Chapter 3

Evaluating Properties

Learning Outcomes

►Demonstrate understanding of key concepts . . . including phase and pure substance, state principle for simple compressible systems, *p-v and T-v* graphs, saturation temperature and saturation pressure, two-phase liquid-vapor mixture, quality, enthalpy, and specific heats.

►Apply energy balance with property data.

Learning Outcomes, cont.

►Locate states on $p\text{-}v$, $T\text{-}v$ and other thermodynamic diagrams $T\text{-}h$, for example.

►Retrieve property data from Tables A-1 through A-23.

►Apply the ideal gas model for thermo-dynamic analysis, including determining when use of the model is warranted.

Phase

►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 (gas)*.

►**Examples**:

►The air we breathe is a gas phase consisting of a mixture of different gases.

►Drinking water with ice cubes contains two phases of water: liquid and solid.

►Vinegar and olive oil salad dressing contains two different liquid phases.

Pure Substance

►A substance 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.

►**Examples**:

  ►Drinking water with ice cubes can be regarded as a pure substance because each phase has the same composition.

  ►A fuel-air mixture in the cylinder of an automobile engine can be regarded as a pure substance until ignition occurs.
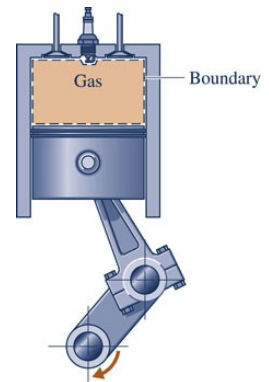
State Principle for Simple Compressible Systems

► Systems of commonly encountered pure substances are called simple compressible systems. These substances include those in appendix tables A-2 through A-18, A-22, and A-23.

► The intensive state of a simple compressible system at equilibrium is described by its intensive properties, including temperature, pressure, specific volume, density, specific internal energy, and specific enthalpy.

► Properties such as velocity and elevation are excluded because their values depend on arbitrary datum choices.

State Principle for Simple Compressible Systems

►Not all of the relevant intensive properties are independent.

    ►Some are related by definitions – **for example**, density is $1/v$ and specific enthalpy is $u + pv$ (Eq. 3.4).

    ►Others are related through expressions developed from experimental data.

    ►Some intensive properties may be independent in a single phase, but become dependent when there is more than one phase present.

State Principle for
Simple Compressible Systems

► For a simple compressible system, values for *any two* independent intensive properties determine the values of *all other* intensive properties. This is the **state principle for simple compressible systems**.

► Among alternative sets of two independent intensive properties, (T, v) and (p, v) are frequently convenient. We soon show that pressure and temperature are not always an independent set.

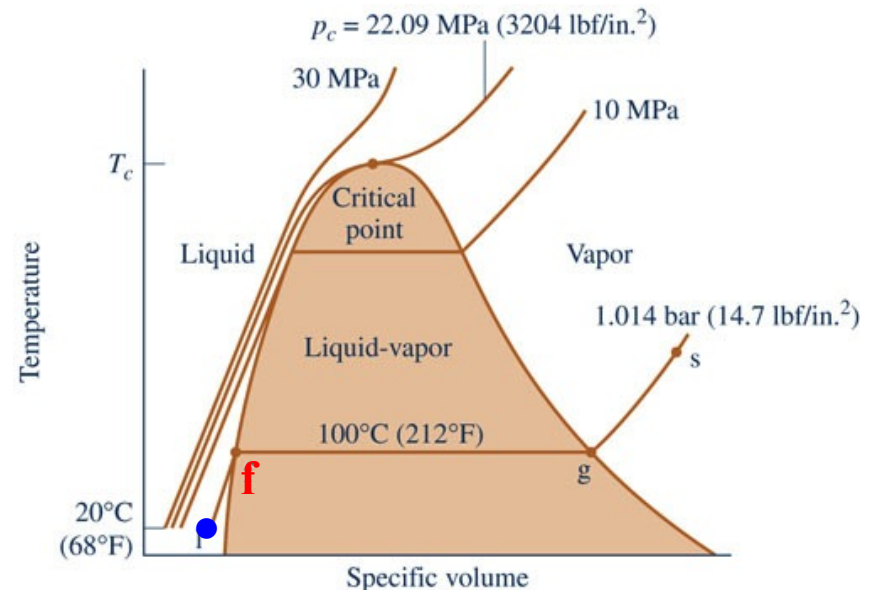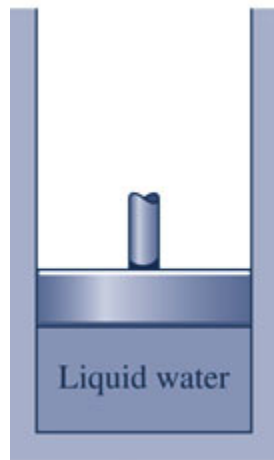# Phase Change

► Consider a closed system consisting of a unit mass of liquid water at 20ºC contained within a piston-cylinder assembly.

► This state is represented by **l** (highlighted by the blue dot).

► Liquid states such as this, where temperature is lower than the saturation temperature corresponding to the pressure at the state, are called **compressed liquid** states.
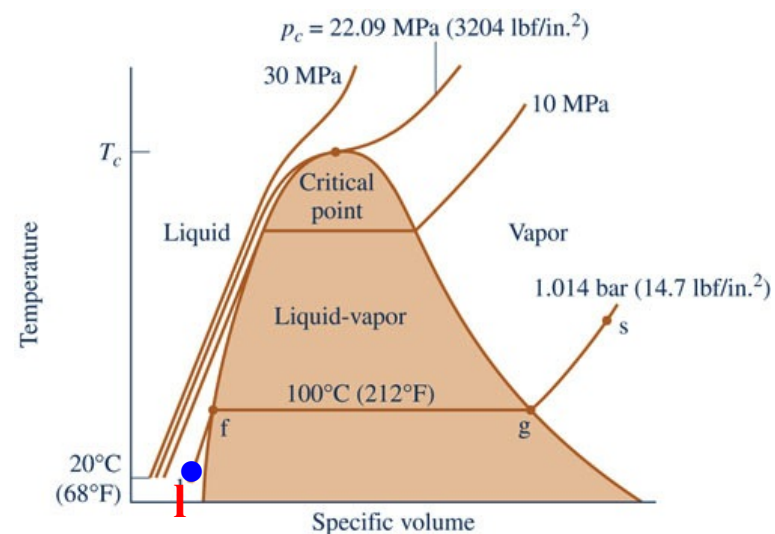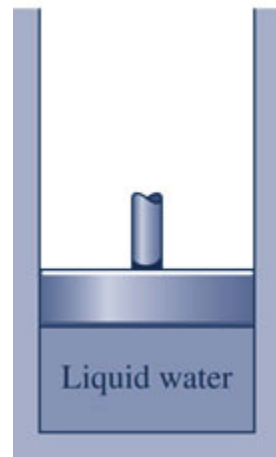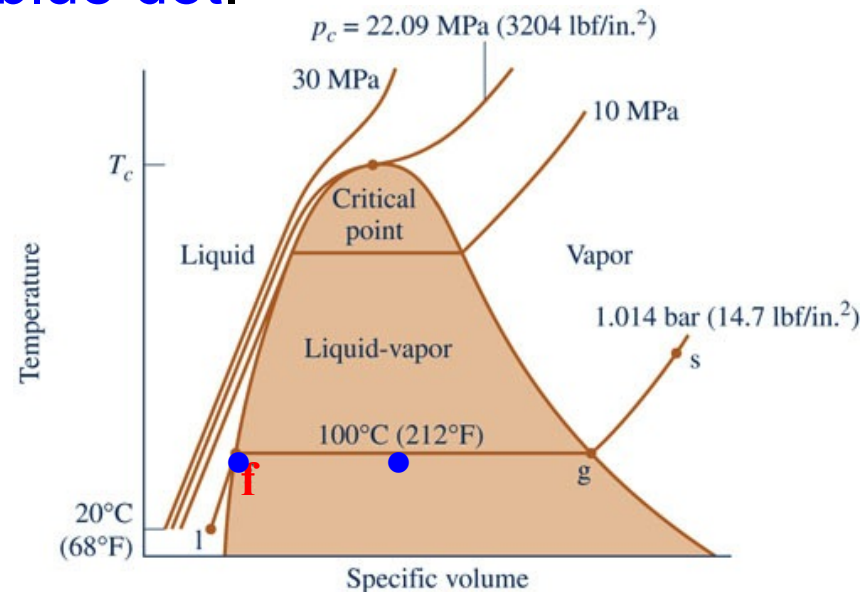
Saturated Liquid

►As the system is heated at constant pressure, the temperature increases considerably while the specific volume increases slightly.

►Eventually, the system is brought to the state represented by **f** (highlighted by the blue dot).

►This is the **saturated liquid** state corresponding to the specified pressure.

Two-Phase Liquid-Vapor Mixture

► When the system is at the saturated liquid state, additional heat transfer at fixed pressure results in the formation of vapor without change in temperature but with a considerable increase in specific volume as shown by movement of the blue dot.

► With additional heating at fixed pressure, more vapor is formed and specific volume increases further as shown by additional movement of the blue dot.

► At these states, the system now consists of a **two-phase liquid-vapor mixture**.

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.

► 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.

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

► The value of quality ranges from 0 to 1.

► At saturated liquid states, $x = 0$.
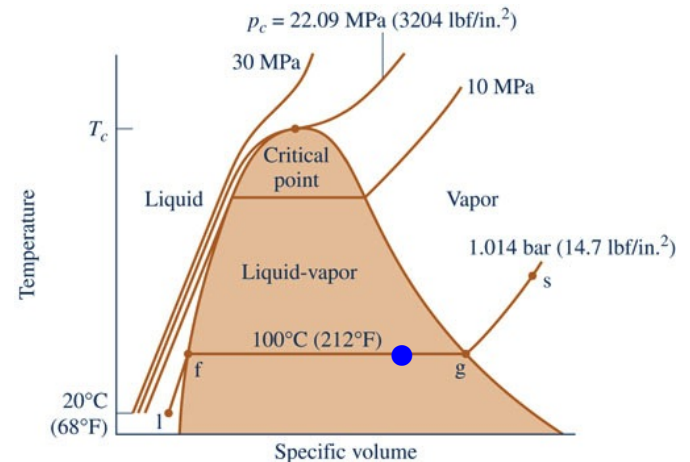
# Saturated Vapor

►If the system is heated further until the last bit of liquid has vaporized it is brought to the **saturated vapor** state.

►This state is represented by **g** (highlighted by the blue dot).

►At saturated vapor states, x = 1.
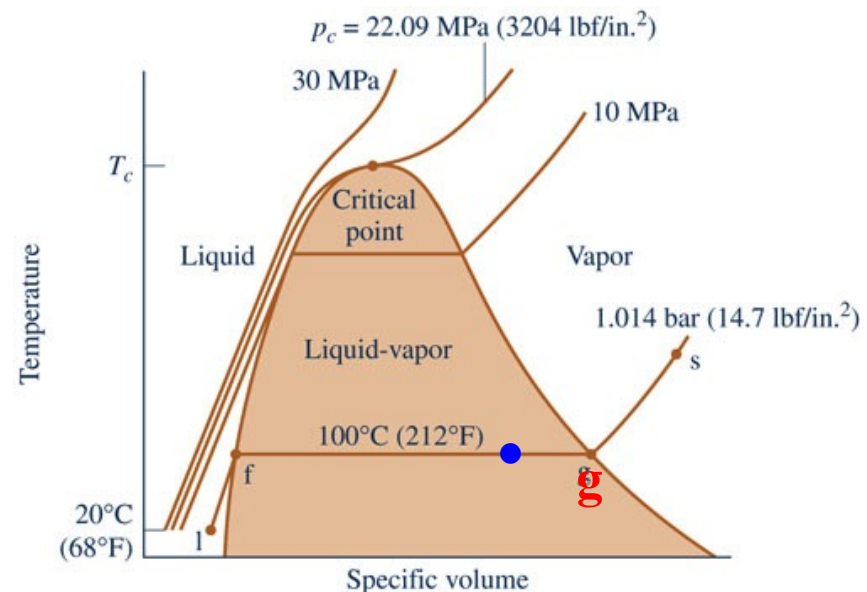
Superheated Vapor

► When the system is at the saturated vapor state, further heating at fixed pressure results in increases in both temperature and specific volume.

► This state is represented by s (highlighted by the blue dot).

► Vapor states such as this, where temperature is higher than the saturation temperature corresponding to the pressure at the state, are called **superheated vapor** states.
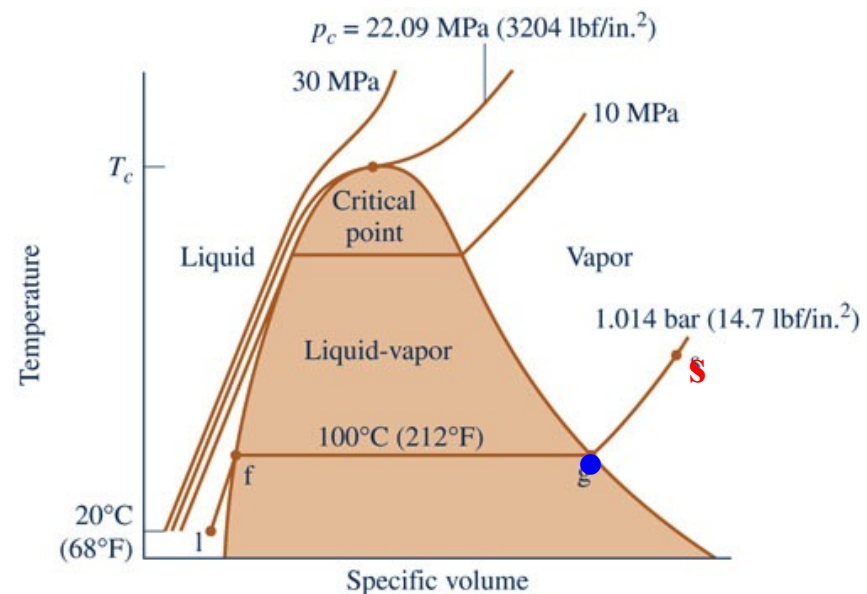
Steam Tables

►Tables of properties for different substances are frequently set up in the same general format. The tables for water, called the steam tables, provide an example of this format. The steam tables are in appendix tables A-2 through A-5.

   ►Table A-4 applies to water as a superheated vapor.

   ►Table A-5 applies to compressed liquid water.

   ►Tables A-2 and A-3 apply to the two-phase, liquid-vapor mixture of water.

Single-Phase Regions

► **Example**: Properties associated with superheated water vapor at 10 MPa and 400°C are found in **Table A-4**.

   ► v = 0.02641 m³/kg   ► h = 3096.5 kJ/kg

   ► u = 2832.4 kJ/kg   ► s = 6.2120 kJ/kg·K

Table A-4

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	p = 80 bar = 8.0 MPa (Tsat = 295.06°C)				p = 100 bar = 10.0 MPa (Tsat = 311.06°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

Linear Interpolation

► When a state does not fall exactly on the grid of values provided by property tables, linear interpolation between adjacent entries is used.

► **Example**: Specific volume (v) associated with superheated water vapor at 10 bar and 215ºC is found by linear interpolation between adjacent entries in **Table A-4**.

$$slope = \frac{(0.2275 - 0.2060)\ \text{m}^3/\text{kg}}{(240 - 200)^\circ\text{C}} = \frac{(v - 0.2060)\ \text{m}^3/\text{kg}}{(215 - 200)^\circ\text{C}} \rightarrow v = 0.2141\ \text{m}^3/\text{kg}$$
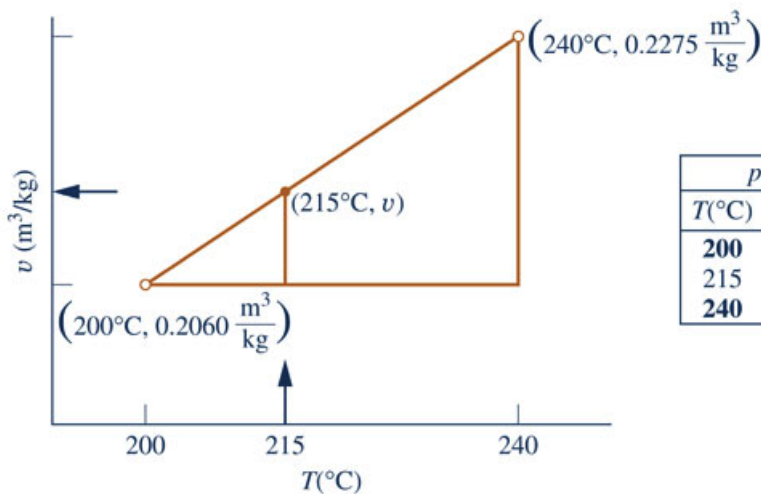
$p = 10$ bar	
$T(^\circ\text{C})$	$v\ (\text{m}^3/\text{kg})$
200	**0.2060**
215	$v = ?$
240	**0.2275**

Table A-4

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
			$p = 10$ bar = 1.0 MPa ($T_{sat} = 179.91^\circ\text{C}$)	
Sat.	0.1944	2583.6	2778.1	6.5865
200	0.2060	2621.9	2827.9	6.6940
240	0.2275	2692.9	2920.4	6.8817