Weeks 10/11:
Properties of Pure Substances

- 3−1 Pure Substance
- 3−2 Phases of a Pure Substance
- 3−3 Phase-Change Processes of Pure Substances
- 3−4 Property Diagrams: PVT surface, Pv diagram, Tv diagram, PT diagram (phase diagram)
- 3−5 Property Tables
- Interpolation

Pure Substance

- **A *substance* that has a fixed chemical composition throughout is called a *pure substance*.**

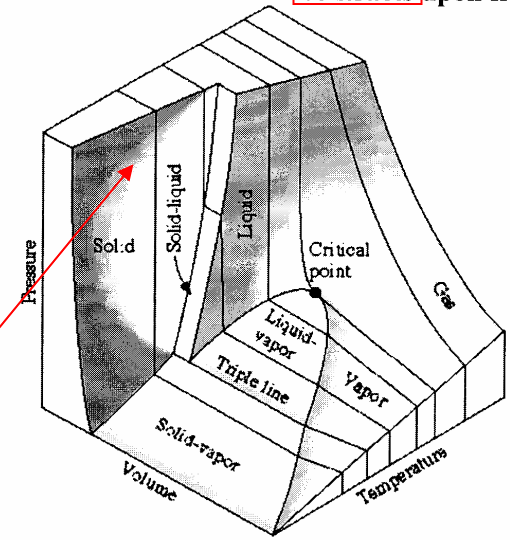
  Ex: Water, nitrogen, helium, and carbon dioxide, for example, are all pure substances.

- **A mixture of ice and liquid water, for example, is a *pure substance* because both phases have the same chemical composition.**

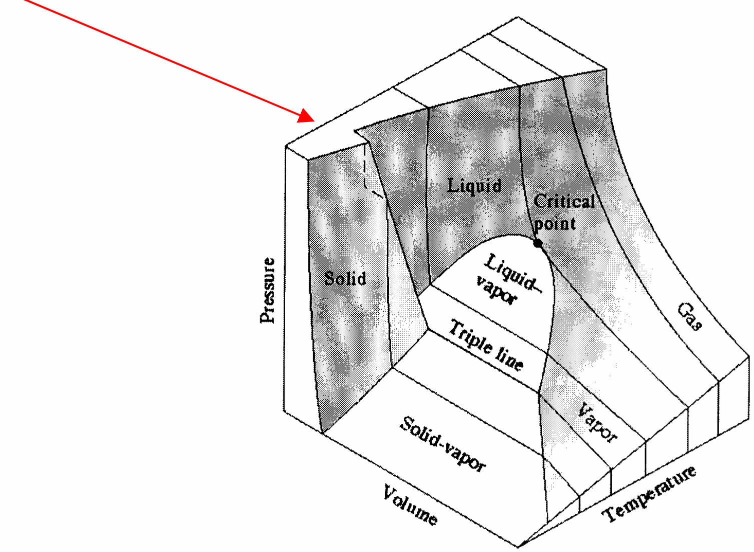
- **A mixture of liquid air and gaseous air, however, is *not* a pure substance since the composition of liquid air is different from the composition of gaseous air, and thus the mixture is no longer chemically homogeneous.**

The *P-V-T* Surface for a Real Substance

- *P-V-T* Surface for a Substance that contracts upon freezing



- *P-V-T* Surface for a Substance that expands upon freezing



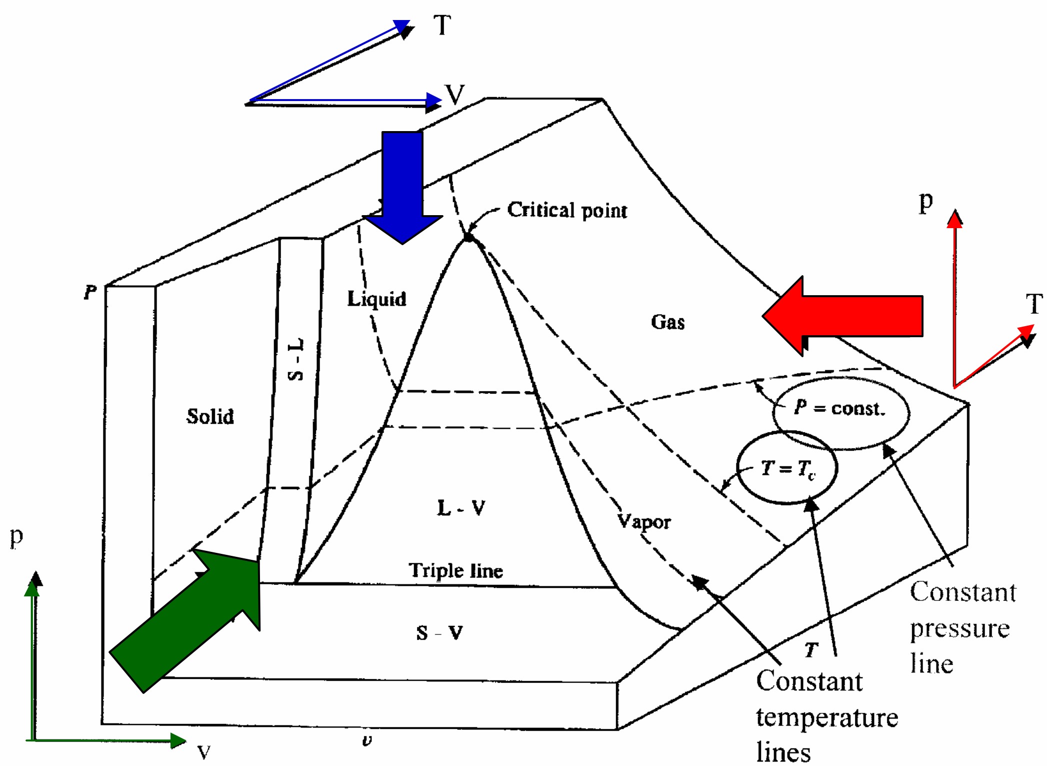


Fig. 2-3 The *P-v-T* rendering of a substance that contracts on freezing.

3−2 Phases of Pure Substance

- **A phase is identified as having a distinct molecular arrangement that is homogeneous throughout and separated from the other by easily identifiable boundary surfaces.**
  - **Solid**
  - **Liquid**
  - **gas**

Phase $\neq$ State

3−3 Phase Change Processes of Pure Substances

Water will be used to demonstrate the basic principles that phase change is involved.

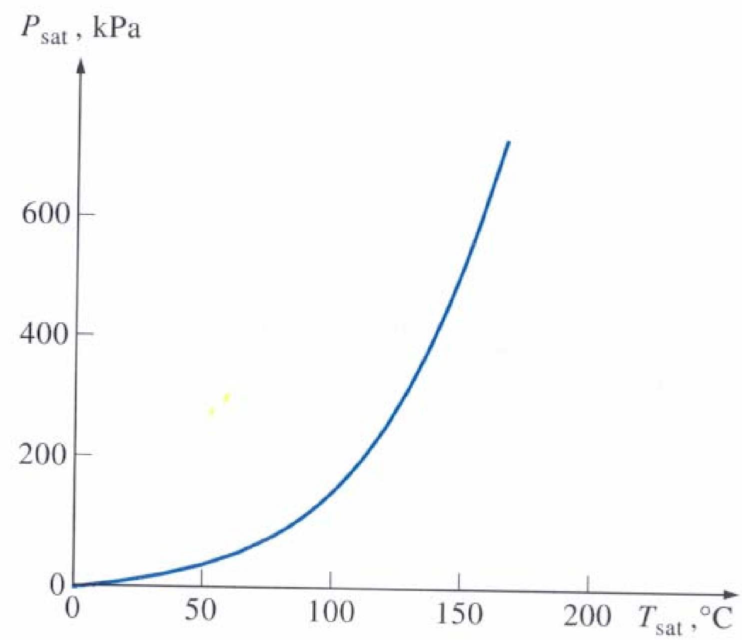
- **Water at 20°C and 1 atm pressure is in *compressed* (or subcooled) *liquid* state, meaning that it is not about to vaporize.**
- **When water temperature reaches 100°C (at 1atm), it is about to vaporize is called a *saturated liquid*.**
- **Once boiling starts, the temperature will stop rising until the liquid is completely vaporized. During this boiling process, the only change we will observe is a large increase in the volume and a steady decline in the liquid level.**

Saturation Temperature and Pressure

- A vapor that is about to condense is called a ***saturated vapor***.
- A substance at states between saturated liquid and saturated vapor is often referred as a ***saturated liquid-vapor mixture***.
- A vapor that is not about to condense is called a ***superheated vapor***.
- At a given pressure, the temperature at which a pure substance changes phase is called the ***saturation temperature*** T_{sat}.
- Likewise, at a given temperature, the pressure at which a pure substance changes phase is called the ***saturation pressure*** P_{sat}.

Saturation (boiling) pressure of water at various temperatures

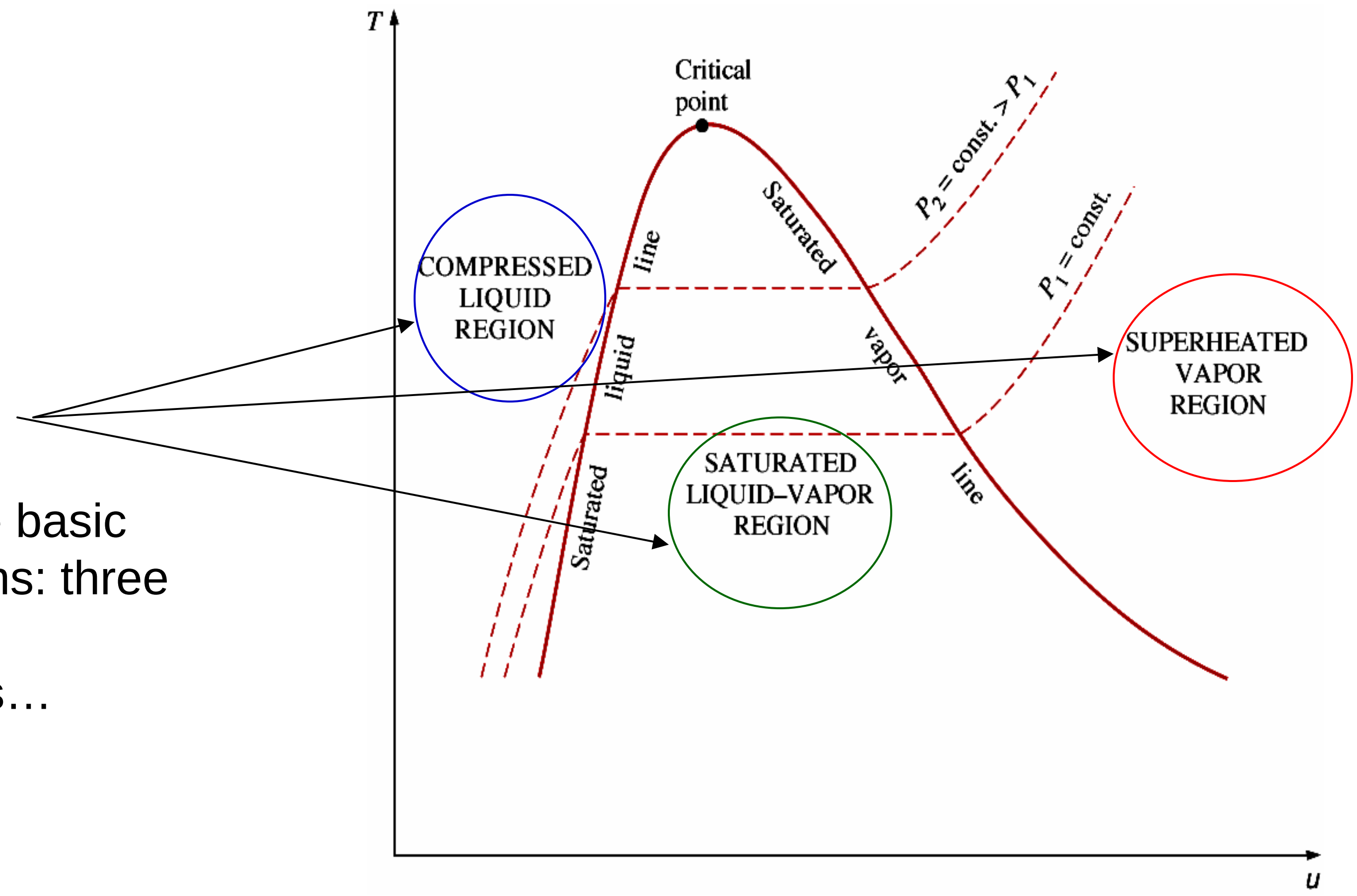
Temperature, T, °C	Saturation pressure, P_{sat}, kPa
−10	0.26
−5	0.40
0	0.61
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3 (1 atm)
150	475.8
200	1554
250	3973
300	8581



Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

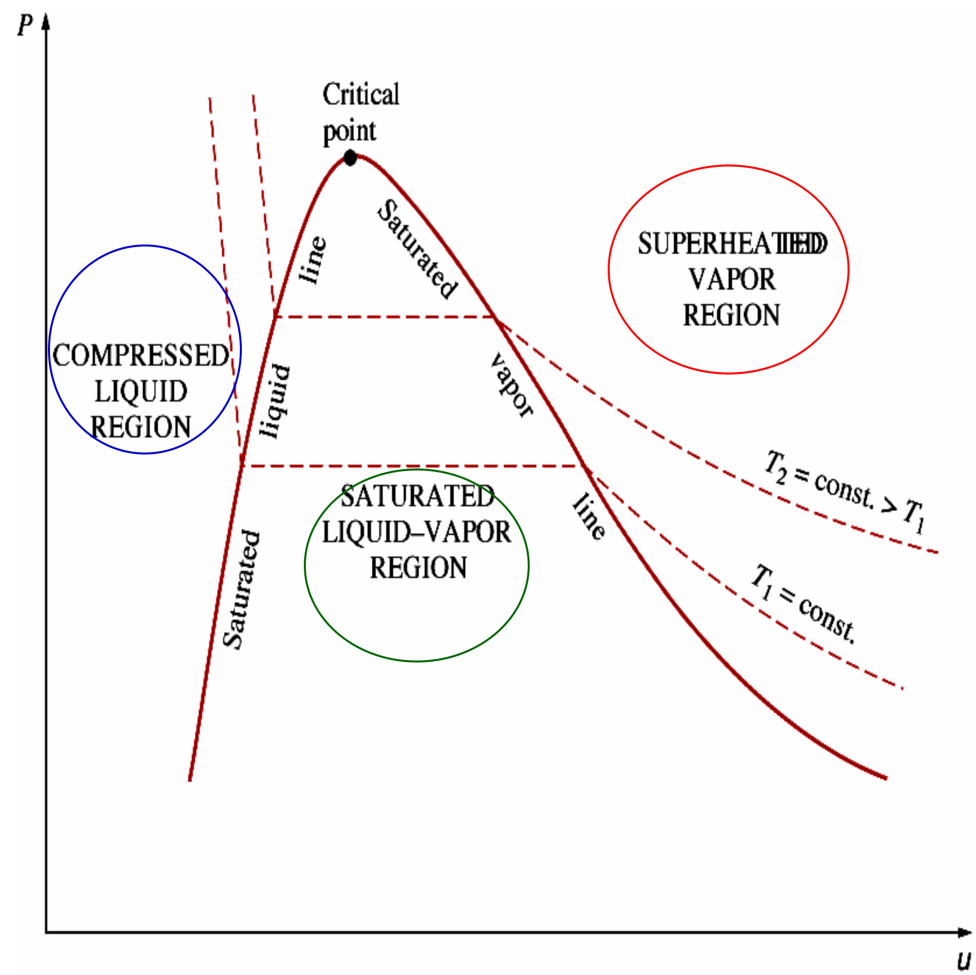
Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.3
2,000	79.50	93.2
5,000	54.05	83.0
10,000	26.50	66.2
20,000	5.53	34.5

The T-υ Diagram



Three basic regions: three basic tables…

The P-υ Diagram

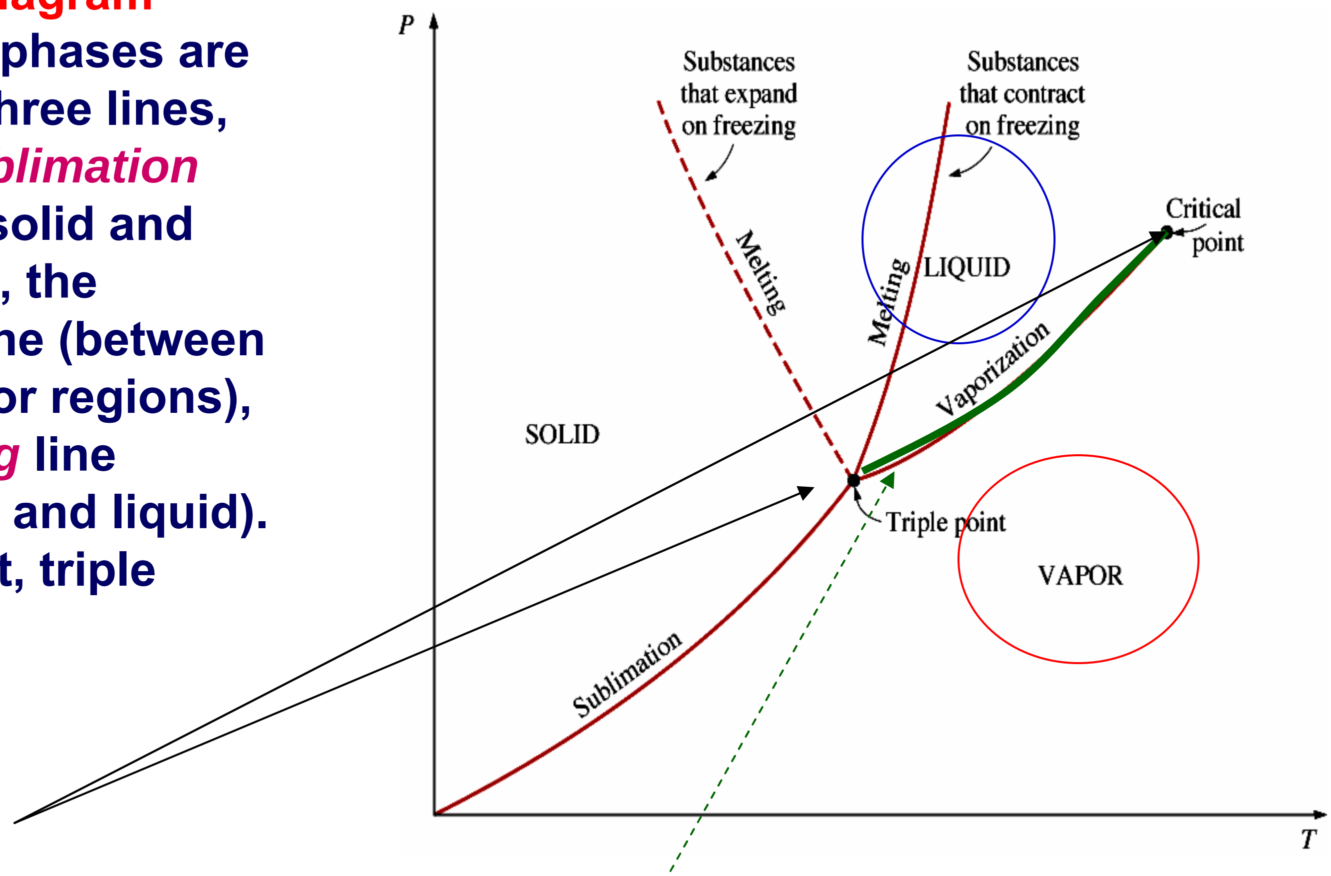


Animation (click)

animation

The P-T Diagram

The P-T diagram is often called phase diagram since all three phases are separated by three lines, namely the *sublimation* line (between solid and vapor regions), the *vaporization* line (between liquid and vapor regions), and the *melting* line (between solid and liquid). … critical point, triple point….



Two important points: critical and triple

Notice what happened to our “green region” the saturated liquid/vapor mixture region

3−6 Property Tables

Enthalpy − A Combination Property

In the analysis of certain types of processes, particularly in power generation and refrigeration, we frequently encounter the combination of internal energy U, and pressure-volume product Pυ. That is

$$H = U + PV \quad (\text{specific enthalpy}, h = u + pv)$$

Three main tables:

Saturation → Define quality, x

Superheated vapor

Compressed Liquid

Not very common, sometimes need to use approximations

Property at (P,T) compressed liquid = property at same T of saturated liquid

For the enthalpy we use extra correction

$$h \cong h_{f@T} + v_f\left(P - P_{sat}\right).$$

Saturated Liquid and saturated vapor

Water Tables A-4 and A-5

Example:

A rigid tank contains 50 kg of saturated liquid water at 90°C. Determine the pressure in the tank and the volume of the tank. (*Answers: 70.14 kPa, 0.0518 m*)

Temp. °C T	Sat. press kPa P_{sat}	Specific volume m³/kg: Sat. liquid υ_f	Specific volume m³/kg: Sat. vapor υ_g
85	57.83	0.001 033	2.828
90	70.14	0.001 036	2.361
95	84.55	0.001 040	1.982

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

Specific volume of saturated vapor

Remember the meaning of the sub-indexes f and g

Saturated Liquid and saturated vapor (continued)
Water Tables A-4 and A-5

Example:

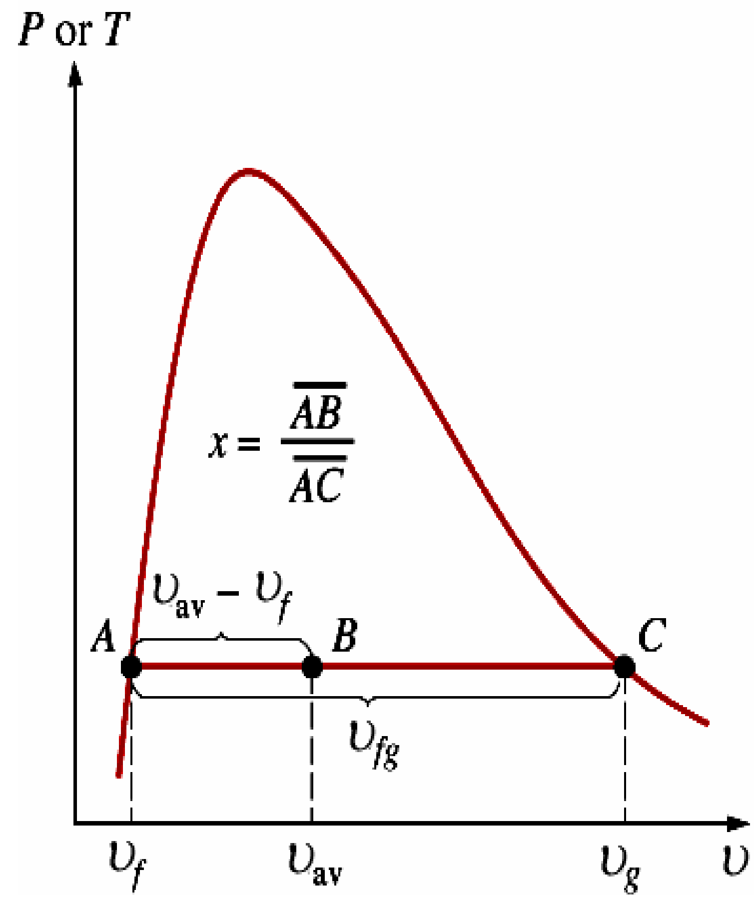
A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (a) the volume change and (b) the amount of energy added to the water. (*Answers: 0.3368 m*^{3}*, 451.6 kJ*)

Saturated Liquid − Vapor Mixture

We define a new property called the *quality*, which can be related to the horizontal distance on a P-υ or T-υ diagram.

$$x \equiv \frac{m_g}{m_f + m_g}, \quad \text{and } \upsilon = \upsilon_f + x\upsilon_{fg};$$

$$u = u_f + xu_{fg}; \quad h = h_f + xh_{fg}$$



Saturated Liquid – Vapor Mixture (continued)

Example:

A rigid tank contains 10 kg of water at 90°C. If 8 kg of water is in the liquid form and the rest is in the vapor form, determine (*a*) the pressure in the tank and (*b*) the volume of the tank. (*Answers: 70.14 kPa, 4.73 m³*)

Example:

An 80-L vessel contains 4 kg of refrigerant 134a at a pressure of 160 kPa. Determine *a*) the temperature of the refrigerant, *b*) the quality, *c*) the enthalpy of the refrigerant, and *d*) the volume occupied by the vapor phase. (*Answers: -15.62°C, 0.158, 62.7 kJ/kg, 0.0777 m³*)

Superheated Vapor

In the region to the right of the saturated vapor line, a substance exists as *superheated vapor*.

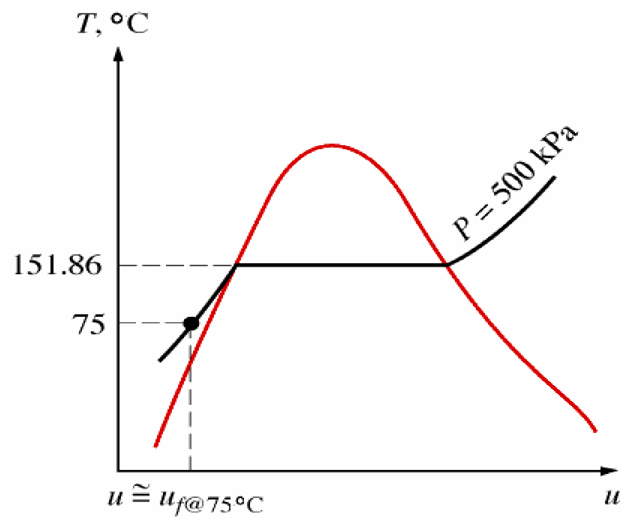
Example:

Determine the temperature of water at a state of *P* = 0.5 MPa and *h* = 2890 kJ/kg. (*Answers: 216.4* ^{o}C)

T,°C	*v*, m³/kg	*u*, kJ/kg	*h*, kJ/kg
	P = 0.1 MPa (99.63∞C)		
Sat.	1.6940	2506.1	2675.5
100	1.6958	2506.7	2676.2
150	1.9364	2582.8	2776.4
⋮	⋮	⋮	⋮
1300	7.260	4683.5	5409.5
	P = 0.5 MPa (151.86°C)		
Sat.	0.3749	2561.2	2748.7
200	0.4249	2642.9	2855.4
250	0.4744	2723.5	2960.7

Compressed Liquid

In the region to the left of the saturated liquid line, a substance exists as *compressed liquid*. A general approximation is to treat compressed liquid as saturated liquid at the given temperature. The property most affected by pressure is enthalpy, $h \cong h_{f@T} + v_f\left(P - P_{sat}\right)$.



Example:

Determine the internal energy of compressed liquid water at 80°C and 5 MPa using (*a*) data from the compressed liquid table and (*b*) saturated liquid data. What is the error involved in the second case? (*Answers: 333.72 kJ/kg, 334.86 kJ/kg, 0.34%*)

Reference State and Reference Values

Be aware that there is a reference.

- **The values of *u*, *h*, and *s* cannot be measured directly, and they are calculated from measurable properties using the relations between thermodynamic properties. However, those relations give the changes in properties, not the values of properties at specified state.**
- **Reference values may change from table to table (be aware of this).**
- **For water, the state saturated liquid at 0.01°C is taken as the reference state, and the internal energy and entropy are assigned zero values at that sate.**
- **For refrigerant 134a, the state saturated liquid at -40°C is taken as the reference state, and the enthalpy and entropy are assigned zero values at that state.**

The Use of Steam Table to Determine Properties

Determine the missing properties and the phase descriptions in the following table for water.

	T, °C	*P*, kPa	*u*, kJ/kg	*x*	Phase description
(*a*)		200		0.6	
(*b*)	125		1600		
(*c*)		1000	2950		
(*d*)	75	500			
(*e*)		850		0.0	