

MEC511

Thermodynamics & Fluids

Chapter03

Evaluating Properties



Lecture 09

NOTE!

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3 Evaluating Properties

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- 3.3 Studying Phase Change
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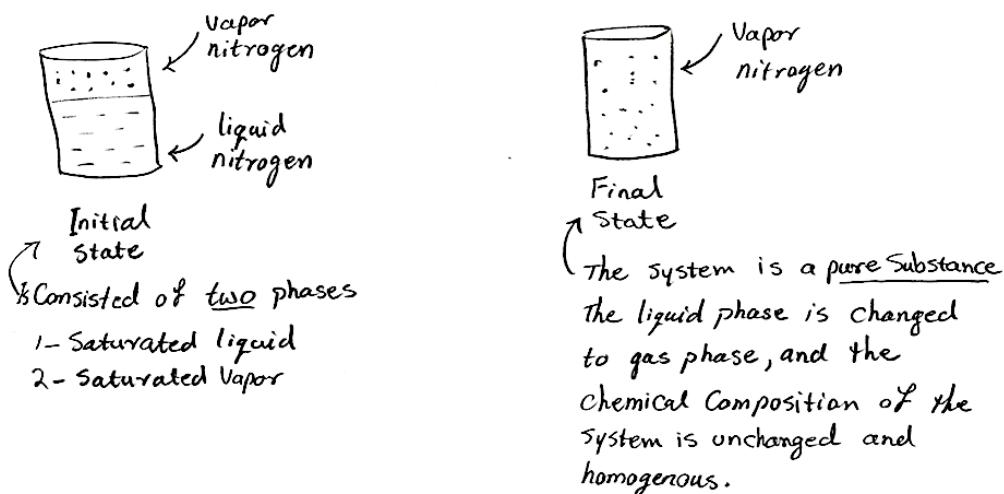
3.1 Getting Started

Phase and Pure Substance

- The term **phase** refers to a quantity of matter that is **homogeneous** throughout in both *chemical* composition and *physical* structure.
- Homogeneity** in physical structure means that the matter is all solid, or all liquid, or all vapor (or equivalently all gas).
- Two phases coexist during the changes in phase called **vaporization**, **melting**, and **sublimation**.
- A **pure substance** is one that is uniform and invariable in chemical composition.
- A pure substance can exist in more than one phase, but its chemical composition must be the same in each phase.

Example:

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



3.1 Getting Started

Fixing the State

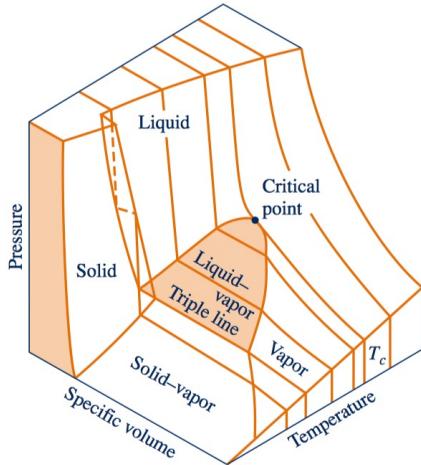
- A general rule known as the **state principle** has been developed as a guide in determining the number of independent properties required to fix the state of a system.
- For simple compressible systems, the state principle indicates that the number of **two** independent **intensive** properties "Fix" the state such that other intensive properties can be found.

For Example

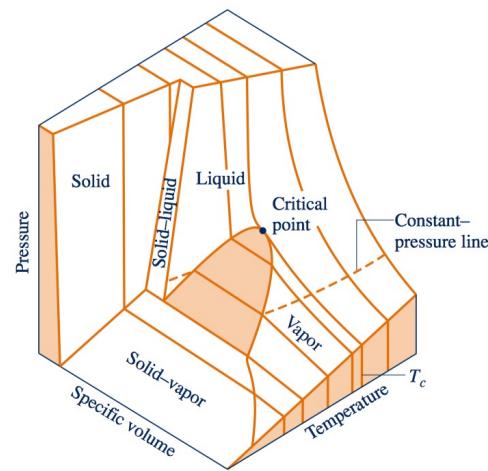
$$\left. \begin{array}{ll} \text{Temperature: } & T \\ \text{Specific volume: } & v \end{array} \right\} \quad p = p(T, v) \quad u = u(T, v)$$

3.2 p - v - T Relation and p - v - T surfaces

From experiment it is known that temperature and specific volume can be regarded as independent and pressure determined as a function of these two: $p = p(T, v)$. The graph of such a function is a surface, the p - v - T surface.

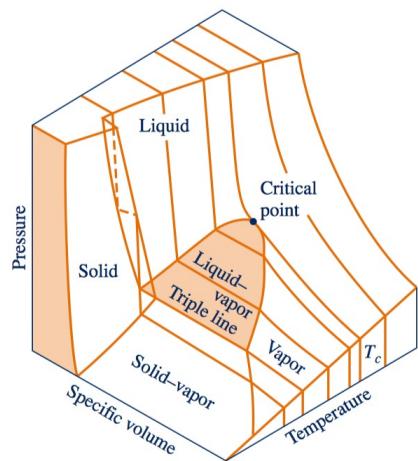


3D view of p - v - T surface and projections for a substance that expands on freezing (Water).

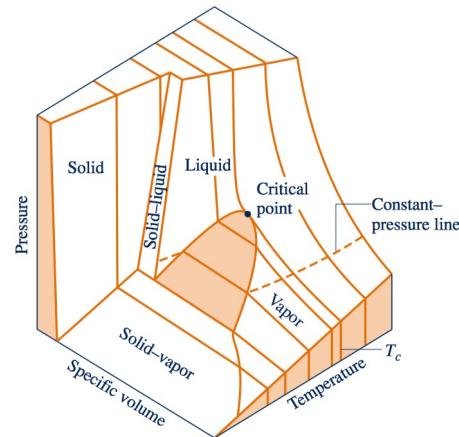


3D view of p - v - T surface for a substance that contracts on freezing. (most substances)

3.2 p - v - T Relation and p - v - T surfaces



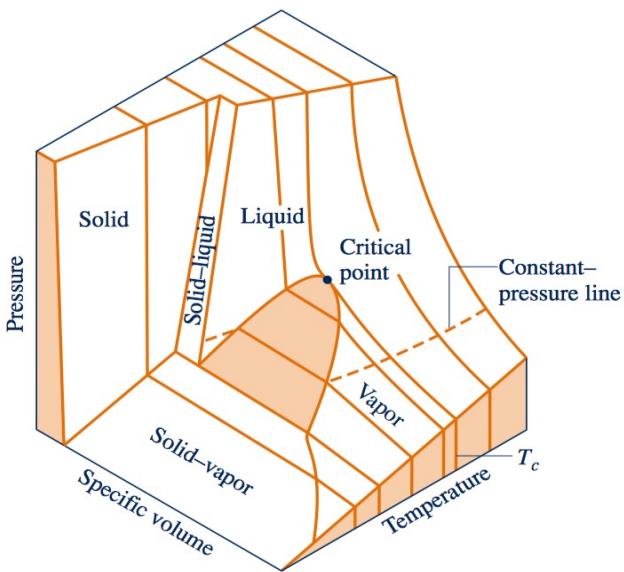
3D view of p - v - T surface and projections for a substance that expands on freezing (Water).



3D view of p - v - T surface for a substance that contracts on freezing. (most substances)

Located between the single-phase regions are two-phase regions where two phases exist in equilibrium: **liquid-vapor**, **solid-liquid**, and **solid-vapor**. Two phases can coexist during changes in phase such as **vaporization**, **melting**, and **sublimation**. Three phases can exist in equilibrium along the line labeled **triple line**.

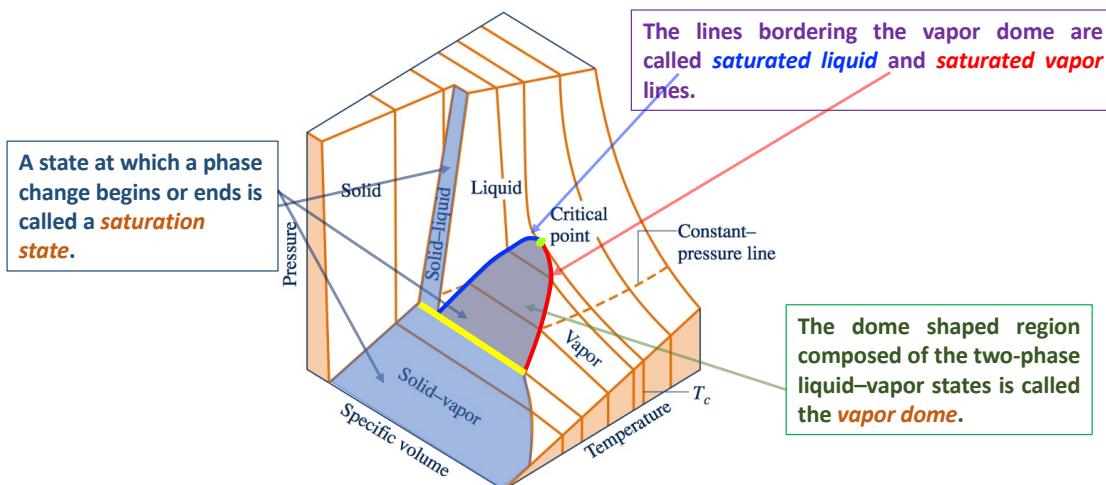
3.2 p - v - T Relation and p - v - T surfaces



In these single-phase regions, the state is fixed by any two of the properties: pressure, specific volume, and temperature, since all of these are independent when there is a single phase present.

Within the two-phase regions pressure and temperature are not independent; one cannot be changed without changing the other. In these regions the state cannot be fixed by temperature and pressure alone; however, the state can be fixed by specific volume and either pressure or temperature. Three phases can exist in equilibrium along the line labeled triple line.

3.2 p - v - T Relation and p - v - T surfaces



At the top of the dome, where the saturated liquid and saturated vapor lines meet, is the **critical point**. The **critical temperature**, T_c , of a pure substance is the maximum temperature at which liquid and vapor phases can coexist in equilibrium. The pressure at the critical point is called the **critical pressure**, p_c . The specific volume at this state is the **critical specific volume**.

3.2 p - v - T Relation and p - v - T surfaces

TABLE A-1

Atomic or Molecular Weights and Critical Properties of Selected Elements and Compounds

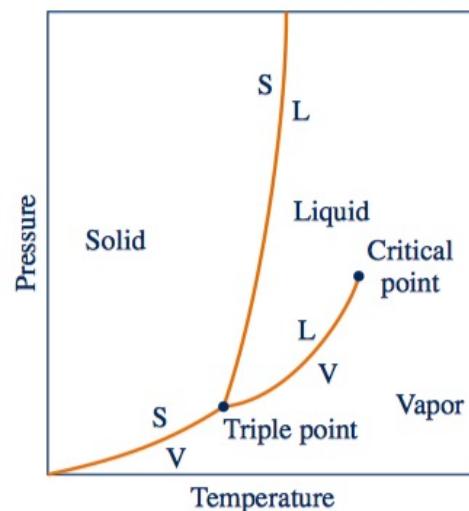
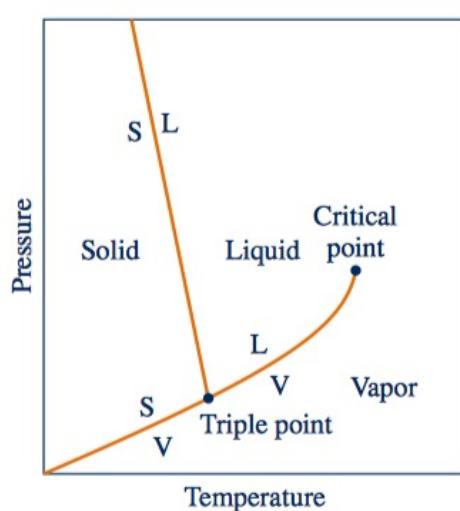
| Substance | Chemical Formula | M (kg/kmol) | T_c (K) | P_c (bar) | $Z_c = \frac{P_c V_c}{R T_c}$ |
|------------------|-----------------------------------|------------------|--------------|----------------|-------------------------------|
| Acetylene | C_2H_2 | 26.04 | 309 | 62.8 | 0.274 |
| Air (equivalent) | — | 28.97 | 133 | 37.7 | 0.284 |
| Ammonia | NH_3 | 17.03 | 406 | 112.8 | 0.242 |
| Argon | Ar | 39.94 | 151 | 48.6 | 0.290 |
| Benzene | C_6H_6 | 78.11 | 563 | 49.3 | 0.274 |
| Butane | C_4H_{10} | 58.12 | 425 | 38.0 | 0.274 |
| Carbon | C | 12.01 | — | — | — |
| Carbon dioxide | CO_2 | 44.01 | 304 | 73.9 | 0.276 |
| Carbon monoxide | CO | 28.01 | 133 | 35.0 | 0.294 |
| Copper | Cu | 63.54 | — | — | — |
| Ethane | C_2H_6 | 30.07 | 305 | 48.8 | 0.285 |
| Ethanol | C_2H_5OH | 46.07 | 516 | 63.8 | 0.249 |
| Ethylene | C_2H_4 | 28.05 | 283 | 51.2 | 0.270 |
| Helium | He | 4.003 | 5.2 | 2.3 | 0.300 |
| Hydrogen | H ₂ | 2.016 | 33.2 | 13.0 | 0.304 |
| Methane | CH ₄ | 16.04 | 191 | 46.4 | 0.290 |
| Methanol | CH ₃ OH | 32.04 | 513 | 79.5 | 0.220 |
| Nitrogen | N ₂ | 28.01 | 126 | 33.9 | 0.291 |
| Octane | C_8H_{18} | 114.22 | 569 | 24.9 | 0.258 |
| Oxygen | O ₂ | 32.00 | 154 | 50.5 | 0.290 |
| Propane | C_3H_8 | 44.09 | 370 | 42.7 | 0.276 |
| Propylene | C_3H_6 | 42.08 | 365 | 46.2 | 0.276 |
| Refrigerant 12 | CCl ₂ F ₂ | 120.92 | 385 | 41.2 | 0.278 |
| Refrigerant 22 | CHClF ₂ | 86.48 | 369 | 49.8 | 0.267 |
| Refrigerant 134a | CF ₃ CH ₂ F | 102.03 | 374 | 40.7 | 0.260 |
| Sulfur dioxide | SO ₂ | 64.06 | 431 | 78.7 | 0.268 |
| Water | H ₂ O | 18.02 | 647.3 | 220.9 | 0.233 |

Sources: Adapted from *International Critical Tables* and L. C. Nelson and E. F. Obert, Generalized Compressibility Charts, *Chem. Eng.*, 61: 203 (1954).

3.2.2 Projections of the p - v - T Surface

THE PHASE DIAGRAM

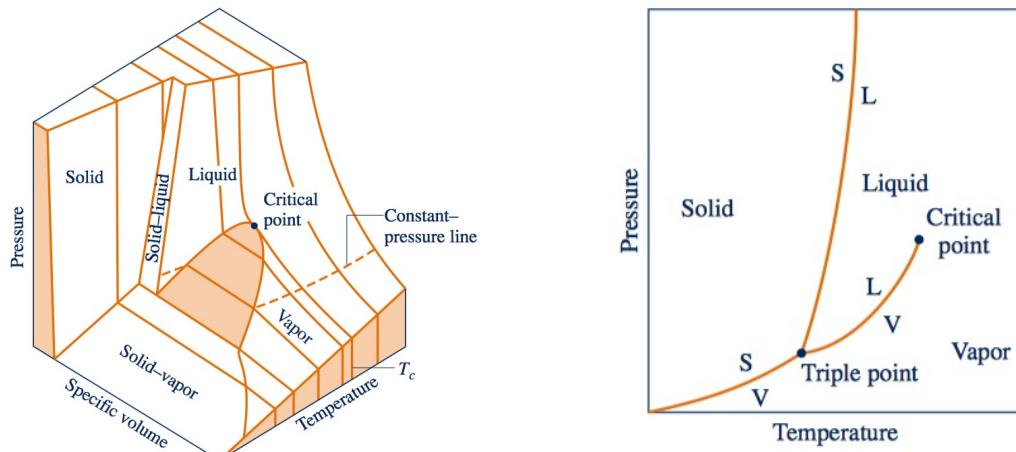
If the p - v - T surface is projected onto the pressure–temperature plane, a property diagram known as a **phase diagram** results.



3.2.2 Projections of the p - v - T Surface

The term **saturation temperature** designates the temperature at which a phase change takes place at a given pressure, and this pressure is called the **saturation pressure** for the given temperature. It is apparent from the phase diagrams that for each saturation pressure there is a unique saturation temperature, and conversely.

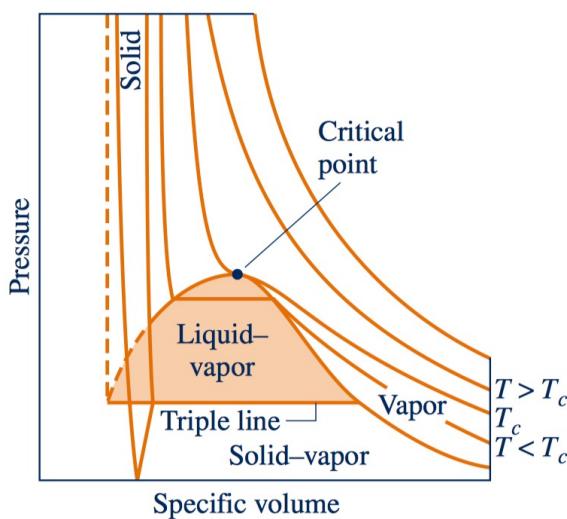
The triple line of the three-dimensional p - v - T surface projects onto a point on the phase diagram. This is called **the triple point**.



3.2.2 Projections of the p - v - T Surface

p - v DIAGRAM

Projecting the p - v - T surface onto the pressure-specific volume plane results in a p - v diagram.

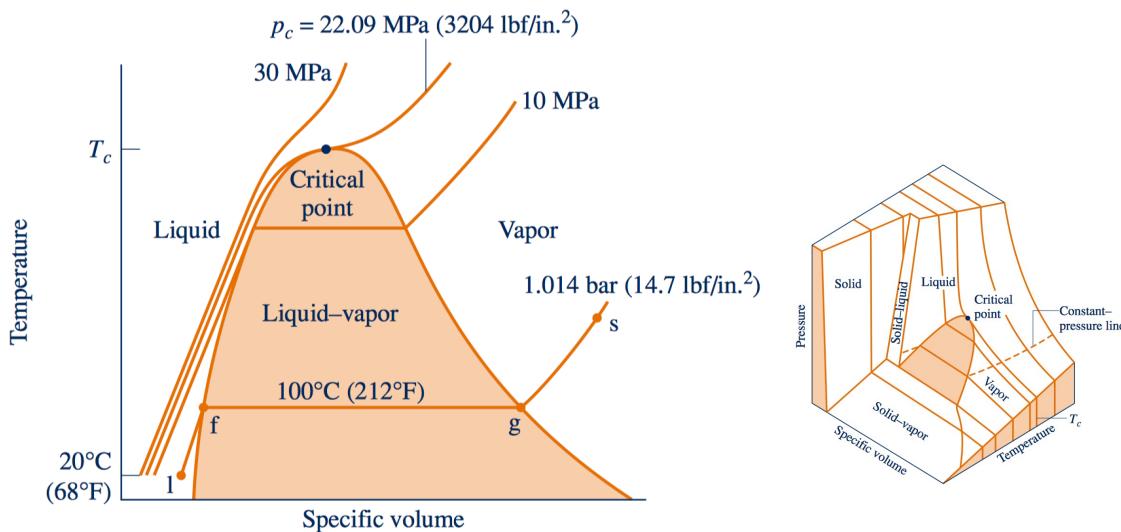


- ❑ For any specified temperature less than the critical temperature, pressure remains constant as the two-phase liquid-vapor region is traversed, but in the single-phase liquid and vapor regions, the pressure decreases at fixed temperature as specific volume increases.
- ❑ For temperatures greater than or equal to the critical temperature, pressure decreases continuously at fixed temperature as specific volume increases.

3.2.2 Projections of the $p-v-T$ Surface

T-v DIAGRAM

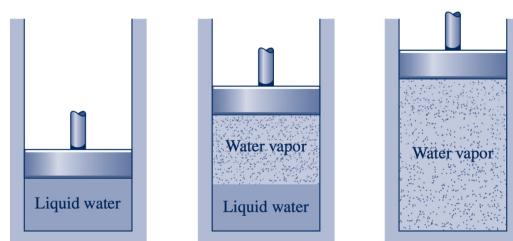
Projecting the liquid, two-phase liquid-vapor, and vapor regions of the $p-v-T$ surface onto the temperature-specific volume plane results in a T-v diagram.



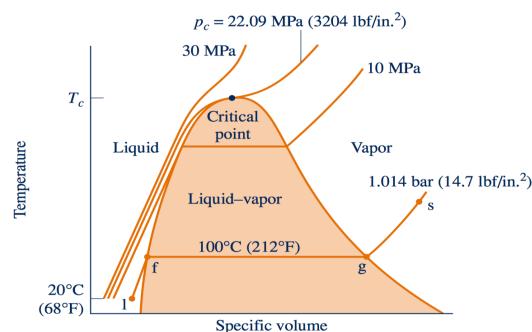
3.3 Studying Phase Change

Liquid States:

- The liquid states along the line segment $l-f$ are sometimes referred to as **subcooled liquid** states because the temperature at these states is less than the saturation temperature at the given pressure.
- These states are also referred to as **compressed liquid** states because the pressure at each state is higher than the saturation pressure corresponding to the temperature at the state.
- The names **liquid**, **subcooled liquid**, and **compressed liquid** are used interchangeably.



Constant-pressure change from liquid to vapor for water



3.3 Studying Phase Change

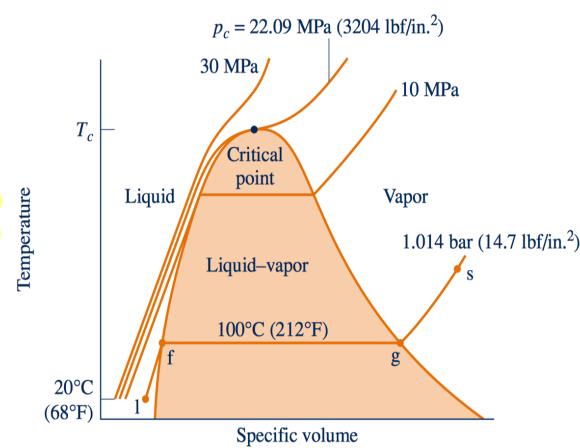
TWO-PHASE, LIQUID–VAPOR MIXTURE

When a mixture of liquid and vapor exists in equilibrium, the liquid phase is a saturated liquid and the vapor phase is a saturated vapor. If the system is heated further until the last bit of liquid has vaporized, it is brought to point *g* on the saturated vapor state.

The intervening two-phase liquid–vapor mixture states can be distinguished from one another by the **quality**, an intensive property.

For a two-phase liquid-vapor mixture, the ratio of the mass of vapor present to the total mass of the mixture is its quality, *x*.

$$x = \frac{m_{\text{vapor}}}{m_{\text{liquid}} + m_{\text{vapor}}}$$



3.4 Retrieving Thermodynamic Properties

Thermodynamic property data can be retrieved

- Tables
- Graphs
- Equations
- Computer software

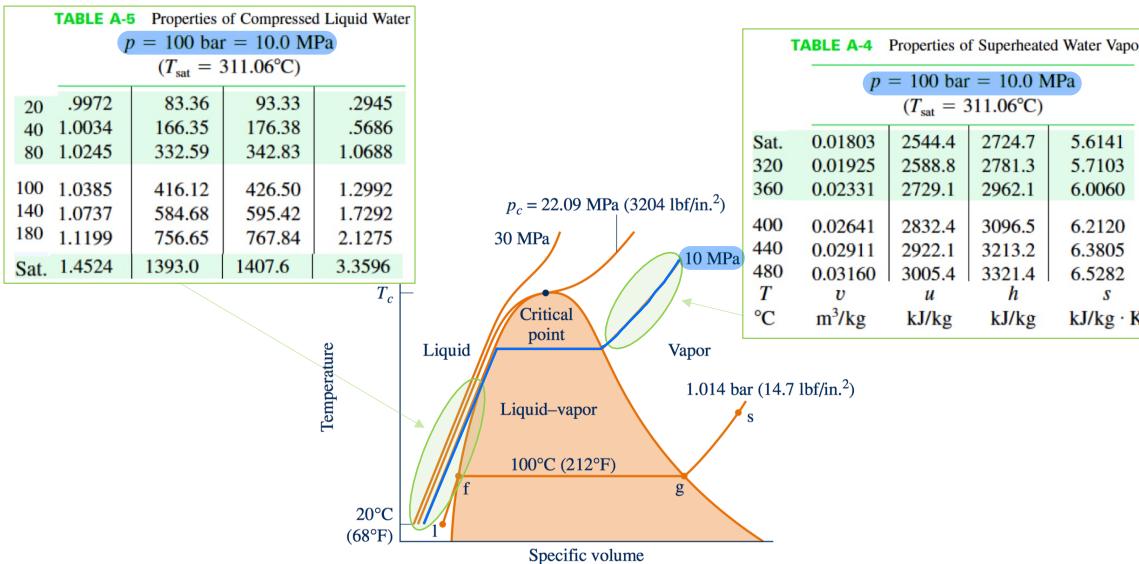
- Tables
- The steam tables (water properties)
 - Propane
 - Refrigerant 134a
 - Ammonia

Index to Tables in SI Units

| | | |
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3.5 Evaluating Pressure, Specific Volume, and Temperature

Vapor and liquid tables



3.5.2 Saturation Tables

The saturation tables, Tables A-2 and A-3, list property values for the saturated liquid and vapor states. The property values at these states are denoted by the subscripts f and g, respectively.

- ❑ Table A-2 is called the **temperature table**, because temperatures are listed in the first column in convenient increments.
- ❑ Table A-3 is called the **pressure table**, because pressures are listed in the first column in convenient increments.

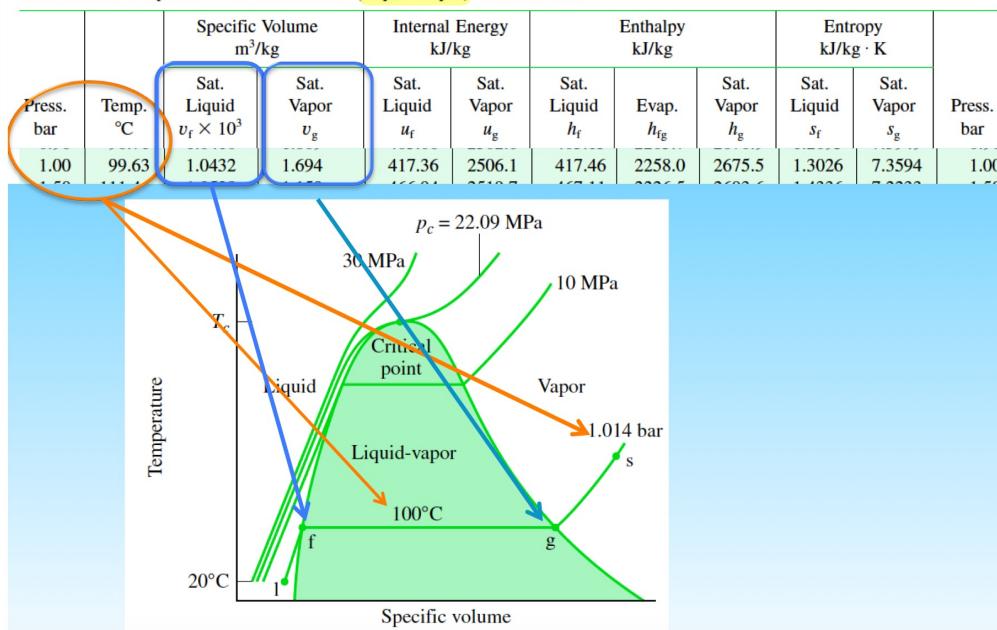
specific volume of saturated liquid, v_f **specific volume of saturated vapor, v_g**

TABLE A-2 Properties of Saturated Water (Liquid–Vapor): Temperature Table

| Temp. °C | Press. bar | Specific Volume m^3/kg | | Internal Energy kJ/kg | | Enthalpy kJ/kg | | Entropy $\text{kJ/kg} \cdot \text{K}$ | | Temp. °C |
|-------------|---------------|---|------------------------|-----------------------------------|------------------------|----------------------------|---------------------------|--|------------------------|-------------|
| | | Sat. Liquid $v_f \times 10^3$ | Sat. Vapor v_g | Sat. Liquid u_f | Sat. Vapor u_g | Sat. Liquid h_f | Sat. Vapor h_{fg} | Sat. Liquid s_f | Sat. Vapor s_g | |
| .01 | 0.00611 | 1.0002 | 206.136 | 0.00 | 2375.3 | 0.01 | 2501.3 | 2501.4 | 0.0000 | 9.1562 |
| 4 | 0.00813 | 1.0001 | 157.232 | 16.77 | 2380.9 | 16.78 | 2491.9 | 2508.7 | 0.0610 | 9.0514 |
| 5 | 0.00872 | 1.0001 | 147.120 | 20.97 | 2382.3 | 20.98 | 2489.6 | 2510.6 | 0.0761 | 9.0257 |
| 6 | 0.00935 | 1.0001 | 137.734 | 25.19 | 2383.6 | 25.20 | 2487.2 | 2512.4 | 0.0912 | 9.0003 |
| 8 | 0.01072 | 1.0002 | 120.917 | 33.59 | 2386.4 | 33.60 | 2482.5 | 2516.1 | 0.1212 | 8.9501 |
| 10 | 0.01228 | 1.0004 | 106.379 | 42.00 | 2389.2 | 42.01 | 2477.7 | 2519.8 | 0.1510 | 8.9008 |
| 11 | 0.01312 | 1.0004 | 99.857 | 46.20 | 2390.5 | 46.20 | 2475.4 | 2521.6 | 0.1658 | 8.8765 |
| 12 | 0.01402 | 1.0005 | 93.784 | 50.41 | 2391.9 | 50.41 | 2473.0 | 2523.4 | 0.1806 | 8.8524 |
| 13 | 0.01497 | 1.0007 | 88.124 | 54.60 | 2393.3 | 54.60 | 2470.7 | 2525.3 | 0.1953 | 8.8285 |
| 14 | 0.01598 | 1.0008 | 82.848 | 58.79 | 2394.7 | 58.80 | 2468.3 | 2527.1 | 0.2099 | 8.8048 |

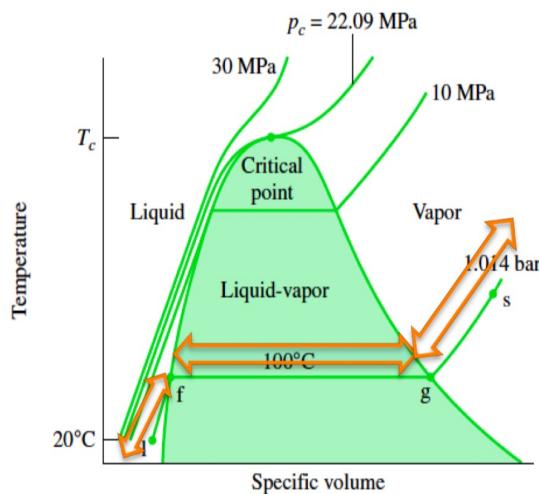
3.5.2 Saturation Tables

TABLE A-3 Properties of Saturated Water (Liquid–Vapor); Pressure Table



3.5 Evaluating Pressure, Specific Volume, and Temperature

- If the given specific volume falls between v_f and v_g , the system consists of a two-phase liquid–vapor mixture, and the pressure is the saturation pressure corresponding to the given temperature. The quality can be found by solving previous Equation.
- If the given specific volume is less than v_f , Table A-5 would be used to determine the pressure and other properties
- If the specific volume is greater than v_g , the state is in the superheated vapor region. Then, by interpolating in Table A-4 the pressure and other properties listed can be determined.



Example:

Determine the phase or phases in a system consisting of H₂O at the following conditions and sketch the p-v and T-v diagrams showing the location of the following state.

a) p = 10 bar, T = 179.9 °C

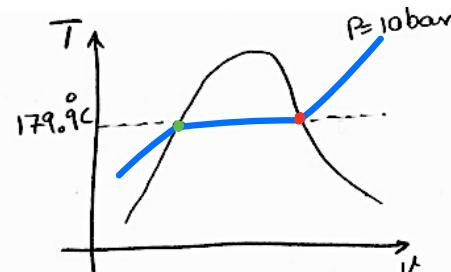
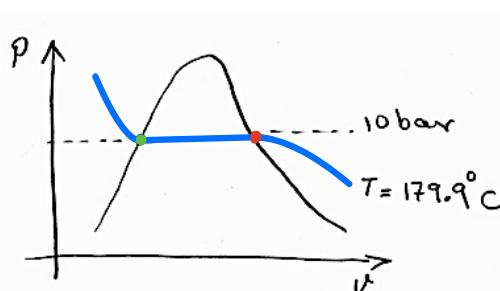
Water at this p and T should be liquid, liquid-vapor, or vapor. By checking at Table A3, we can find that at p=10bar, T_{sat}=179.9°C, so the system is in a two-phase (liquid-vapor mixture) state.

| TABLE A-3 Properties of Saturated Water (Liquid-Vapor): Pressure Table | | | | | | | | | | | |
|---|-------------|---------------------------------------|------------------------|--------------------------|------------------------|-------------------------|-------------------|------------------------|-------------------------|------------------------|---------------|
| Press. bar | Temp. °C | Specific Volume m ³ /kg | | Internal Energy kJ/kg | | Enthalpy kJ/kg | | | Entropy kJ/kg · K | | Press. bar |
| | | Sat. Liquid $v_l \times 10^3$ | Sat. Vapor v_g | Sat. Liquid u_l | Sat. Vapor u_g | Sat. Liquid h_l | Evap. h_{fg} | Sat. Vapor h_g | Sat. Liquid s_l | Sat. Vapor s_g | |
| 0.04 | 28.96 | 1.0040 | 34.800 | 121.45 | 2415.2 | 121.46 | 2432.9 | 2554.4 | 0.4226 | 8.4746 | 0.04 |
| 0.06 | 36.16 | 1.0064 | 23.739 | 151.53 | 2425.0 | 151.53 | 2415.9 | 2567.4 | 0.5210 | 8.3304 | 0.06 |
| 7.00 | 165.0 | 1.1080 | 0.2729 | 696.44 | 2572.5 | 697.22 | 2066.3 | 2763.5 | 1.9922 | 6.7080 | 7.00 |
| 8.00 | 170.4 | 1.1148 | 0.2404 | 720.22 | 2576.8 | 721.11 | 2048.0 | 2769.1 | 2.0462 | 6.6628 | 8.00 |
| 9.00 | 175.4 | 1.1212 | 0.2150 | 741.83 | 2580.5 | 742.83 | 2031.1 | 2773.9 | 2.0946 | 6.6226 | 9.00 |
| 10.0 | 179.9 | 1.1273 | 0.1944 | 761.68 | 2583.6 | 762.81 | 2015.3 | 2778.1 | 2.1387 | 6.5863 | 10.0 |
| 15.0 | 198.3 | 1.1539 | 0.1318 | 843.16 | 2594.5 | 844.84 | 1947.3 | 2792.2 | 2.3150 | 6.4448 | 15.0 |
| 20.0 | 212.4 | 1.1767 | 0.09963 | 906.44 | 2600.3 | 908.79 | 1890.7 | 2799.5 | 2.4474 | 6.3409 | 20.0 |

Example:

Determine the phase or phases in a system consisting of H₂O at the following conditions and sketch the p-v and T-v diagrams showing the location of the following state.

a) p = 10 bar, T = 179.9 °C



Example:

Determine the phase or phases in a system consisting of H_2O at the following conditions and sketch the p - v and T - v diagrams showing the location of the following state.

b) $p = 10 \text{ bar}$, $T = 150^\circ\text{C}$

Water at this p and T should be liquid, liquid-vapor, or vapor. By checking the Table A3, we can find that at $p=10\text{bar}$, $T_{\text{sat}}=179.9^\circ\text{C}$, the current T is less than $T_{\text{sat@10bar}}$, so its curve is below the $T_{\text{sat@10bar}}$ curve on the p - v diagram (see the fig), therefore its intersection with the $p=10\text{bar}$ -line will locate on the left side of the vapor dome. so the phase of the system at this state is compressed liquid or sub-cooled liquid.

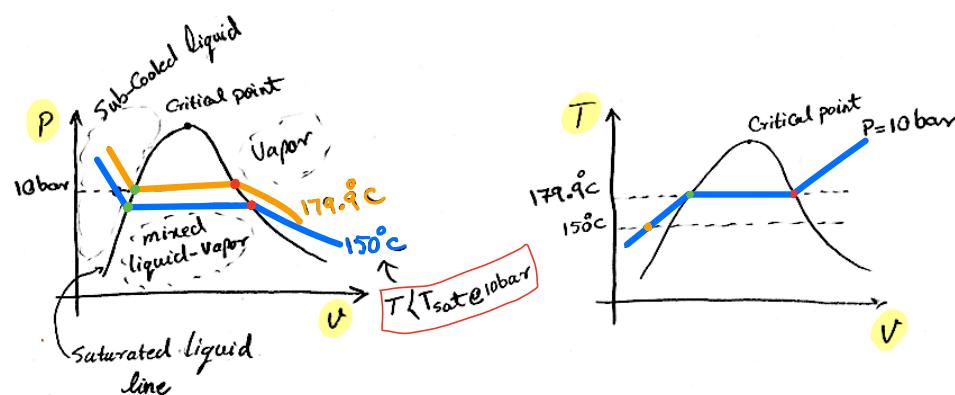
| TABLE A-3 Properties of Saturated Water (Liquid-Vapor): Pressure Table | | | | | | | | | | | |
|---|-------------|---|------------------------|-----------------------------------|------------------------|----------------------------|------------------------|--|------------------------|--|------------------------|
| Press. bar | Temp. °C | Specific Volume m^3/kg | | Internal Energy kJ/kg | | Enthalpy kJ/kg | | Entropy $\text{kJ/kg} \cdot \text{K}$ | | Sat. Liquid $\alpha \times 10^3$ | Sat. Vapor e_g |
| | | Sat. Liquid α | Sat. Vapor e_g | Sat. Liquid h_f | Sat. Vapor h_g | Sat. Liquid h_f | Sat. Vapor h_g | Sat. Liquid α | Sat. Vapor e_g | | |
| 0.04 | 28.96 | 1.0040 | 34.800 | 121.45 | 2415.2 | 121.46 | 2432.9 | 2554.4 | 0.4226 | 8.4746 | 0.04 |
| 0.06 | 36.16 | 1.0064 | 23.739 | 151.53 | 2425.0 | 151.53 | 2415.9 | 2567.4 | 0.5210 | 8.3304 | 0.06 |
| 7.00 | 165.0 | 1.1080 | 0.2729 | 696.44 | 2572.5 | 697.22 | 2066.3 | 2763.5 | 1.9922 | 6.7080 | 7.00 |
| 8.00 | 170.4 | 1.1148 | 0.2404 | 720.22 | 2576.8 | 721.11 | 2048.0 | 2769.1 | 2.0462 | 6.6628 | 8.00 |
| 9.00 | 175.4 | 1.1212 | 0.2150 | 741.83 | 2580.5 | 742.83 | 2031.1 | 2773.9 | 2.0946 | 6.6226 | 9.00 |
| 10.0 | 179.9 | 1.1273 | 0.1944 | 761.68 | 2583.6 | 762.81 | 2015.3 | 2778.1 | 2.1387 | 6.5863 | 10.0 |
| 15.0 | 198.3 | 1.1539 | 0.1318 | 843.16 | 2594.5 | 844.84 | 1947.3 | 2792.2 | 2.3150 | 6.4448 | 15.0 |
| 20.0 | 212.4 | 1.1767 | 0.09963 | 906.44 | 2600.3 | 908.79 | 1890.7 | 2799.5 | 2.4474 | 6.3409 | 20.0 |

Example:

Determine the phase or phases in a system consisting of H_2O at the following conditions and sketch the p - v and T - v diagrams showing the location of the following state.

b) $p = 10 \text{ bar}$, $T = 150^\circ\text{C}$

Water at this p and T should be liquid, liquid-vapor, or vapor. By checking the Table A3, we can find that at $p=10\text{bar}$, $T_{\text{sat}}=179.9^\circ\text{C}$, the current T is less than $T_{\text{sat@10bar}}$, so its curve is below the $T_{\text{sat@10bar}}$ curve on the p - v diagram (see the fig), therefore its intersection with the $p=10\text{bar}$ -line will locate on the left side of the vapor dome. so the phase of the system at this state is compressed liquid or sub-cooled liquid. Similarly we can sketch the T - v diagram.



Example:

Determine the phase or phases in a system consisting of H₂O at the following conditions and sketch the p-v and T-v diagrams showing the location of the following state.

c) T = 100 °C, p = 0.5 bar

Water at this p and T should be liquid, liquid-vapor, or vapor. For T=100°C, by checking the Table A2, we can find that at T=100°C, p_{sat}=1.014bar. in the current state, p is less than p_{sat@100°C}, therefore on the p-v diagram, the p=0.5bar line intersects with p_{sat@100°C} curve on the right side of vapor dome (see the fig). So the phase of the system at this state is superheated vapor. Similarly, on the T-v diagram, the p=0.5bar curve is below the p=1.014bar curve, hence the T=100°C line intersects with p=0.5bar curve on the right side of the vapor dome.

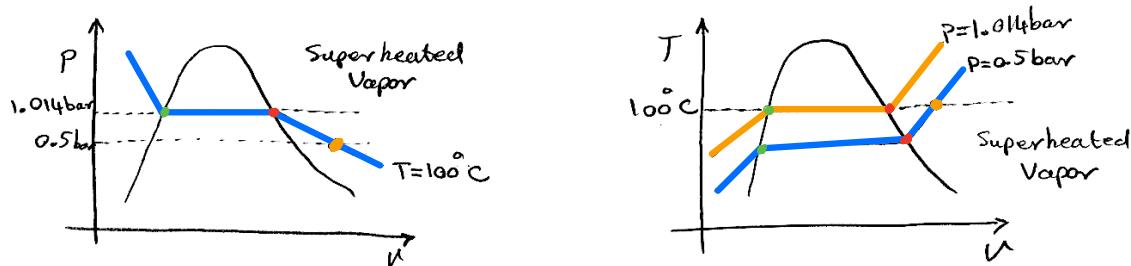
| TABLE A-2 | | (Continued) | | | | | | | | | |
|-------------|---------------|---------------------------------------|------------------------|--------------------------|------------------------|-------------------------|----------------|------------------------|-------------------------|------------------------|-------------|
| Temp. °C | Press. bar | Specific Volume m ³ /kg | | Internal Energy kJ/kg | | Enthalpy kJ/kg | | | Entropy kJ/kg · K | | Temp. °C |
| | | Sat. Liquid $v_l \times 10^3$ | Sat. Vapor v_g | Sat. Liquid u_l | Sat. Vapor u_g | Sat. Liquid h_l | Evap. h_b | Sat. Vapor h_g | Sat. Liquid s_l | Sat. Vapor s_g | |
| 50 | .1235 | 1.0121 | 12.032 | 209.32 | 2443.5 | 209.33 | 2382.7 | 2592.1 | .7038 | 8.0763 | 50 |
| 95 | .8455 | 1.0397 | 1.982 | 397.88 | 2500.6 | 397.96 | 2270.2 | 2668.1 | 1.2500 | 7.4159 | 95 |
| 100 | 1.014 | 1.0435 | 1.673 | 418.94 | 2506.5 | 419.04 | 2257.0 | 2676.1 | 1.3069 | 7.3549 | 100 |
| 110 | 1.433 | 1.0516 | 1.210 | 461.14 | 2518.1 | 461.30 | 2230.2 | 2691.5 | 1.4185 | 7.2387 | 110 |

Example:

Determine the phase or phases in a system consisting of H₂O at the following conditions and sketch the p-v and T-v diagrams showing the location of the following state.

c) T = 100 °C, p = 0.5 bar

Water at this p and T should be liquid, liquid-vapor, or vapor. For T=100°C, by checking the Table A2, we can find that at T=100°C, p_{sat}=1.014bar. in the current state, p is less than p_{sat@100°C}, therefore on the p-v diagram, the p=0.5bar line intersects with p_{sat@100°C} curve on the right side of vapor dome (see the fig). So the phase of the system at this state is superheated vapor. Similarly, on the T-v diagram, the p=0.5bar curve is below the p=1.014bar curve, hence the T=100°C line intersects with p=0.5bar curve on the right side of the vapor dome.



Example:

Determine the phase or phases in a system consisting of H₂O at the following conditions and sketch the p-v and T-v diagrams showing the location of the following state.

d) T = -6 °C, p = 1 bar

The temperature in this state is below the triple water point temperature. From Table A6 we can find that at T=-6°C, p_{sat}=0.003689bar, since the p>p_{sat}, on the p-v diagram, the p=1bar line intersects with T_{sat}@0.003689bar curve on the right side of the solid-vapor dome, so the phase of the current state is solid. similarly, we can sketch the T-v diagram.

TABLE A-6

Properties of Saturated Water (Solid-Vapor): Temperature Table

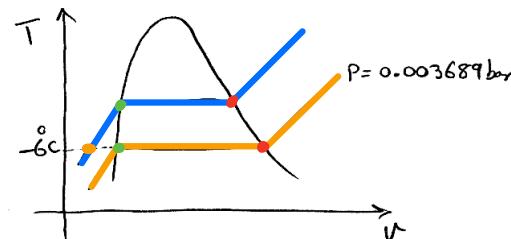
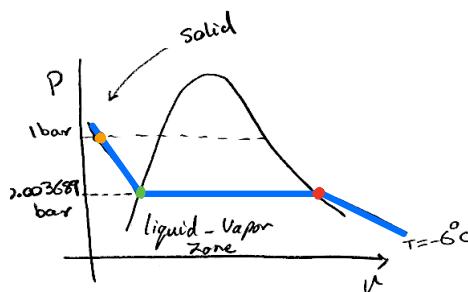
| Pressure Conversions: bar = 0.1 MPa = 10 ⁵ Pa | | Specific Volume m ³ /kg | | | | Internal Energy kJ/kg | | | | Enthalpy kJ/kg | | | | Entropy kJ/kg · K | |
|--|-----------------|---------------------------------------|------------------------|------------------------|----------------|--------------------------|------------------------|----------------|------------------------|------------------------|----------------|--|--|----------------------|--|
| Temp. °C | Pressure kPa | Sat. Solid $v_1 \times 10^3$ | Sat. Vapor v_g | Sat. Solid u_1 | Subl. u_g | Sat. Vapor u_g | Sat. Solid h_1 | Subl. h_g | Sat. Vapor h_g | Sat. Solid s_1 | Subl. s_g | | | | |
| .01 | .6113 | 1.0908 | 206.1 | -333.40 | 2708.7 | 2375.3 | -333.40 | 2834.8 | 2501.4 | -1.221 | 10.378 | | | | |
| 0 | .6108 | 1.0908 | 206.3 | -333.43 | 2708.8 | 2375.3 | -333.43 | 2834.8 | 2501.3 | -1.221 | 10.378 | | | | |
| -2 | .5176 | 1.0904 | 241.7 | -337.62 | 2710.2 | 2372.6 | -337.62 | 2835.3 | 2497.7 | -1.237 | 10.456 | | | | |
| -4 | .4375 | 1.0901 | 283.8 | -341.78 | 2711.6 | 2369.8 | -341.78 | 2835.7 | 2494.0 | -1.253 | 10.536 | | | | |
| -6 | .3689 | 1.0898 | 334.2 | -345.91 | 2712.9 | 2367.0 | -345.91 | 2836.2 | 2490.3 | -1.268 | 10.616 | | | | |
| -8 | .3102 | 1.0894 | 394.4 | -350.02 | 2714.2 | 2364.2 | -350.02 | 2836.6 | 2486.6 | -1.284 | 10.698 | | | | |

Example:

Determine the phase or phases in a system consisting of H₂O at the following conditions and sketch the p-v and T-v diagrams showing the location of the following state.

d) T = -6 °C, p = 1 bar

The temperature in this state is below the triple water point temperature. From Table A6 we can find that at T=-6°C, p_{sat}=0.003689bar, since the p>p_{sat}, on the p-v diagram, the p=1bar line intersects with T_{sat}@0.003689bar curve on the right side of the solid-vapor dome, so the phase of the current state is solid. similarly, we can sketch the T-v diagram.



Example:

For H_2O , locate each of the following states on sketches of the $p-v$, $T-v$, and phase diagrams.

- (a) $T = 120^\circ\text{C}$, $p = 5 \text{ bar}$.
- (b) $T = 120^\circ\text{C}$, $v = 0.6 \text{ m}^3/\text{kg}$.
- (c) $T = 120^\circ\text{C}$, $p = 1 \text{ bar}$.

| TABLE A-2 (Continued) | | | | | | | | | | | | |
|---------------------------|---------------|--|------------------------|---|------------------------|-----------------------------------|-------------------|----------------------------|-------------------------|--|---------------------------|--|
| | | Pressure Conversions: 1 bar = 0.1 MPa = 10^5 kPa | | Specific Volume m^3/kg | | Internal Energy kJ/kg | | Enthalpy kJ/kg | | Entropy $\text{kJ/kg} \cdot \text{K}$ | | |
| Temp. $^\circ\text{C}$ | Press. bar | Sat. Liquid $v_f \times 10^3$ | Sat. Vapor v_g | Sat. Liquid u_f | Sat. Vapor u_g | Sat. Liquid h_f | Evap. h_{fg} | Sat. Vapor h_g | Sat. Liquid s_f | Sat. Vapor s_g | Temp. $^\circ\text{C}$ | |
| 100 | 1.014 | 1.0435 | 1.673 | 418.94 | 2506.5 | 419.04 | 2257.0 | 2676.1 | 1.3069 | 7.3549 | 100 | |
| 110 | 1.433 | 1.0516 | 1.210 | 461.14 | 2518.1 | 461.30 | 2230.2 | 2691.5 | 1.4185 | 7.2387 | 110 | |
| 120 | 1.985 | 1.0603 | 0.8919 | 503.50 | 2529.3 | 503.71 | 2202.6 | 2706.3 | 1.5276 | 7.1296 | 120 | |
| 130 | 2.701 | 1.0697 | 0.6685 | 546.02 | 2539.9 | 546.31 | 2174.2 | 2720.5 | 1.6344 | 7.0269 | 130 | |

Example:

For H_2O , locate each of the following states on sketches of the $p-v$, $T-v$, and phase diagrams.

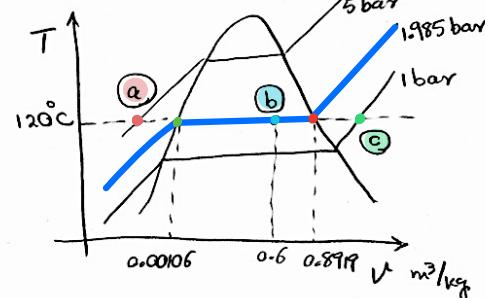
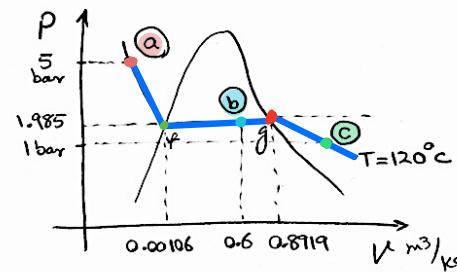
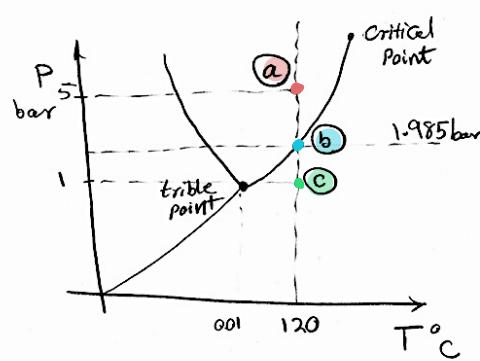
- (a) $T = 120^\circ\text{C}$, $p = 5 \text{ bar}$.
- (b) $T = 120^\circ\text{C}$, $v = 0.6 \text{ m}^3/\text{kg}$.
- (c) $T = 120^\circ\text{C}$, $p = 1 \text{ bar}$.

Since $T = 120^\circ\text{C}$ from Table A2 we can find v_f and v_g

and P_{sat} .

Table A2

- $v_f = 1.0603 \times 10^3 \text{ m}^3/\text{kg}$
- $v_g = 0.8919 \text{ m}^3/\text{kg}$
- $P_{\text{sat}} = 1.985 \text{ bar}$



Example:

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

| $p = 1.0 \text{ MPa}$ | | $p = 1.5 \text{ MPa}$ | |
|--------------------------------|---------------------------|--------------------------------|---------------------------|
| $T (\text{ }^{\circ}\text{C})$ | $v(\text{m}^3/\text{kg})$ | $T (\text{ }^{\circ}\text{C})$ | $v(\text{m}^3/\text{kg})$ |
| 200 | 0.2060 | 200 | 0.1325 |
| 240 | 0.2275 | 240 | 0.1483 |
| 280 | 0.2480 | 280 | 0.1627 |

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

- the specific volume at $T = 240\text{ }^{\circ}\text{C}$, $p = 1.25 \text{ MPa}$, in m^3/kg .
- the temperature at $p = 1.5 \text{ MPa}$, $v = 0.1555 \text{ m}^3/\text{kg}$, in $^{\circ}\text{C}$.

Interpolation

| $p = 1.0 \text{ MPa}$ | | $p = 1.5 \text{ MPa}$ | |
|--------------------------------|---------------------------|--------------------------------|---------------------------|
| $T (\text{ }^{\circ}\text{C})$ | $v(\text{m}^3/\text{kg})$ | $T (\text{ }^{\circ}\text{C})$ | $v(\text{m}^3/\text{kg})$ |
| 200 | 0.2060 | 200 | 0.1325 |
| 240 | 0.2275 | 240 | 0.1483 |
| 280 | 0.2480 | 280 | 0.1627 |

at $T = 240\text{ }^{\circ}\text{C}$

| | |
|-----------------------------------|---|
| <u>$P \text{ mpa}$</u> | <u>$v \text{ m}^3/\text{kg}$</u> |
| <u>1</u> | <u>0.2275</u> |
| <u>1.25</u> | <u>0.1483</u> |
| <u>1.5</u> | |

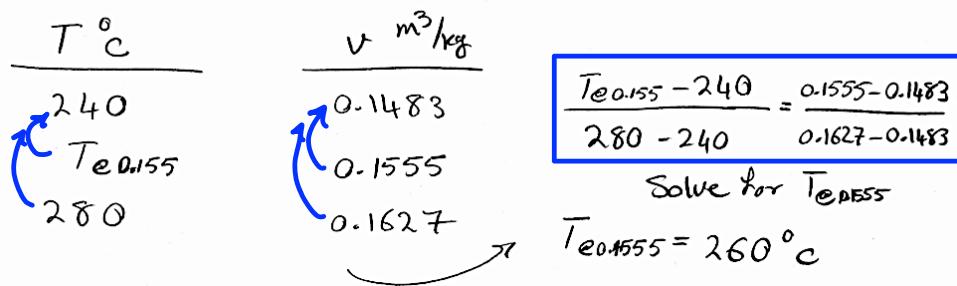
$$\frac{1.25 - 1}{1.5 - 1} = \frac{V_{1.25\text{ mpa}} - 0.2275}{0.1483 - 0.2275}$$
Solve for $V_{1.25\text{ mpa}}$

$V_{1.25\text{ mpa}} = 0.188 \text{ m}^3/\text{kg}$

Interpolation

| $p = 1.0 \text{ MPa}$ | | $p = 1.5 \text{ MPa}$ | |
|--------------------------------|---------------------------|--------------------------------|---------------------------|
| $T (\text{ }^{\circ}\text{C})$ | $v(\text{m}^3/\text{kg})$ | $T (\text{ }^{\circ}\text{C})$ | $v(\text{m}^3/\text{kg})$ |
| 200 | 0.2060 | 200 | 0.1325 |
| 240 | 0.2275 | 240 | 0.1483 |
| 280 | 0.2480 | 280 | 0.1627 |

at $P = 1.5 \text{ MPa}$



Total volume of the mixture

The **total volume of the mixture** is the sum of the volumes of the liquid and vapor phases

$$V = V_{liq} + V_{vap} \quad \rightarrow \quad v = \frac{V}{m} = \frac{V_{liq}}{m} + \frac{V_{vap}}{m}$$

Since the liquid phase is a saturated liquid and the vapor phase is a saturated vapor,

$$\begin{aligned} V_{liq} &= m_{liq} v_f \\ V_{vap} &= m_{vap} v_g \end{aligned} \quad \rightarrow \quad v = \left(\frac{m_{liq}}{m} \right) v_f + \left(\frac{m_{vap}}{m} \right) v_g$$

Quality $\rightarrow x = \frac{m_{vap}}{m}, \frac{m_{liq}}{m} = 1 - x$

$$v = (1 - x)v_f + xv_g = v_f + x(v_g - v_f) = v_f + xv_{fg}$$

Example:

A closed, rigid tank contains a two-phase liquid–vapor mixture of Refrigerant 22 initially at -20°C with a quality of 50.36%. Energy transfer by heat into the tank occurs until the refrigerant is at a final pressure of 6 bar. Determine:

- a) the final temperature, in °C. If the final state is in the superheated vapor region,
- b) at what temperature, in °C, does the tank contain only saturated vapor.

3.6 Evaluating Specific Internal Energy and Enthalpy

In many thermodynamic analyses the sum of the internal energy U and the product of pressure p and volume V appears. This combination name is **enthalpy**.

$$H=U+pV$$

Enthalpy Internal energy Product of P V
J or kJ J or kJ J or kJ

On Unit mass bases

$$h=u + p v \quad J/kg \text{ or } kJ/kg$$

3.6 Evaluating Specific Internal Energy and Enthalpy

- Data for specific internal energy u and enthalpy h are retrieved from the property tables.
- For saturation states, the values of u_f and u_g , as well as h_f and h_g , are tabulated versus both saturation pressure and saturation temperature.
- The specific internal energy for a two-phase liquid–vapor mixture is calculated as:

$$u = (1 - x)u_f + xu_g = u_f + x(u_g - u_f) = u_f + xu_{fg}$$

- The specific enthalpy for a two-phase liquid–vapor mixture is calculated in terms of the quality by

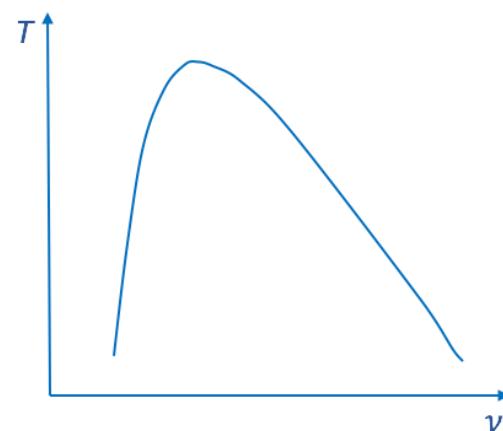
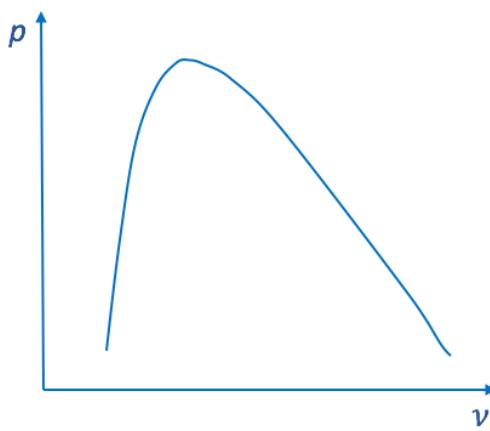
$$h = (1 - x)h_f + xh_g = h_f + x(h_g - h_f) = h_f + xh_{fg}$$

3.6 Evaluating Specific Internal Energy and Enthalpy

Example:

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

a) At $T=320^\circ\text{C}$, $v=0.03 \text{ m}^3/\text{kg}$, find p in MPa and u in kJ/kg.



3.6 Evaluating Specific Internal Energy and Enthalpy

Solution:

We Check Table A-2 for mix liquid-vapor Water:

| TABLE A-2 | | Properties of Saturated Water (Liquid–Vapor): Temperature Table | | | | | | | | | | |
|-------------|---------------|---|------------------------|--------------------------|------------------------|-------------------------|-------------------|------------------------|-------------------------|------------------------|-------------|--|
| Temp. °C | Press. bar | Specific Volume m ³ /kg | | Internal Energy kJ/kg | | Enthalpy kJ/kg | | | Entropy kJ/kg · K | | Temp. °C | |
| | | Sat. Liquid $v_l \times 10^3$ | Sat. Vapor v_g | Sat. Liquid u_l | Sat. Vapor u_g | Sat. Liquid h_l | Evap. h_{fg} | Sat. Vapor h_g | Sat. Liquid s_l | Sat. Vapor s_g | | |
| 300 | 85.81 | 1.4036 | 0.02167 | 1332.0 | 2563.0 | 1344.0 | 1404.9 | 2749.0 | 3.2534 | 5.7045 | 300 | |
| 320 | 112.7 | 1.4988 | 0.01549 | 1444.6 | 2525.5 | 1461.5 | 1238.6 | 2700.1 | 3.4480 | 5.5362 | 320 | |
| 340 | 145.9 | 1.6379 | 0.01080 | 1570.3 | 2464.6 | 1594.2 | 1027.9 | 2622.0 | 3.6594 | 5.3357 | 340 | |

It is found that $v > v_g @ 320^\circ\text{C}$, so the indicated state is a super heated state. We should look up the Table A-4 for super-heated water;

3.6 Evaluating Specific Internal Energy and Enthalpy

Solution:

By Check Table A-4 we can see that at $T=320^\circ\text{C}$, the $v=0.03$ state falls between 60 and 80 bar.

| At $T=320^\circ\text{C}$ | v (m ³ /kg) | p (bar) | u (kJ/kg) |
|--------------------------|--------------------------|-----------|-------------|
| 0.03876 | 60 | 2720.0 | |
| 0.03 | $p=?$ | $u=?$ | |
| 0.02682 | 80 | 2662.7 | |

Doing a linear interpolation for $v=0.03$ m³/kg, p and u are calculated as:

$$\frac{p - 60}{80 - 60} = \frac{0.03 - 0.03876}{0.02682 - 0.03876}$$

$$\frac{u - 2720}{2662.7 - 2720} = \frac{0.03 - 0.03876}{0.02682 - 0.03876}$$

Solving for p and for u:

$P=74.67\text{bar or } 0.7467\text{MPa}$

$u=2677.96\text{ kJ/kg}$

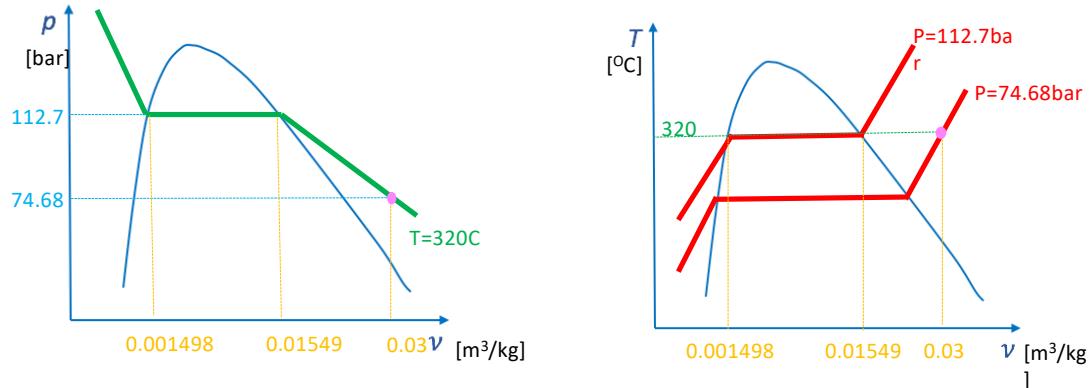
TABLE A-4

(Continued)

| T °C | v m ³ /kg | u kJ/kg | h kJ/kg | s kJ/kg · K | v m ³ /kg | u kJ/kg | h kJ/kg | s kJ/kg · K |
|--|---------------------------|--------------|--------------|------------------|---------------------------|--------------|--------------|------------------|
| $p = 40\text{ bar} = 4.0\text{ MPa}$ ($T_{sat} = 250.4^\circ\text{C}$) | | | | | | | | |
| $p = 60\text{ bar} = 6.0\text{ MPa}$ ($T_{sat} = 275.64^\circ\text{C}$) | | | | | | | | |
| Sat. | 0.04978 | 2602.3 | 2801.4 | 6.0701 | 0.03244 | 2589.7 | 2784.3 | 5.8892 |
| 280 | 0.05546 | 2680.0 | 2901.8 | 6.2568 | 0.03317 | 2605.2 | 2804.2 | 5.9252 |
| 320 | 0.06199 | 2767.4 | 3015.4 | 6.4553 | 0.03876 | 2720.0 | 2952.6 | 6.1846 |
| 360 | 0.06788 | 2845.7 | 3117.2 | 6.6215 | 0.04331 | 2811.2 | 3071.1 | 6.3782 |
| 400 | 0.07341 | 2919.9 | 3213.6 | 6.7690 | 0.04739 | 2892.9 | 3177.2 | 6.5408 |
| 440 | 0.07872 | 2992.2 | 3307.1 | 6.9041 | 0.05122 | 2970.0 | 3277.3 | 6.6853 |
| 500 | 0.08643 | 3099.5 | 3445.3 | 7.0901 | 0.05665 | 3082.2 | 3422.2 | 6.8803 |
| 540 | 0.09145 | 3171.1 | 3536.9 | 7.2056 | 0.06015 | 3156.1 | 3517.0 | 6.9999 |
| 600 | 0.09885 | 3279.1 | 3674.4 | 7.3688 | 0.06525 | 3266.9 | 3658.4 | 7.1677 |
| 640 | 0.1037 | 3351.8 | 3766.6 | 7.4720 | 0.06859 | 3341.0 | 3752.6 | 7.2731 |
| 700 | 0.1110 | 3462.1 | 3905.9 | 7.6198 | 0.07352 | 3453.1 | 3894.1 | 7.4234 |
| 740 | 0.1157 | 3536.6 | 3999.6 | 7.7141 | 0.07677 | 3528.3 | 3989.2 | 7.5190 |
| $p = 80\text{ bar} = 8.0\text{ MPa}$ ($T_{sat} = 295.06^\circ\text{C}$) | | | | | | | | |
| $p = 100\text{ bar} = 10.0\text{ MPa}$ ($T_{sat} = 311.06^\circ\text{C}$) | | | | | | | | |
| Sat. | 0.02352 | 2569.8 | 2758.0 | 5.7432 | 0.01803 | 2544.4 | 2724.7 | 5.6141 |
| 320 | 0.02682 | 2662.7 | 2877.2 | 5.9489 | 0.01925 | 2588.8 | 2781.3 | 5.7103 |
| 360 | 0.03089 | 2772.7 | 3019.8 | 6.1819 | 0.02331 | 2729.1 | 2962.1 | 6.0060 |
| 400 | 0.03432 | 2863.8 | 3138.3 | 6.3634 | 0.02641 | 2832.4 | 3096.5 | 6.2120 |
| 440 | 0.03742 | 2946.7 | 3246.1 | 6.5190 | 0.02911 | 2922.1 | 3213.2 | 6.3805 |
| 480 | 0.04034 | 3025.7 | 3348.4 | 6.6586 | 0.03160 | 3005.4 | 3321.4 | 6.5282 |

3.6 Evaluating Specific Internal Energy and Enthalpy

Solution:



3.8.1 Applying the Energy Balance Using Property Tables and Software

For thermodynamics process where changes in potential and kinetic energy between two states can be ignored;

$$U_2 - U_1 = Q - W$$

The internal energy term is evaluated in **three** representative cases of systems involving a single substance:

Case 1: A system *consisting initially and finally of a single phase of water, vapor or liquid.*

$$m(u_2 - u_1) = Q - W$$

Case 2: A system consisting *initially of water vapor and finally as a two phase mixture of liquid water and water vapor.*

$$U_1 = mu_1$$

$$U_2 = (U_{\text{liq}} + U_{\text{vap}}) = m_{\text{liq}}u_f + m_{\text{vap}}u_g = mu_2.$$

$$u_2 = (1-x)u_f + xu_g = u_f + x(u_g - u_f) = u_f + xu_{fg}$$

Case 3: a system consisting *initially of two separate masses of water vapor that mix to form a total mass of water vapor.*

$$U_1 = m'u(T', p') + m''u(T'', p'')$$

$$U_2 = (m' + m'')u(T_2, p_2)$$

$$= mu(T_2, p_2)$$

3.8.1 Applying the Energy Balance Using Property Tables and Software

Example 3.47:

A closed, rigid tank contains Refrigerant 134a, initially at 100°C . The refrigerant is cooled until it becomes saturated vapor at 20°C . For the refrigerant, determine the initial and final pressures, each in bar, and the heat transfer, in kJ/kg . Kinetic and potential energy effects can be ignored.

3.8.1 Applying the Energy Balance Using Property Tables and Software

Example 3.50:

Refrigerant 22 undergoes a constant-pressure process within a piston–cylinder assembly from saturated vapor at 4 bar to a final temperature of 30°C . Kinetic and potential energy effects are negligible. For the refrigerant, show the process on a p – v diagram. Evaluate the work and the heat transfer, each in kJ per kg of refrigerant.