text{m}^3}{3 \text{kg}} = .0358 \text{m}^3/\text{kg} \]

\[ v_g = .0358 \text{m}^3/\text{kg} \text{ at } 20 \text{ C, .5716 MPa} \text{ page 842, Table A - 11} \]

During the heating process the pressure is constant.

at \( V_2 = .15 \text{m}^3 \),

\[ v_2 = \frac{V_2}{m} = \frac{.15}{5} = .03 \text{ m}^3/\text{kg} \]

\[ v_2 = .03 \text{ m}^3/\text{kg} = v_f \text{ at } 20 \text{ C} + x \times v_{fg} \text{ at } 20 \text{ C} \]

\[ x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{.03 - .0008157}{.0358 - .0008157} = .834 (83.4\%) \]

\[ x = \frac{\text{property} - (\text{property})_f}{(\text{property})_{fg}} \]

property = (property)_r + x \times (property)_{fg}
1. **Problem Statement**
   Carbon dioxide is contained in a cylinder with a piston. The carbon dioxide is compressed with heat removal from $T_1, p_1$ to $T_2, p_2$. The gas is then heated from $T_2, p_2$ to $T_3, p_3$ at constant volume and then expanded without heat transfer to the original state point.

2. **Schematic**

3. **Select Thermodynamic System**
   open - closed - control volume
   a closed thermodynamic system composed to the mass of carbon dioxide in the cylinder

4. **Property Diagram**
   state points - processes - cycle

5. **Property Determination**

6. **Laws of Thermodynamics**
   $Q=? \quad W=? \quad E=? \quad$ material flows=?
Linear Interpolation with 3 Variables

\[ h(T = 470 \text{ C}, p = 27 \text{ MPa}) \quad \text{Steam Superheat Table} \]

\[
\begin{array}{ccc}
\text{p} & \text{25 MPa} & \text{27 MPa} & \text{30 MPa} \\
\text{T} & \text{450} & \text{h} = 2949.7 & \text{h} = 2898.4 & \text{h} = 2821.4 \\
\text{T} & \text{470} & \text{h} = 2991.0 \\
\text{T} & \text{500} & \text{h} = 3161.4 & \text{h} = 3129.88 & \text{h} = 3081.1
\end{array}
\]

Interpolate first at 450 C and at 500 C between p = 25 and P = 30 to get
\[ h(T = 450 \text{ and } 500, p = 27). \]
Then interpolate at p = 27 MPa
between 450 C and 500 C.

\[
\begin{align*}
\text{pressure} & \quad \frac{27 - 25}{30 - 25} = \frac{2}{5} = .4 \\
\text{Temperature} & \quad \frac{470 - 450}{500 - 450} = \frac{20}{50} = .4
\end{align*}
\]

EES

\[ h = \text{enthalpy(steam, } T = 470, , p = 27000,) \]

\[ h = 3003.95 \text{ kJ/kg, .47% difference, table and interpolation} \]
Linear Interpolation with 3 Variables

### Steam Superheat Table

<table>
<thead>
<tr>
<th>p (MPa)</th>
<th>h (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>2949.7</td>
</tr>
<tr>
<td>27</td>
<td>2898.4</td>
</tr>
<tr>
<td>30</td>
<td>2821.4</td>
</tr>
</tbody>
</table>

Interpolate at 450°C and 500°C between p = 25 and p = 30 to get h@ (T = 450 and 500, p = 27). Then interpolate at p = 27 MPa between 450°C and 500°C.

\[
h = m x + b = \left( \frac{A}{C} \right) B + h(T = 450, p = 27)
\]

\[
h = \frac{(3129.88 - 2898.4)}{(500 - 450)}(470 - 450) + 2898.4
\]

\[
h = 2991.0
\]

\[
h = \text{enthalpy(steam, } T = 470, p = 27000. \text{)}
\]

\[
h = 3003.95 \text{ kJ/kg, } .47\% \text{ difference, table and interpolation}
\]
**Ideal Gas Law**

**AVOGADROS LAW**

One (1) mole of any gas = 22.4 liters.

6.023×10²³ molecules/mole of gas at STP (1 atm and 0° C)

**BOLYÉS LAW**

\[ p_1 \times v_1 = p_2 \times v_2 \]

**CHARLES LAW**

\[ \frac{v_1}{v_2} = \frac{T_1}{T_2} \]

\[ \frac{p_1}{p_2} = \frac{T_1}{T_2} \]

**IDEAL (PERFECT) GAS LAW**

\[ pv = RT \]

\[ pV = mRT \]

\[ p - \text{absolute pressure, psia, kPa} \]

\[ T - \text{absolute temperature, °R, °K} \]

\[ R = \frac{R^*}{\text{molecular weight}} \]

\[ R^* = 1545.15 \ \frac{\text{lbf/lbm}}{\text{°R}} \]

\[ R^* = 8.314 \ \frac{\text{kJ}}{\text{kmole °K}} \text{ or } \frac{\text{kPa m}^3}{\text{kmole °K}} \]

mass = moles × Molecular Weight

\[ m = n \times \text{Molecular Weight} \]

\[ pv = R^*T \]

\[ pV = nR^*T \]
Ideal Gas

\[ pv = RT \]

constant specific heat
What is the mass of 1.2 m³ of oxygen at 24°C and a gage pressure of 500 kPa. Atmospheric pressure is 97 kPa

\[
p = p_{\text{gage}} + p_{\text{atmosphere}} = 500 \text{ kPa} + 97 \text{ kPa} = 597 \text{ kPa}
\]

\[
R_{O_2} = \frac{8.314 \text{kJ/kmole} \cdot \text{K or kPa m}^3/\text{kmole} \cdot \text{K}}{32} = .259813 \text{ kPa m}^3/\text{kg} \quad \text{also Table A-1}
\]

\[
m = \frac{pV}{RT} = \frac{597 \text{ kPa} \times 1.2 \text{ m}^3}{.259813 \text{ kPa m}^3/\text{kg} \times (24^\circ \text{C} + 273.16^\circ \text{K})} = 9.28 \text{ kg}
\]

What is the volumetric mass of 1.2 lbm of air at 124°F and a gage pressure of 500 psia. Atmospheric pressure is 14.7 psia.

\[
p = p_{\text{gage}} + p_{\text{atmosphere}} = 500 \text{ psia} + 14.7 \text{ psia} = 514 \text{ psia}
\]

\[
R_{\text{air}} = \frac{1545.15 \text{lbf} / \text{lbm} \cdot \text{R} / \text{lbmole}}{28.97} = 53.336 \frac{\text{ft lbf}}{\text{lb mole} \cdot \text{R}} \quad \text{also Table A-1E in molar units}
\]

\[
V = \frac{mRT}{p} = \frac{1.2 \text{ lbm} \times 53.336 \text{ ft lbf} / \text{lbm} \cdot \text{R} \times (124^\circ \text{F} + 459.69^\circ \text{R})}{514 \text{ psia} \times 144 \text{ ft}^2/\text{in}^2}
\]

\[
V = .5047 \text{ ft}^3
\]
IDEAL GAS EQUATION FORMS - For Air

\[ P \cdot v = m \quad R \quad T \]

- \( \text{kPa} \quad \text{m}^3 = \text{kg mole} \quad \frac{8.314 \text{kPa m}^3}{\text{kg mole} \, ^0\text{K}} \quad ^0\text{K} \)
- \( \text{kPa} \quad \text{m}^3 = \text{kg} \quad \frac{.287 \text{kPa m}^3}{\text{kg mole} \, ^0\text{K}} \quad ^0\text{K} \)
- \( \text{lb/ft}^2 \quad \text{ft}^3 = \text{lbmole} \quad 1545.15 \frac{\text{ft lbf}}{\text{lbm} \, ^0\text{R}} \quad ^0\text{R} \)
- \( \text{lb/ft}^2 \quad \text{ft}^3 = \text{lbm} \quad 53.35 \frac{\text{ft lbf}}{\text{lbm} \, ^0\text{R}} \quad ^0\text{R} \)
- \( \text{psi} \quad \text{ft}^3 = \text{lbmole} \quad 10.73 \frac{\text{psi lbf}}{\text{lbmole} \, ^0\text{R}} \quad ^0\text{R} \)
- \( \text{lb/ft}^2 \quad \text{ft}^3 = \text{lbm} \quad .06855 \frac{\text{BTU}}{\text{lbm} \, ^0\text{R}} \quad ^0\text{R} \)

\( R = 8.314 \frac{\text{kPa m}^3}{\text{kg mole} \, ^0\text{K}} / 28.96 \)
\( R = 1545.15 \frac{\text{ft lbf}^3}{\text{lbm} \, ^0\text{R}} / 28.96 \)
\( R = 1545.15 \frac{\text{ft lbf}}{\text{lbm} \, ^0\text{R}} / 144 \)
\( R = 1545.15 \frac{\text{ft lbf}}{\text{lbm} \, ^0\text{R}} / 28.96 / 778 \)
The specific volume of air at 75° F and 14.7 psia

\[ R_{\text{air}} = \frac{1545.15}{28.96} = 53.35 \text{ ft lbf/lbm R} \]

\[ v = \frac{RT}{p} = \frac{53.35 \text{ ft lbf/lbm R} \times (459.69^\circ \text{R} + 75^\circ \text{F})}{14.7 \text{ lbf/in}^2 \times 144 \text{ in}^2/\text{ft}^2} \]

\[ v = 13.476 \text{ ft}^3/\text{lb} \]

The specific volume of air at 24° C and 101.325 kPa

\[ R = 8.314 \frac{\text{kPa m}^3}{\text{kg mole}^0\text{K}} / 28.96 \]

\[ v = \frac{RT}{p} = \frac{.287 \text{ kPa m}^3/\text{kg} \times (273.15^0\text{K} + 24^\circ \text{F})}{101.325 \text{ kPa}^2} \]

\[ v = .8417 \text{ m}^3/\text{kg} \]
Air initially at a volume of 12 m³ and a pressure of 225 kPa expands at a constant temperature to a volume of 23 m³. What is the final pressure?

mass = constant, \( T = \text{constant} \)

\[
m = \frac{RT_1}{p_1 V_1} = \frac{.286 \times (273.15 + T_1)}{224 \text{ kPa} \times 23 \text{ m}^3}
\]

\[
m = \frac{RT_1}{p_1 V_1} = \frac{RT_2}{p_2 V_2}
\]

\[
p_2 = \frac{R T_2 p_1 V_1}{R T_1 V_2} = p_1 \frac{V_1}{V_2}
\]

\[
p_2 = 225 \text{ kPa} \frac{12 \text{ m}^3}{23 \text{ m}^3}
\]

\[
p_2 = 117.39 \text{ kPa}
\]
### SPECIFIC HEATS FOR GASSES

#### TABLE A-2

<table>
<thead>
<tr>
<th>Gas</th>
<th>Formula</th>
<th>Specific Heat at 300 K</th>
<th>Specific Heat at 300 K</th>
<th>Specific Heat at 300 K</th>
<th>Specific Heat at 300 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>—</td>
<td>0.2870</td>
<td>1.006</td>
<td>0.718</td>
<td>1.400</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>0.2091</td>
<td>0.5203</td>
<td>0.3122</td>
<td>1.667</td>
</tr>
<tr>
<td>Butane</td>
<td>C₂H₁₀</td>
<td>0.1433</td>
<td>1.7164</td>
<td>1.5734</td>
<td>1.091</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>0.1889</td>
<td>0.846</td>
<td>0.657</td>
<td>1.289</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>CO</td>
<td>0.2968</td>
<td>1.040</td>
<td>0.744</td>
<td>1.400</td>
</tr>
<tr>
<td>Ethane</td>
<td>C₂H₆</td>
<td>0.2765</td>
<td>1.7662</td>
<td>1.4897</td>
<td>1.186</td>
</tr>
<tr>
<td>Ethylene</td>
<td>C₂H₄</td>
<td>0.2964</td>
<td>1.5482</td>
<td>1.2518</td>
<td>1.237</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>2.0769</td>
<td>5.1926</td>
<td>3.1156</td>
<td>1.667</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H₂</td>
<td>4.1240</td>
<td>14.307</td>
<td>10.183</td>
<td>1.405</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Octane</td>
<td>C₈H₁₈</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propane</td>
<td>C₃H₈</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam</td>
<td>H₂O</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The unit kJ/kg · K is equivalent to kJ/kg · °C.


#### TABLE A-2E

<table>
<thead>
<tr>
<th>Gas</th>
<th>Formula</th>
<th>Specific Heat at 80°F</th>
<th>Specific Heat at 80°F</th>
<th>Specific Heat at 80°F</th>
<th>Specific Heat at 80°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>—</td>
<td>0.06855</td>
<td>0.240</td>
<td>0.171</td>
<td>1.400</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>0.04971</td>
<td>0.1253</td>
<td>0.0756</td>
<td>1.667</td>
</tr>
<tr>
<td>Butane</td>
<td>C₄H₁₀</td>
<td>0.03424</td>
<td>0.415</td>
<td>0.381</td>
<td>1.09</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>0.04513</td>
<td>0.203</td>
<td>0.158</td>
<td>1.285</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>CO</td>
<td>0.07090</td>
<td>0.249</td>
<td>0.178</td>
<td>1.399</td>
</tr>
<tr>
<td>Ethane</td>
<td>C₂H₆</td>
<td>0.06616</td>
<td>0.427</td>
<td>0.361</td>
<td>1.183</td>
</tr>
<tr>
<td>Ethylene</td>
<td>C₂H₄</td>
<td>0.07079</td>
<td>0.411</td>
<td>0.340</td>
<td>1.208</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>0.4961</td>
<td>1.25</td>
<td>0.753</td>
<td>1.667</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H₂</td>
<td>0.9851</td>
<td>3.43</td>
<td>2.44</td>
<td>1.404</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>0.1238</td>
<td>0.532</td>
<td>0.403</td>
<td>1.32</td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>0.09840</td>
<td>0.246</td>
<td>0.1477</td>
<td>1.667</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>0.07090</td>
<td>0.248</td>
<td>0.177</td>
<td>1.400</td>
</tr>
<tr>
<td>Octane</td>
<td>O₈H₁₈</td>
<td>0.01742</td>
<td>0.409</td>
<td>0.392</td>
<td>1.044</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>0.06206</td>
<td>0.219</td>
<td>0.157</td>
<td>1.395</td>
</tr>
<tr>
<td>Propane</td>
<td>C₃H₈</td>
<td>0.04504</td>
<td>0.407</td>
<td>0.362</td>
<td>1.124</td>
</tr>
<tr>
<td>Steam</td>
<td>H₂O</td>
<td>0.1102</td>
<td>0.445</td>
<td>0.335</td>
<td>1.329</td>
</tr>
</tbody>
</table>

SPECIFIC HEAT

\[ C_p = \left( \frac{\partial h}{\partial T} \right)_{p=\text{const}} \quad C_v = \left( \frac{\partial u}{\partial T} \right)_{v=\text{const}} \]

\[ \Delta h = \int c_p(T) \, dT \quad \Delta u = \int c_v(T) \, dT \]

For an ideal gas specific heats are assumed constant

\[ \Delta h = c_p \int dT \quad \Delta u = c_v \int dT \]

\[ dh = c_p \, dT \quad du = c_v \, dT \]

By definition \( h = u + pv \)

substituting \( pv = RT \)

\[ h = u + RT \]

differentiating \( dh = du + RdT \)

substituting for \( dh \) and \( du \)

\[ c_p \, dT = c_v \, dT + RdT \]

\[ c_p = c_v + R \]

with same units and \( k = \frac{c_p}{c_v} \)

FOR IDEAL GAS ONLY

\[ c_p - c_v = R \quad k - 1 = \frac{R}{c_v} \]
**IDEAL GAS IMPROVEMENTS**

Enthalpy, $h$, internal energy, $u$, and entropy, $s$, are not absolute but Differences from a base.

\[
h = \int_{\text{Table Base State}}^{T} c_p(T) \, dT
\]

\[
u = \int_{\text{Table Base State}}^{T} c_v(T) \, dT
\]

\[
c_p = c_p(T), \quad c_v = c_v(T)
\]

Tables A-17, A-17 to A-22, A-22E
IDEAL GAS WITH VARIABLE SPECIFIC HEAT

<table>
<thead>
<tr>
<th>T (K)</th>
<th>h (Btu/lbmol)</th>
<th>u (Btu/lbmol)</th>
<th>s° (Btu/lbmol · R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900</td>
<td>13,742</td>
<td>9,968</td>
<td>54.896</td>
</tr>
<tr>
<td>1940</td>
<td>14,058</td>
<td>10,205</td>
<td>55.061</td>
</tr>
<tr>
<td>1980</td>
<td>14,375</td>
<td>10,443</td>
<td>55.223</td>
</tr>
<tr>
<td>2020</td>
<td>14,694</td>
<td>10,682</td>
<td>55.383</td>
</tr>
<tr>
<td>2060</td>
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Determine the enthalpy change, $\Delta h$, of nitrogen in kJ/kg as it is heated from $600^\circ K$ to $1000^\circ K$ ($726^\circ C, 1340^\circ F$) using:

a) empirical specific heat equation Table A - 2c,

\[ \Delta \bar{h} = \int c_p(T) \, dT, \quad c_p = a + bT + cT^2 + dT^3 \]

\[ \Delta \bar{h} = 28.9(1000 - 600) + .5(0.0001571)(1000^2 - 600^1) \]

\[ + \frac{1}{3}(8081 \times 10^{-5})(1000^3 - 600^3) - \frac{1}{4}(2.8738081 \times 10^{-9})(1000^4 - 600^4) = 12544 \text{ kJ/kmole} \]

\[ \Delta h = 2544 \text{ kJ/kmole/28.013} = 447.8 \text{ kJ/kg} \]

b) Average specific heat over the temperature range, \( c_p@800^\circ K = 1.121 \text{ kJ/kgK} \)

\[ \Delta h = c_p \Delta T = 1.121 \text{ kJ/kg K (1000 – 600)} = 448.5 \text{ kJ/kg} \]

c) Room temperature specific heat, \( c_p@800^\circ K = 1.0394485 \text{ kJ/kg} \)

\[ \Delta h = 1.039448 \text{ kJ/kg (1000 – 600)} = 415.6 \text{ kJ/kg} \]

d) Table A – 18E

\[ \Delta \bar{h} = h@1000^\circ K - h@600^\circ K = 30129 \text{ kJ/kgmole} - 17563 \text{ kJ/kgmole} = 12566 \text{ kJ/kgmole} \]

\[ \Delta h = 12566 \text{ kJ/kgmole/28.013 kg/kgmole} = 448.58 \text{ kJ/kg} \]

e) EES

\[ \Delta h = \text{enthalpy(nitrogen, } T = 1000.\text{, } p = 101.325) - \text{enthalpy(nitrogen, } T = 600.\text{, } p = 101.325) \]

\[ \Delta h = 449.46 \text{ kJ/kg} \]
PRINCIPAL OF CORRESPONDING STATES
COMPRESSIBILITY FACTOR Z

Z is about the same for all gasses at the same reduced temperature and the same reduced pressure where:

\[
Z = \frac{pV}{RT}
\]

\[
Z = \frac{pV}{mRT}
\]

\[
P_R = \frac{p}{p_{critical}} \quad (2 - 20)
\]

\[
T_R = \frac{T}{T_{critical}}
\]
VAN DER WAALS EQUATION OF STATE - 1873

\[
\left(p + \frac{a}{v^2}\right)(v - b) = RT \quad (2 - 22)
\]

\[\frac{a}{v^2} - \text{intermolecular forces}\]

\[b - \text{volume of gas molecules}\]

\[p = \frac{RT_{\text{critical}}}{v_{\text{critical}}} - \frac{a}{v^2_{\text{critical}}}\]

\[
\left(\frac{\partial p}{\partial v}\right)_{T_{\text{critical}}} = 0 \quad \left(\frac{\partial^2 p}{\partial v^2}\right)_{T_{\text{critical}}} = 0
\]

\[a = \frac{27 R^2 T_{\text{critical}}^2}{64 p_{\text{critical}}} \quad b = \frac{R T_{\text{critical}}}{8 p_{\text{critical}}}\]
THERMODYNAMIC PROPERTY MEASUREMENT

Thermodynamic properties are independent of path or process and are exact differentials. Heat and Work are not exact differentials but are dependent on process or path.

\[
\begin{align*}
  u &= f(s, v) \\
  du &= \left( \frac{\partial u}{\partial s} \right)_v ds + \left( \frac{\partial u}{\partial v} \right)_s dv
\end{align*}
\]

6 thermodynamic properites
2 at a time, 60 equations

\[
\begin{align*}
  \left( \frac{\partial h}{\partial T} \right)_p &= c_p \\
  \left( \frac{\partial u}{\partial T} \right)_v &= c_v \\
  \left( \frac{\partial T}{\partial p} \right)_h &= \text{Joule Tompson Coefficient} \\
  \left( \frac{\partial T}{\partial p} \right)_h &= 0 \text{ for an ideal gas, a value for a real gas}
\end{align*}
\]

used with the First Law

\[
\begin{align*}
  \left( \frac{\partial s}{\partial v} \right)_T &= \left( \frac{\partial p}{\partial T} \right)_v
\end{align*}
\]
\[
\left( \frac{\partial T}{\partial p} \right)_h = \text{JT Coefficient}
\]

*Figure A-9E*

T-s diagram for water. [Source: Joseph H. Keenan, Frederick G. Keyes, Philip G. Hill, and Joan G. Moore, *Steam Tables* (New York: John Wiley & Sons, 1969).*]
Beattie-Bridgeman Equation of State

The Beattie-Bridgeman equation, proposed in 1928, is an equation of state based on five experimentally determined constants. It was proposed as

\[ P = \frac{R_u T}{\bar{v}} \left( 1 - \frac{c}{\bar{v} T^3} \right) (\bar{v} + B) - \frac{A}{\bar{v}^2} \]  

(2-24)

where

\[ A = A_0 \left( 1 - \frac{a}{\bar{v}} \right) \quad \text{and} \quad B = B_0 \left( 1 - \frac{b}{\bar{v}} \right) \]  

(2-25)

The constants appearing in the above equation are given in Table 2–4 for various substances. The Beattie-Bridgeman equation is known to be reasonably accurate for densities up to about 0.8\( \rho_{cr} \), where \( \rho_{cr} \) is the density of the substance at the critical point.

Benedict-Webb-Rubin Equation of State

Benedict, Webb, and Rubin extended the Beattie-Bridgeman equation in 1940 by raising the number of constants to eight. It is expressed as

\[ P = \frac{R_u T}{\bar{v}} + \left( B_0 R_u T - A_0 - \frac{C_0}{T^2} \right) \frac{1}{\bar{v}^2} + \frac{b R_u T - a}{\bar{v}^3} + \frac{a \alpha}{\bar{v}^6} + \frac{c}{\bar{v}^3 T^2} \left( 1 + \frac{\gamma}{\bar{v}^3} \right) e^{-\gamma/\bar{v}^2} \]  

(2-26)

The values of the constants appearing in this equation are given in Table 2–4. This equation can handle substances at densities up to about 2.5\( \rho_{cr} \). In 1962, Strobridge further extended this equation by raising the number of constants to 16 (Fig. 2–59).

Course Property Sources

1) Ideal Gas Law with constant specific heats

2) Tables
   - Steam
   - Refrigerant
   - Air

3) EES CD
   - NIST
   for home work convenience
EQUATION OF STATE ERRORS

nitrogen
Thermophysical Properties of Fluid Systems

Accurate thermophysical properties are available for several fluids. These data include the following:

- Density
- Specific volume
- Enthalpy
- Internal energy
- Viscosity
- Joule-Thomson coefficient
- Speed of Sound
- Thermal conductivity
- Surface tension (saturation curve only)

Please follow the steps below to select the data required:

1. Please select the species of interest:
   - Water

2. Please choose the units you wish to use:

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<th>Quantity</th>
<th>Units</th>
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<td>Temperature</td>
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</tr>
<tr>
<td>Pressure</td>
<td>MPa, bar, atm, torr, psia</td>
</tr>
<tr>
<td>Density</td>
<td>mol/l, mol/cm³, g/cm³, kg/m³, lb-mol/l, lb/cm³</td>
</tr>
<tr>
<td>Energy</td>
<td>kJ/mol, kcal/mol, cal/mol, Btu/lb-mole, kcal/Btu</td>
</tr>
<tr>
<td>Velocity</td>
<td>m/s, ft/s, mph</td>
</tr>
<tr>
<td>Viscosity</td>
<td>uPa<em>s, Pa</em>s, cp, lb*s/ft²</td>
</tr>
<tr>
<td>Surface tension</td>
<td>N/m, dyn/cm, lb/in</td>
</tr>
</tbody>
</table>

*Surface tension values are only available along the saturation curve.

3. Choose the desired type of data:
   - Isothermal properties
   - Saturation properties -- temperature increments
   - Isochoric properties
   - Saturation properties -- pressure increments

4. Please select the desired standard state convention:
   - Default for fluid

5. Press to Continue

Select Units

Select Table Type

NIST Webbook Properties
ftp://webbook.nist.gov/chemistry/fluid
Temperature Table for Water in .1 degree increments from 40 to 40 degrees.
Thermophysical Properties of Fluid Systems

Accurate thermophysical properties are available for several fluids. These data include the following:

- Density
- C
- Enthalpy
- Internal energy
- Viscosity
- Joule-Thomson coefficient
- Specific volume
- C
- Entropy
- Speed of Sound
- Thermal conductivity
- Surface tension (saturation curve only)

Please follow the steps below to select the data required:

1. Please select the species of interest:
   - Water
2. Choose the desired type of data:
   - Isothermal properties
   - Saturation properties -- temperature increments
   - Isochore properties
   - Saturation properties -- pressure increments
   - Isentropic properties
3. Please select the desired standard state convention:
   - Default for fluid
4. Press to Continue

Set low and high temperature and temperature increment.
Saturation Properties for Water -- Temperature Increments

- Fluid Data
- Auxiliary Data
- References
- Additional Information
- Notes
- Other Data Available:
  - View data in HTML form
  - Download data as a tab-delimited text file
  - See NIST Chemistry WebBook page for this species
  - Recommended citation for data from this page
  - Fluid data for other species

Fluid Data

Data on Saturation Curve

![Graph showing the relationship between pressure and temperature for water saturation properties.](image-url)
Saturation Properties for Water – Temperature Increments

- Fluid Data
- Auxiliary Data
- References
- Additional Information
- Notice

Other Data Available:
- View data in HTML table.
- Download data as a tab-delimited text file.
- Main NIST Chemistry WebBook page for this species.
- Recommended citation for data from this page.
- Fluid data for other species

Fluid Data

Data on Saturation Curve

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