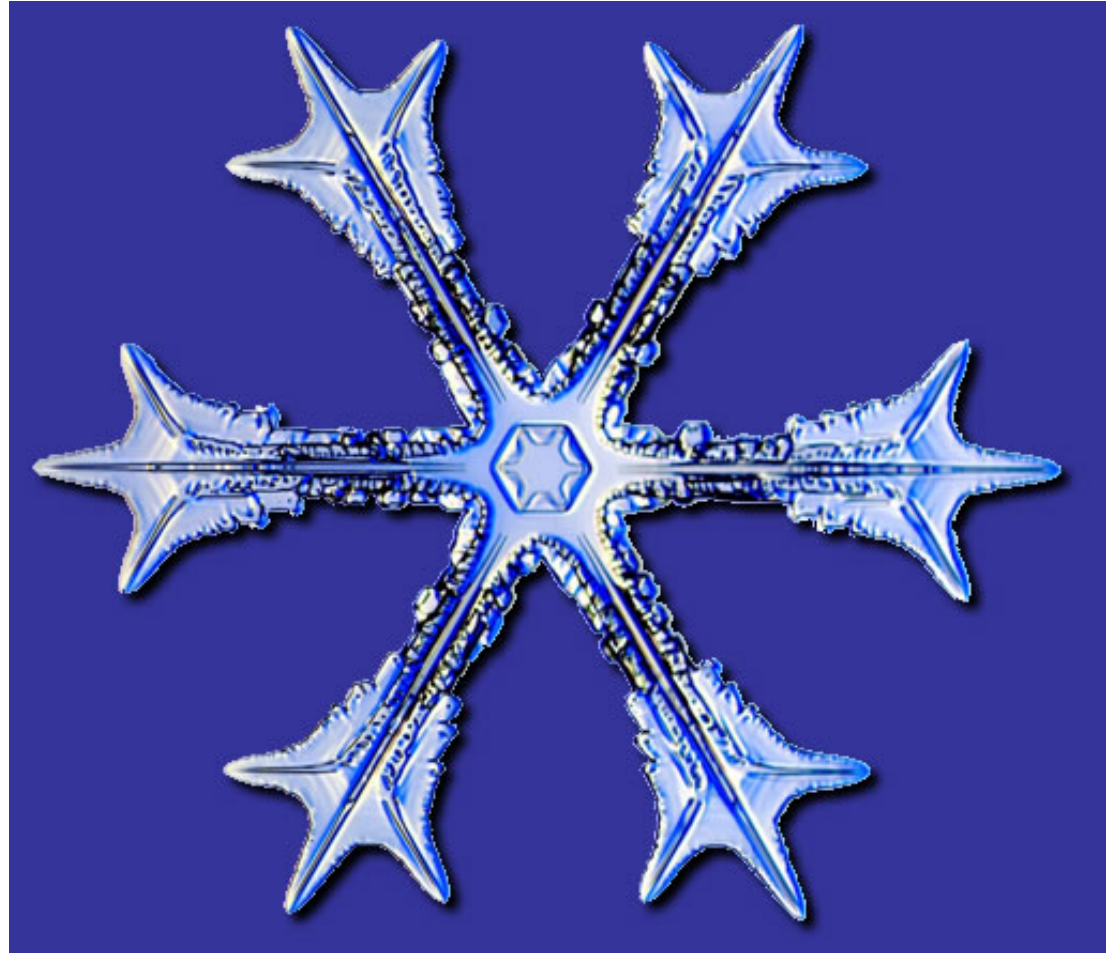# Class 3: Thermodynamic Properties of Pure Substances: Water
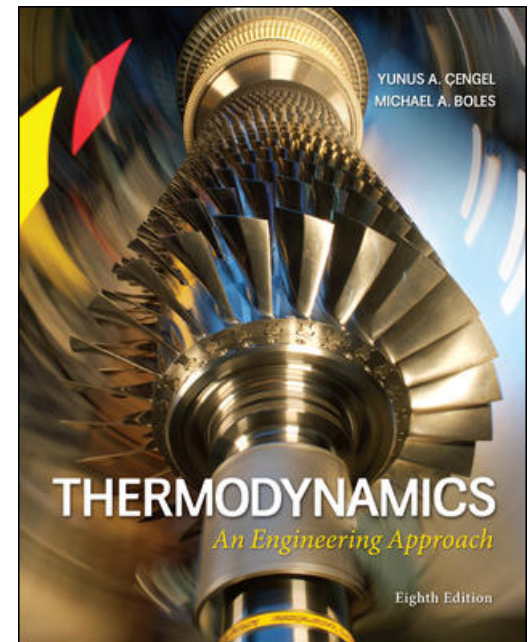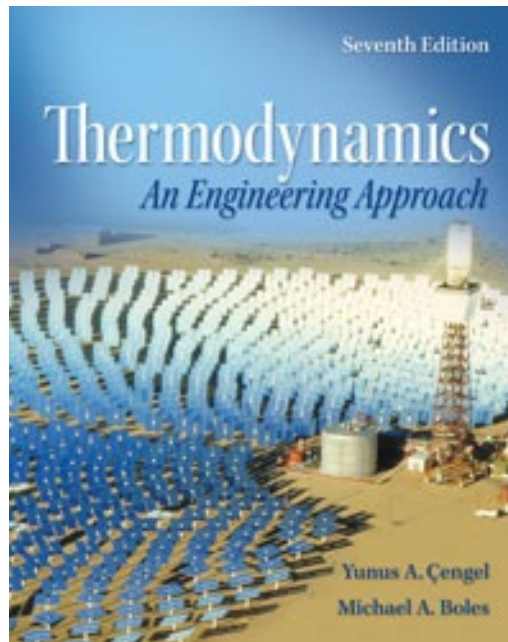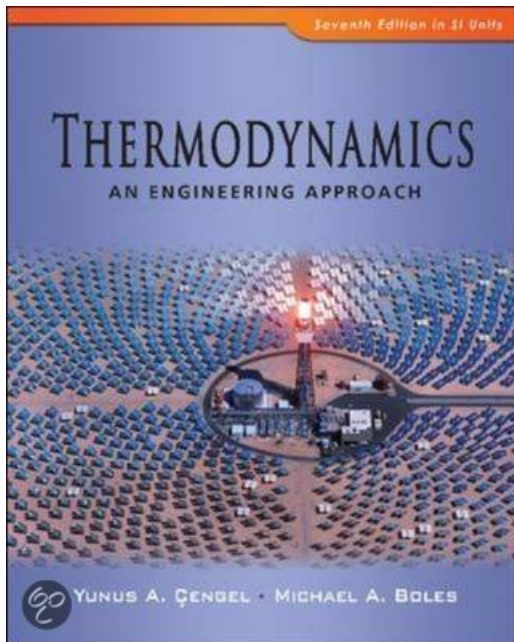
A snowflake at high magnification. The solid phase of water in one of its forms.

(Courtesy of Kenneth G. Libbrecht, Cal Tech)

Announcement

- Take the book to the next on campus tutorial
- Tables are needed for determining the thermodynamic properties of substances

- Open book exam, practice using the book

Roadmap Engineering Thermodynamics

- Using thermodynamics for practical applications requires knowledge of:

Concepts and definitions (Class 1) ➡ Various forms of energy (Class 2)
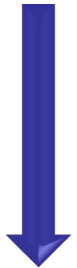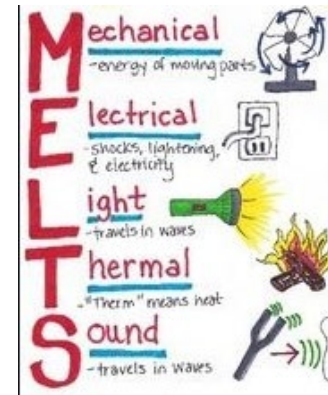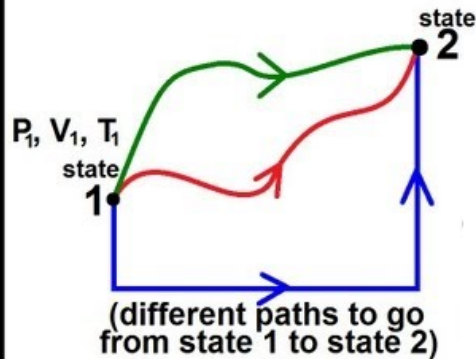
Power cycles (Class 6 – 11) ⬅ Laws of Thermo (Class 4 and 5) ⬅ Properties of Substances (Class 3, 9)
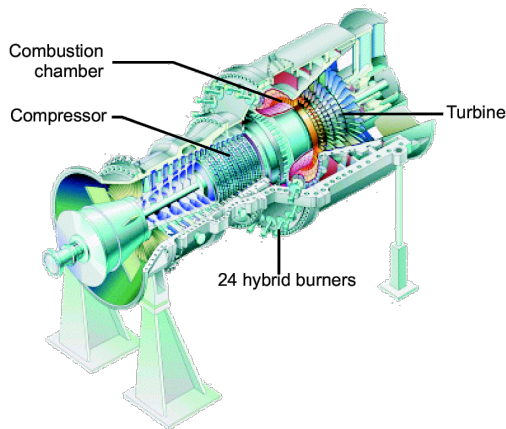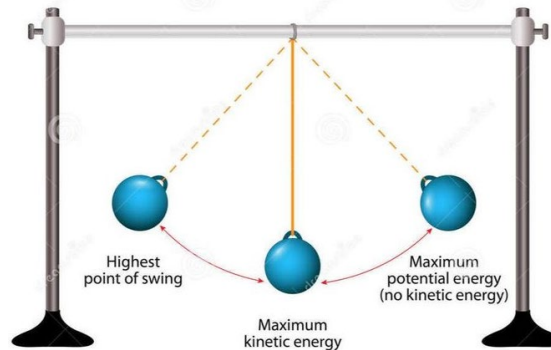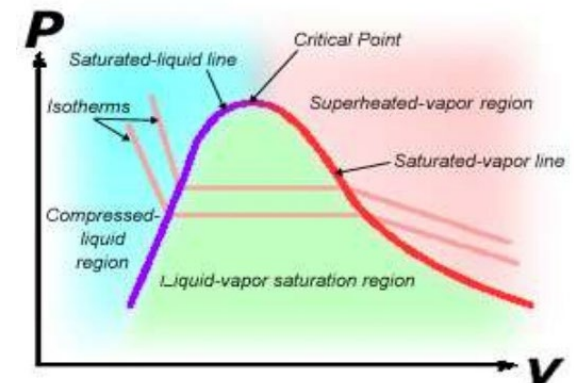
Roadmap Engineering Thermodynamics

Thermodynamic cycles (Class 6)
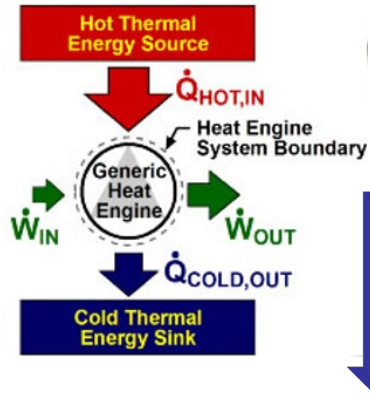
Vapor power cycles – Rankine cycle (Class 7, 8)
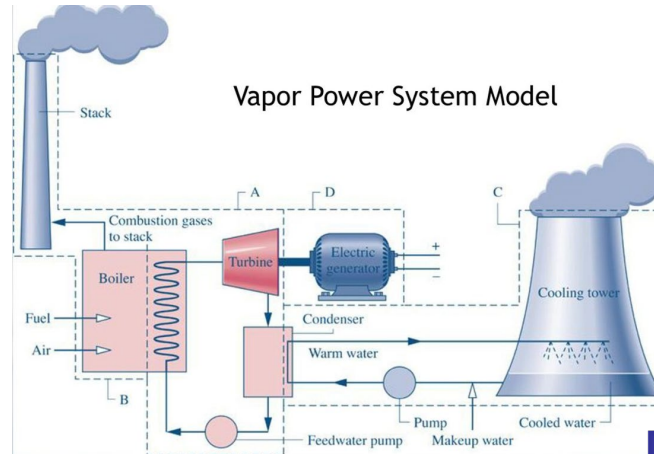
Properties of water (Class 3)
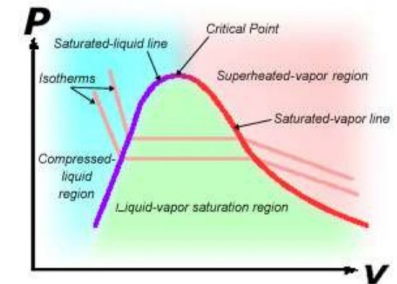
Gas power cycles – Brayton cycle (Class 10, 11)
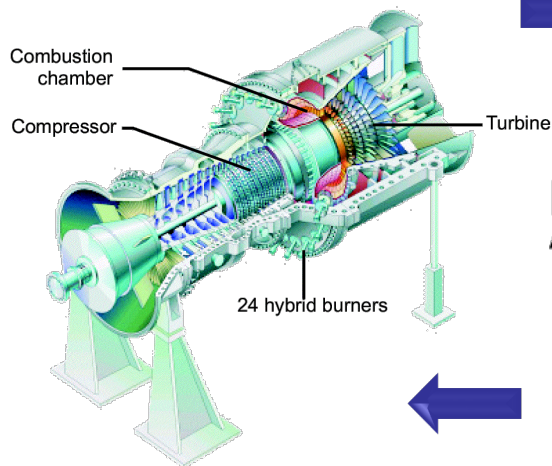
Properties of air (Class 9)
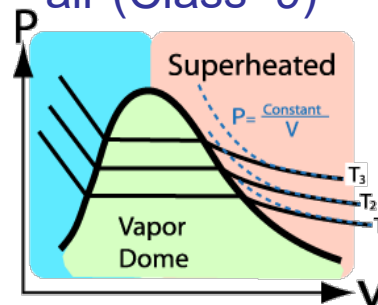
Combined cycles Combined heat & power (Class 8, 11)
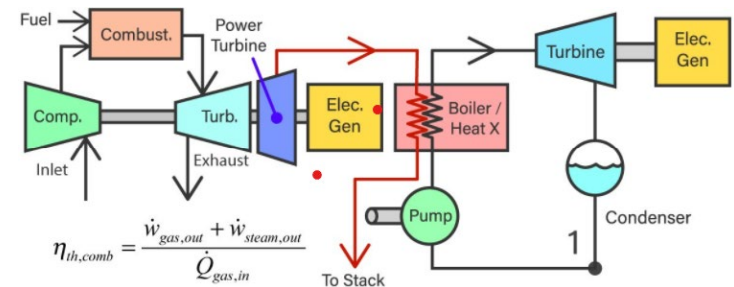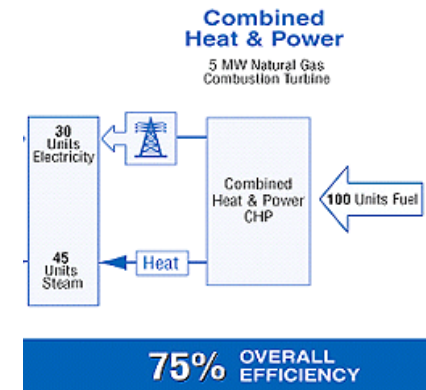
Recapitulate class 2

- Energy within system boundaries
  - Kinetic / potential / internal energy / total energy
- State and path functions
- Mechanisms of energy transfer across system boundaries
  - Work
    - Boundary work, $\delta W = PdV$ or $\delta w = Pdv$
    - P-v diagrams (compare to F-s diagram)
    - Mechanical work
  - Heat transfer, due to a temperature difference
  - Flow work (Pv), energy transfer due to mass transport across the boundaries of an open system
- The rate of doing work (power) / heat transfer / mass
- First law of thermodynamics (conservation of energy)
- Energy balances, $E_{in} - E_{out} = \Delta E_{system}$
- New properties
  - Enthalpy, $h = u + Pv$, open systems
  - Entropy
- Efficiencies of energy conversion processes
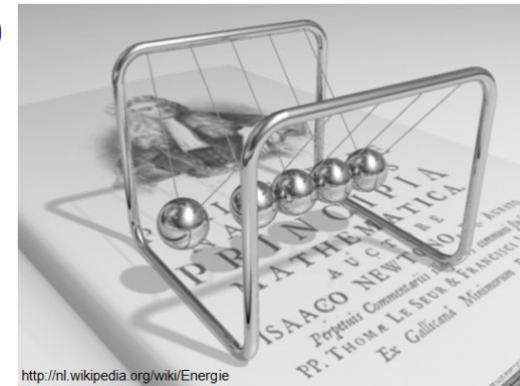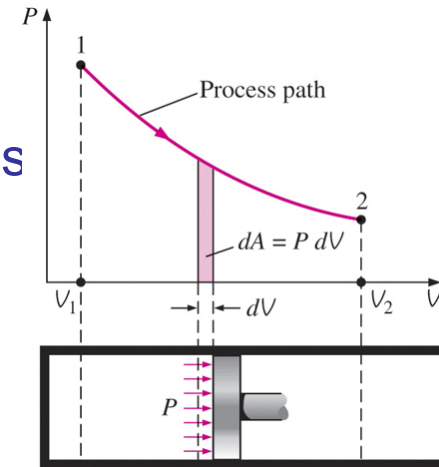
Content Class 3

- **Thermodynamic properties of pure substances: water**

- Pure substances
- Physics of phase change processes
- Phase P-v-T surface, diagrams
- Liquid - steam - mixture
- Saturation - quality
- Diagrams and tables to obtain thermodynamic properties of water
- Specific heat of water

- **Learning goal:** declare and explain the behavior of fluids at different temperatures and pressures and draw and interpret phase diagrams

shmoop.com

Properties of Saturated Water - Press. Table (SI)

P	T	Specific Volume, m³/kg		
kPa	^{0}C	v_L	v_{LV}	v_V
80	93.511	0.001038	2.0866	2.0876
100	99.632	0.001043	1.6933	1.6943
150	111.38	0.001053	1.1584	1.1595

Old Faithful Geyser (Yellowstone Nat. Park)

Old Faithful Geyser
ERUPTION HEIGHT
AVG. 130 FT.
MAX. 184 FT.
WATER DISCHARGE 10,000 - 12,000 GAL. PER ERUPTION
ERUPTION INTERVAL
MIN. 33 min
AVG. 64.5
MAX. 91 min
DURATION 2 - 5 min
WATER TEMPERATURE 204°F AT VENT
Expected Eruption

Old Faithful Geyser Eruptions, 2006
Total of 5220 eruptions
Mean=1.5201, Standard Deviation=0.134873, Skewness=-1.04087
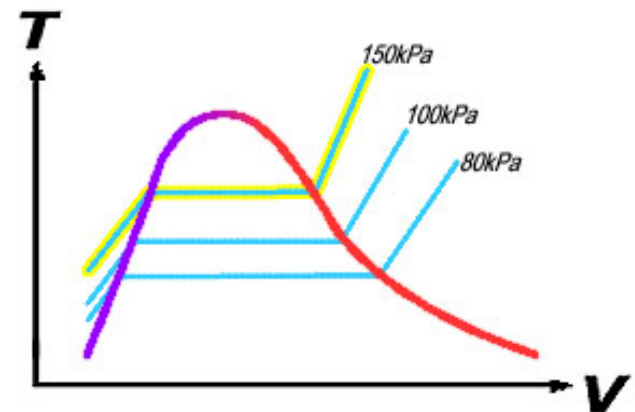
Old Faithfull eruption

http://www.youtube.com/watch_popup?v=tShhZvvIM84&vq=medium#t=32

How does it work?
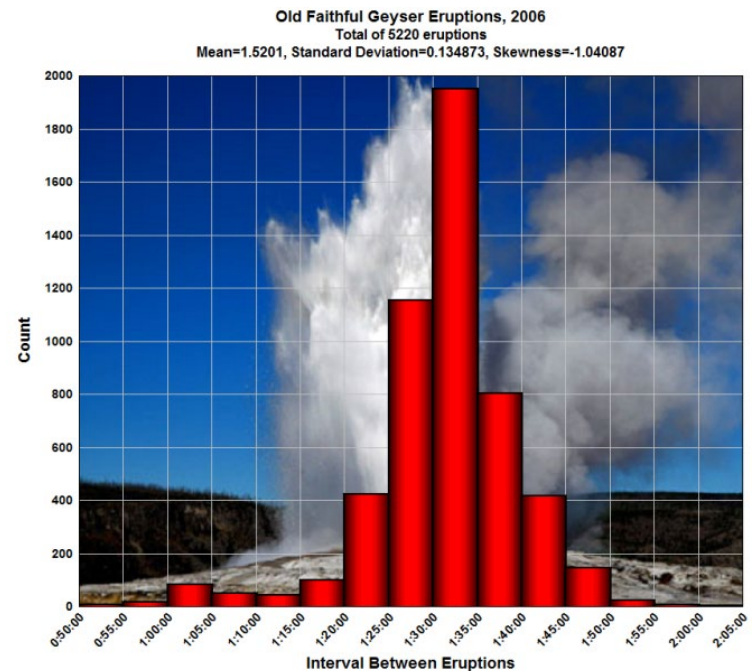
Geyser

- How can the working of a natural geyser be explained?

State Postulate

- From class 1 the state postulate is known

  > Sate postulate: The state of a simple compressible system is completely specified by two independent, intensive properties

- Simple compressible system: If a system involves no electrical, magnetic, gravitational, motion and surface tension effects

Table of Steam Properties

P (kPa)	T (^{0}C)	v (m^3/kg)
100	100	1.696
100	120	1.793
100	160	1.984

ThermoNet: John Wiley Publishers

- A postulate is not proven, but accepted as a basic theorem, which is never contradicted by observations
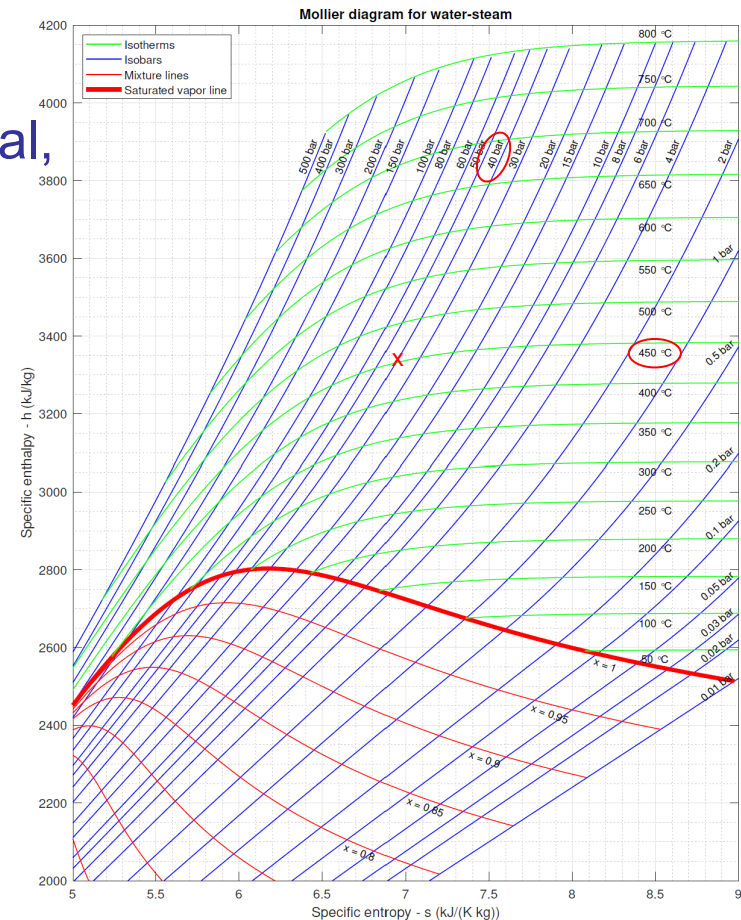
Pure Substances

- **Pure substances** are composed of a single chemical species (e.g. either O_2 or CO_2 but not a mixture of O_2 and CO_2).

- However pure substances may exist in more than one phase (e.g. solid and liquid or liquid and vapor)

A mixture of
snow, ice, liquid water
and water vapor
is a
pure substance

- **Mixtures of substances** are treated in chapter 14 (not in this course)

Phase Change and Tv - Diagram

- Everyday example: Heat a pan of water on the furnace
- Heat added at constant pressure to the water, what happens?

- In thermodynamic terms you can translate this problem to
  Constant pressure heating in piston-cylinder at P = 1 atm

How does the

Tv-diagram look?

P = 1 atm
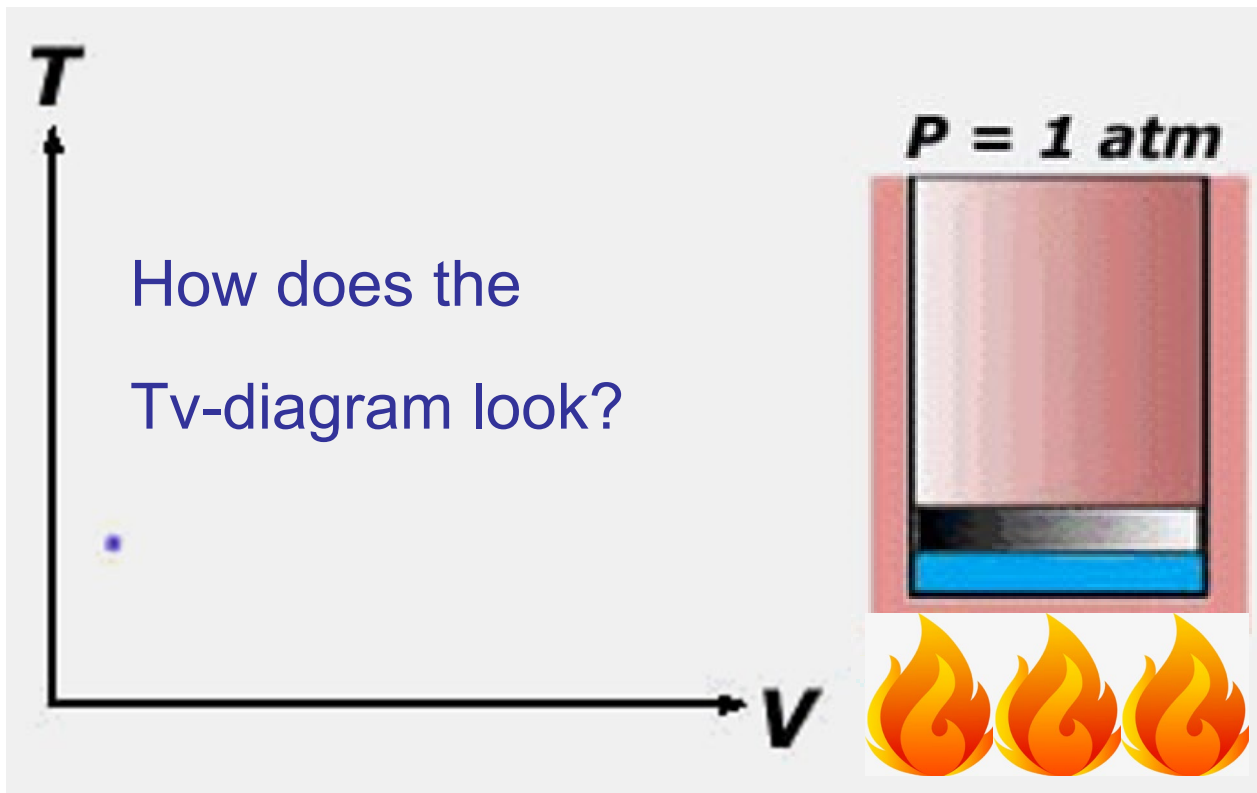
Phase Change and Tv - Diagram

- Everyday example: Heat a pan of water on the furnace
- Heat added at constant pressure to the water, what happens?

- In thermodynamic terms you can translate this problem to **Constant pressure heating in piston-cylinder at P = 1 atm**

- Which line is correct?
  - Red
  - Blue
  - Green
  - Purle
  - No one

Phase Change and Tv - Diagram

- Everyday example: Heat a pan of water on the furnace
- Heat added at constant pressure to the water, what happens?

- In thermodynamic terms you can translate this problem to **Constant pressure heating in piston-cylinder at P = 1 atm**

All vapor at T > 100°C
Volume even larger

All water just turned into vapor, large volume, still 100°C

Mixture of saturated liquid and vapor, still 100°C but volume increased, where goes the energy from heat?

Water starts boiling 100°C
Volume has increased

Start: water T < 100°C
Small volume

P = 1 atm

Phase Change and Tv - Diagram

- Everyday example: Heat a pan of water on the furnace
- Heat added at constant pressure to the water, what happens?

- In thermodynamic terms you can translate this problem to
  Constant pressure heating in piston-cylinder at P = 1 atm

Which line ?   **The green line is correct**

Phase Change and Tv - Diagram

- Replace the pan by a high pressure one (P = 2 atm)
- Again add heat at constant pressure, what is the difference with 1 atm ?

- In thermodynamic terms you can translate this problem to
  Constant pressure heating in piston-cylinder at P = 2 atm

- **What happens ?**

- How will the diagram look in this case compared to the line at 1 atm?
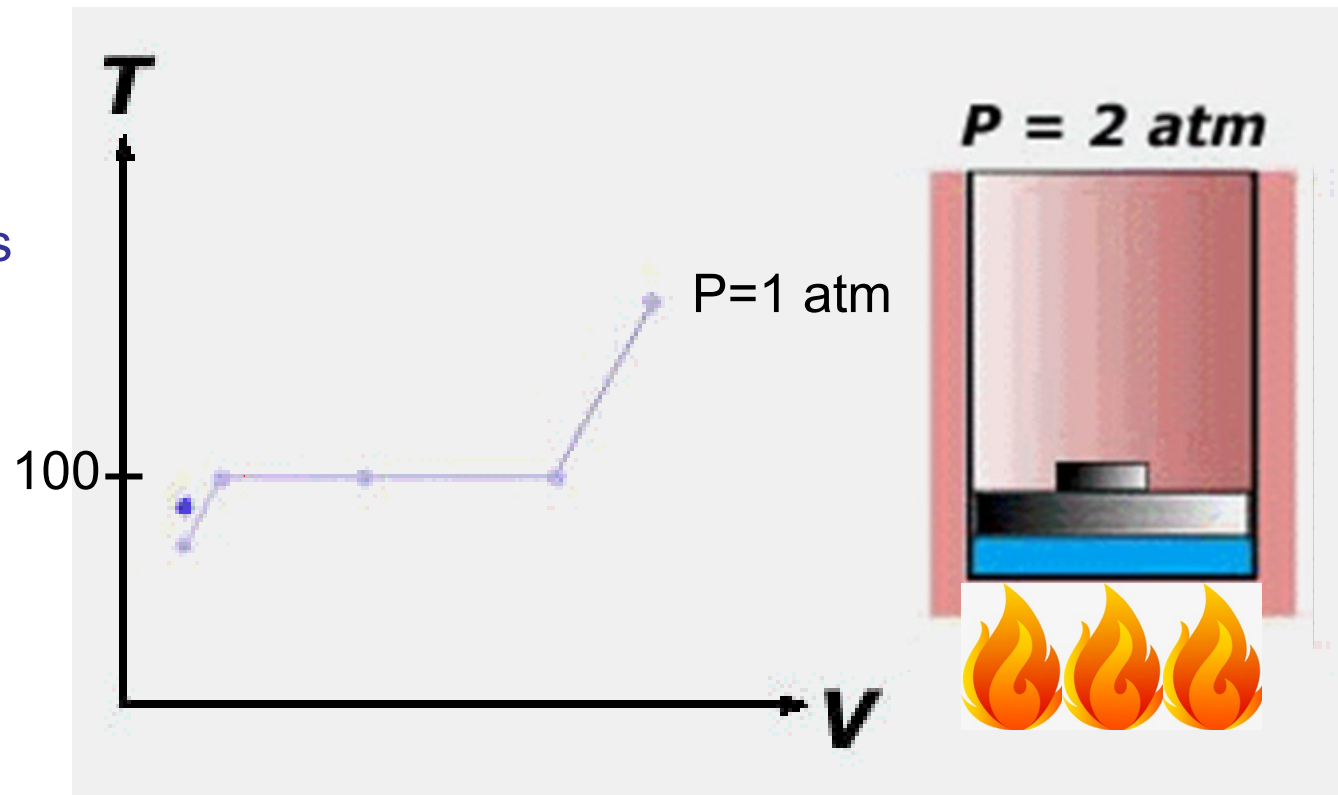
Phase Change and Tv - Diagram

- Replace the pan by a high pressure one (P = 2 atm)
- Again add heat at constant pressure, what is the difference with 1 atm ?

- In thermodynamic terms you can translate this problem to **Constant pressure heating in piston-cylinder at P = 2 atm**

- **What happens?**
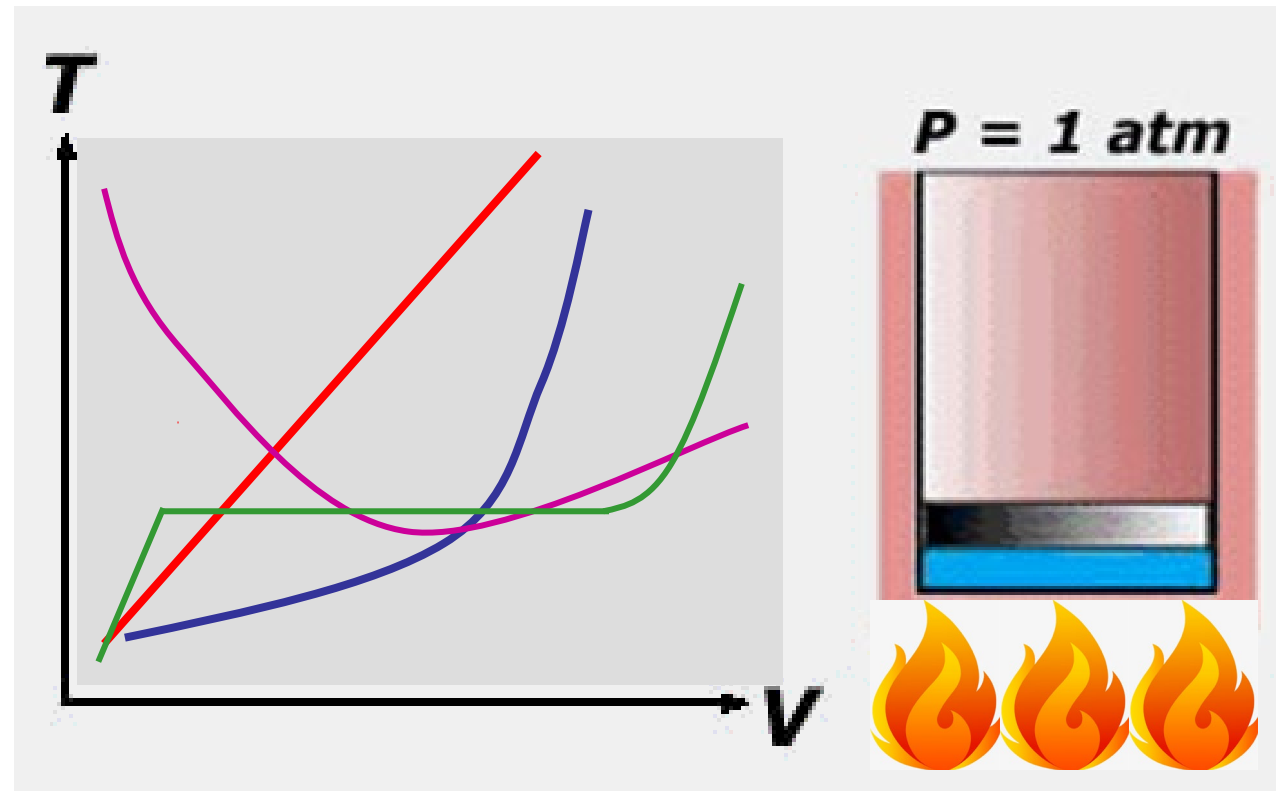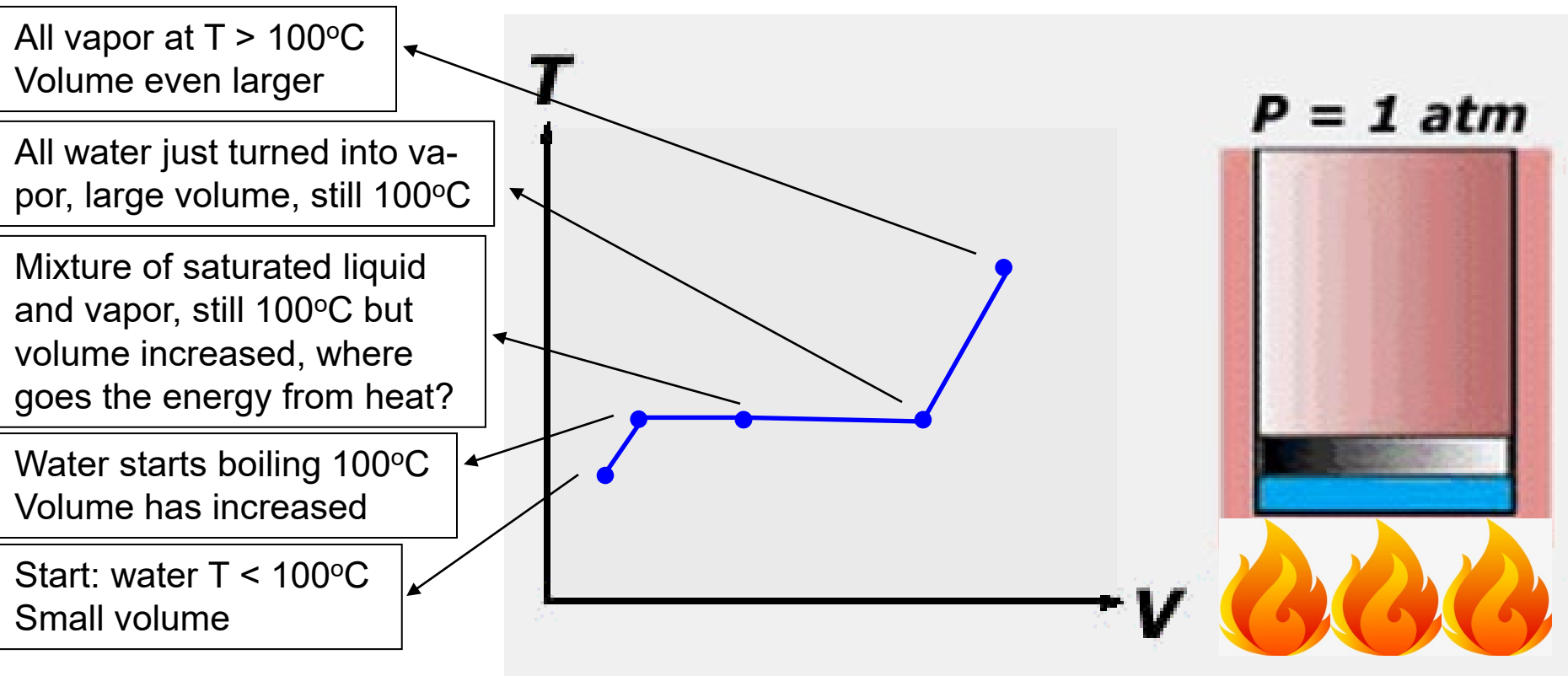- Actually the same happens as at 1 atm
- However the temperatures and volumes are different
- At **every** pressure same behavior but at different combinations of volume-pressure-temperature
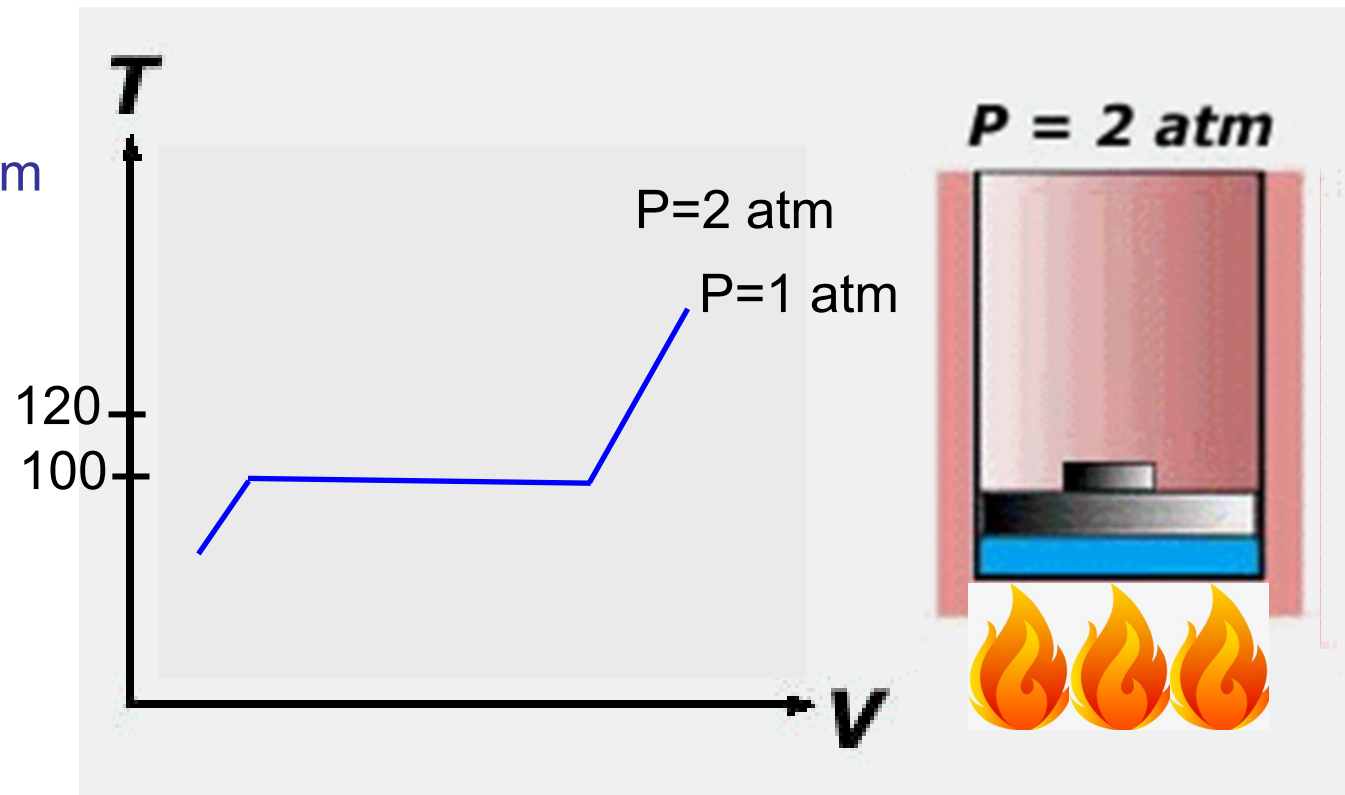
Phase Change and Tv - Diagram

- Repeating this process with different pressures results in the horizontal line to become a point, **critical point** (above this point the fluid is supercritical)

- A dome can be drawn around the vertical lines, this **saturation dome (or vapor dome)** divides the T-v diagram into different regions

  - Region under the dome: **liquid-vapor region or two phase region**

  - Region left of the dome: **compressed liquid region**

  - Region right of the dome: **superheated vapor region**

- The dome consists of two lines

  - **Saturated liquid line** (between the compressed liquid and two phase region)

  - **Saturated vapor line** (between the two phase region & the superheated vapor)
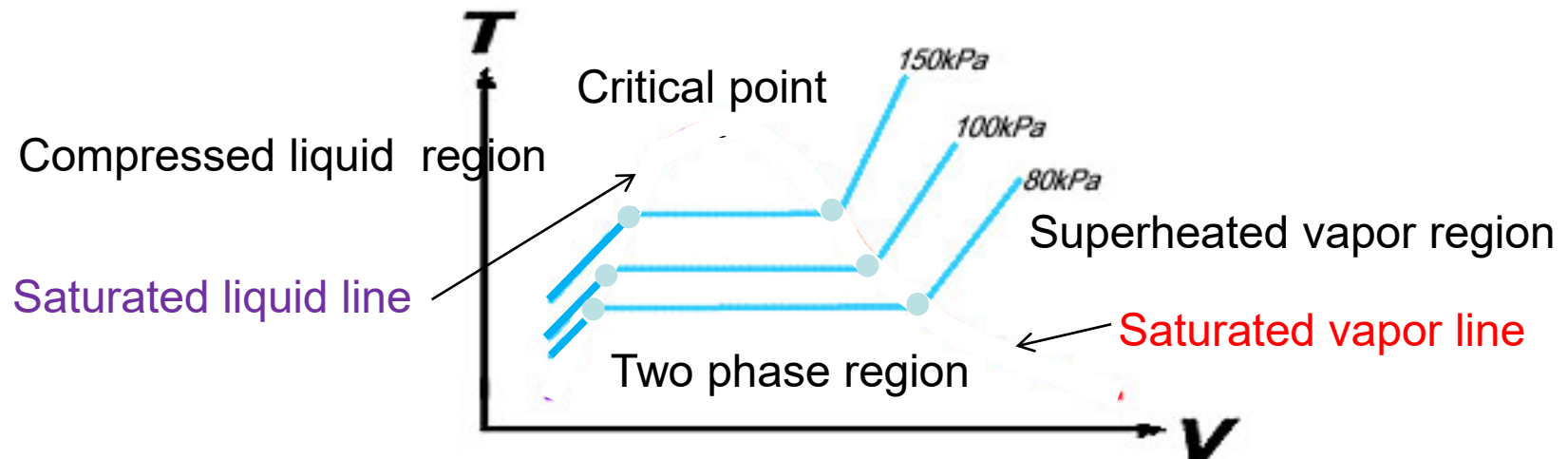
Supercritical Fluid versus Plasma

- A **supercritical fluid** is any substance at a temperature and pressure above its critical point.

    - Diffuse through solids like a gas, and dissolve materials like a liquid.

    - Close to the critical point , small changes in pressure or temperature result in large changes in density: properties of a supercritical fluid to be "fine-tuned".

    - Supercritical fluids are suitable as a substitute for organic solvents in a range of industrial and laboratory processes.

    - CO_2 and water are the most commonly used supercritical fluids, being used for decaffeination and power generation.

- In physics and chemistry, **plasma** is a gas in which a certain portion of the particles are ionized.

    - It responds strongly to electromagnetic fields.

    - Plasma therefore has properties quite unlike those of solids, liquids, or gases and is sometimes considered to be a distinct state of matter.

    - The transition from gas to plasma is continues while there is a sharp distinction between the solid, liquid and gas phase.

Plasma   Light

Plasma Globe,

http://en.wikipedia.org/wiki/Plasma
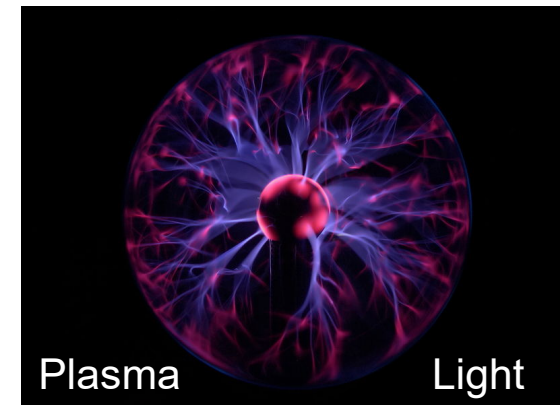
(Extra information, not part of the exam)

Supercritical Carbon Dioxide

The process of carbon dioxide undergoing a phase transition to form a supercritical fluid
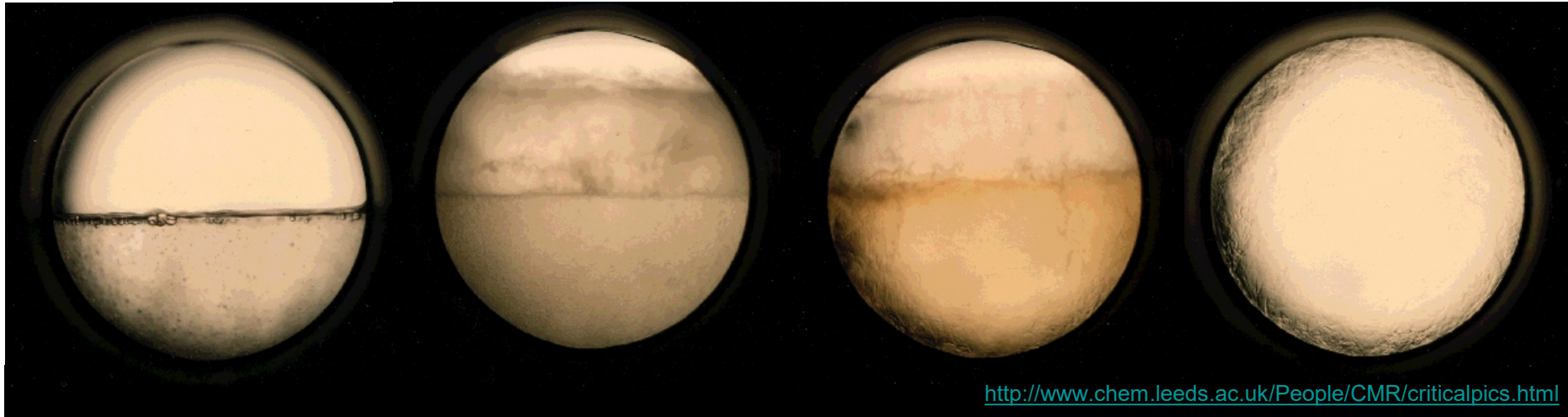
1. Here we can see the seperate phases of carbon dioxide (fluid at the bottom and gas above). The meniscus is easily observed.

2. With an increase in temperature the meniscus begins to diminish.

3. Increasing the temperature further causes the gas and liquid densities to become more similar. The meniscus is less easily observed but still evident.

4. Once the critical temperature and pressure have been reached the two distinct phases of liquid and gas are no longer visible. The meniscus can no longer be seen. One homogenous phase called the "supercritical fluid" phase occurs which shows properties of both liquids and gases.

A movie of SF_6: http://www.rsc.org/suppdata/jm/b3/b315262f-e/

(Extra information, not part of the exam)

Example: Supercritial fluid extraction

The use of classic organic solvents in the food industry entails environmental and health risks. That is why it has been studied for years which mild solvents can be used in extraction processes to replace these organic solvents. CO2 is such a solvent.

A substance is called supercritical when the phase transition between liquid and gaseous is no longer perceptible. This phenomenon occurs above a specific pressure and temperature and depends on the substance. In supercritical extraction - supercritical fluid extraction (SFE) in English - specific components are extracted from the starting material using a supercritical solvent.

Various solvents can be used for this, but CO2 is generally used. Water is also easily soluble in supercritical CO2. As a result, the technology also has the potential to be used as a drying technique = specific extraction of water as an alternative to freeze drying.

The critical temperature of CO2 is 31.3 ˚C at a critical pressure of 72.9 bar, see Figure 1. (For comparison: for water the critical temperature is 374.4˚C at a critical pressure of 226.8 bar.)

Physico-chemical properties can change significantly when a substance becomes supercritical. In this state, the physicochemical properties of CO2 resemble those of liquid CO2 in some cases and gaseous CO2 in other cases. For example, supercritical CO2 (abbreviated as scCO2) has the physical properties of gaseous CO2 (high diffusivity, low viscosity, no surface tension) and the chemical properties of liquid CO2 (high density and high dissolving power).

These physicochemical properties can be changed quite significantly by adjusting pressure and / or temperature. In other words, it is possible to adapt the properties of scCO2 to the specific application, so that scCO2 can be used in many processes.
(Extra information, not part of the exam)
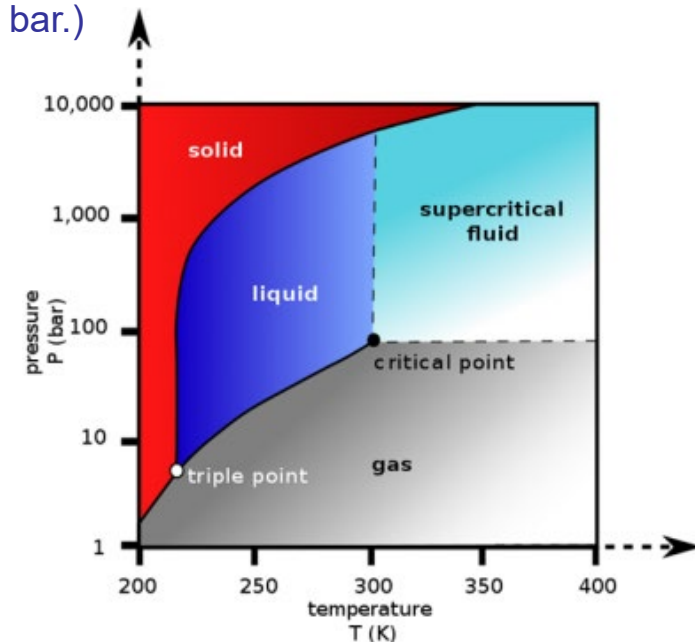
Phase Change and PvT - Surface

- Regions on T-v diagram

- Note saturation lines, **saturated liquid** and **saturated vapor**
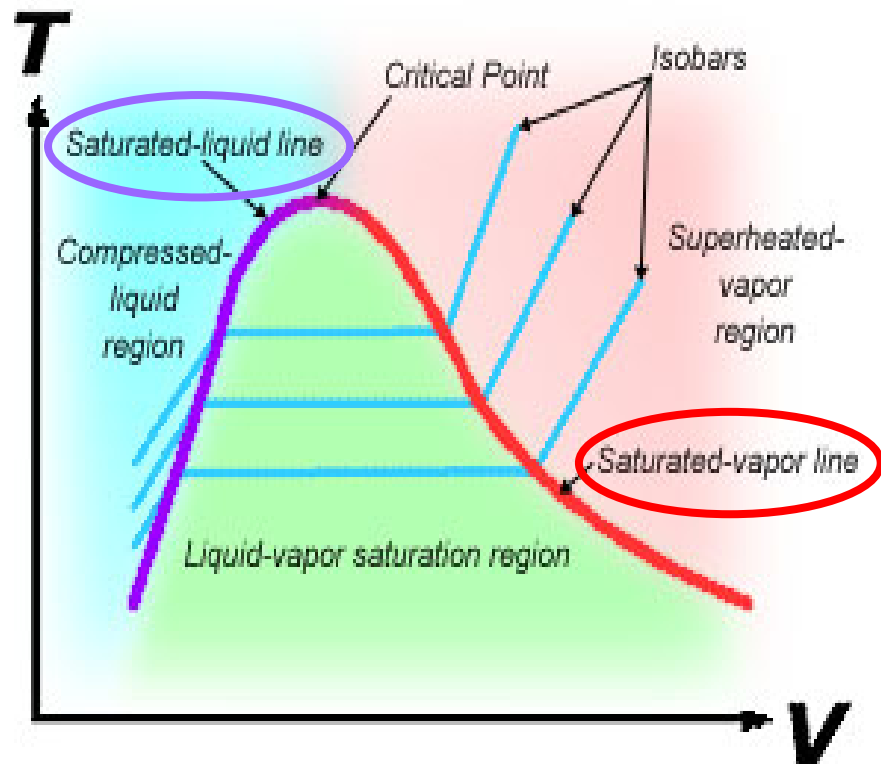
- Regions on P-v diagram

- Note saturation lines, **saturated liquid** and **saturated vapor**
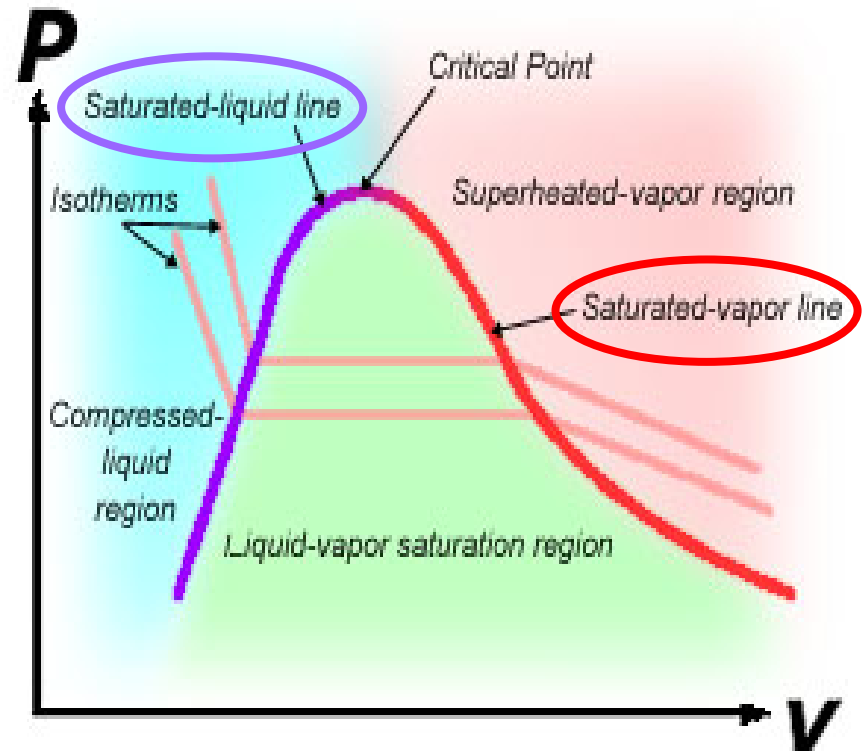
Phase Change and PvT - Surface

- Regions on T-v diagram

- Note directions of **isobars** (constant pressure lines) horizontal inside the dome

- Rising slope outside
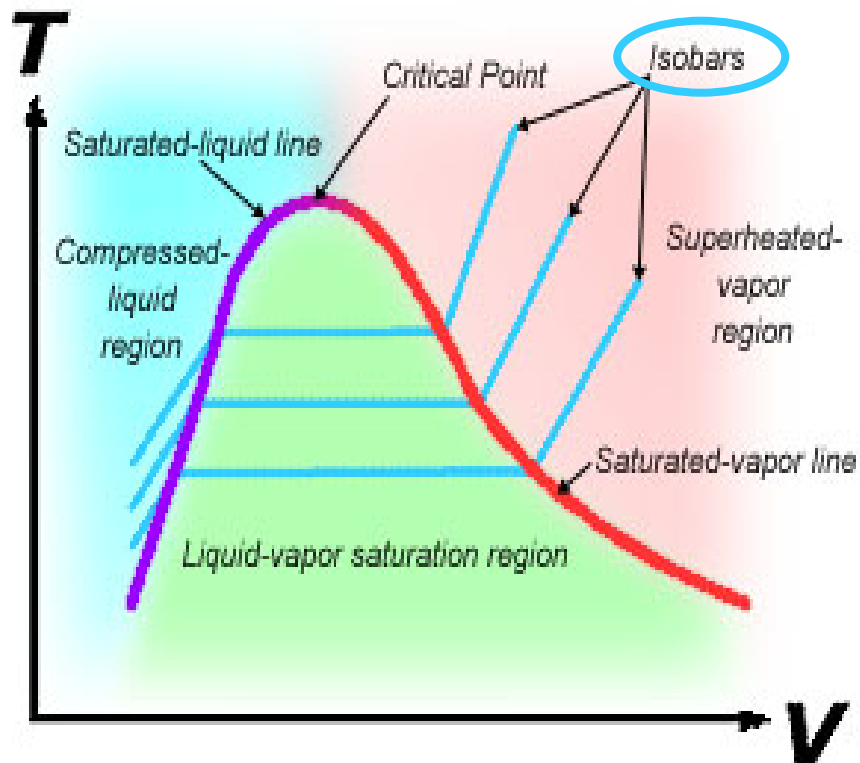
- Regions on P-v diagram

- Note directions of **isotherms** (constant temperature lines) horizontal inside the dome

- Decreasing slope outside
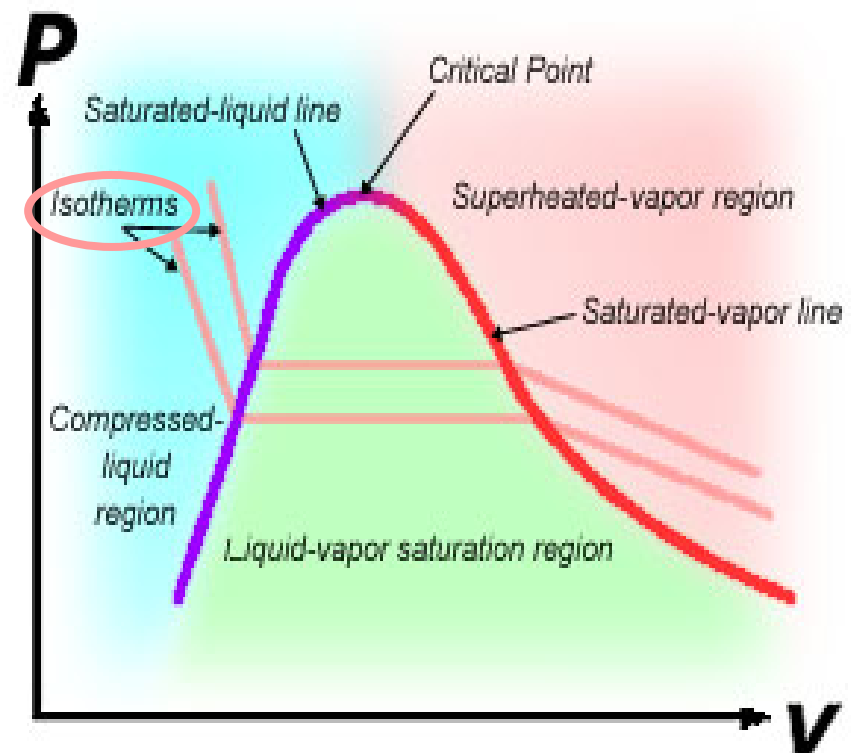
Phase Change and PvT - Surface

Some questions arise from the diagrams

1. Why is the pressure for boiling higher for higher temperatures?
2. Why are the lines in the vapor dome on the Tv and Pv - diagram horizontal, i.e. why does the temperature or pressure not increase inside the dome?
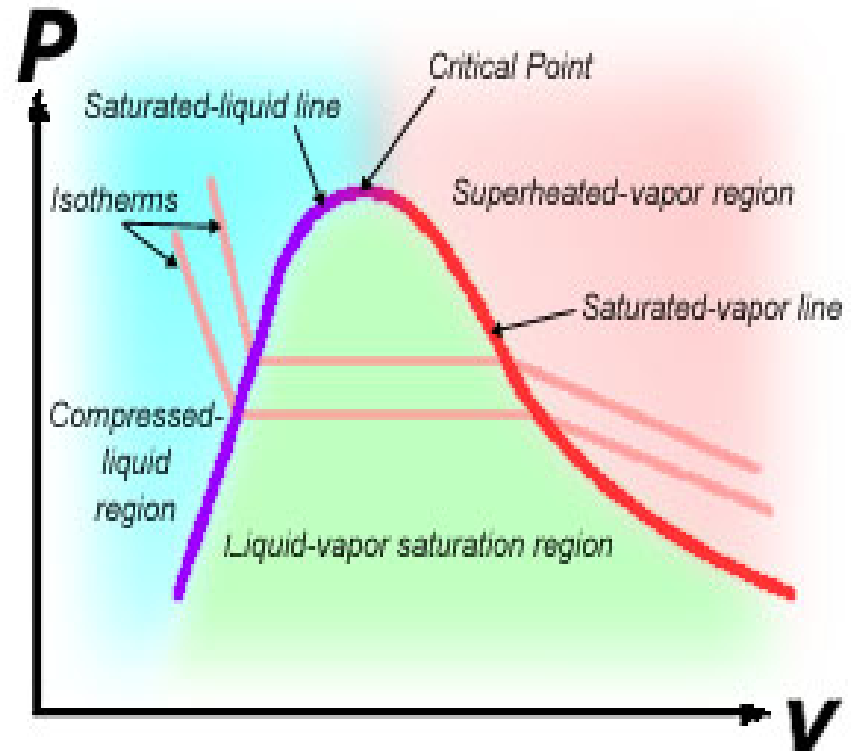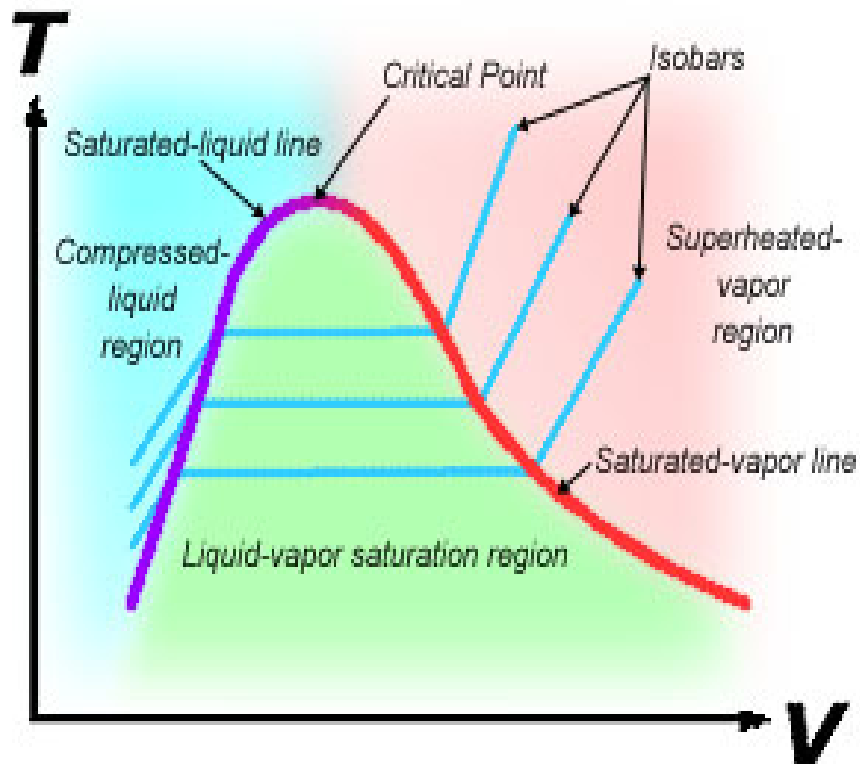
Saturation Temperature and Pressure

Some questions arise from the diagrams

1. Why is the pressure for boiling higher for higher temperatures?

- The temperature at which a liquid starts to boil depends on the pressure
- The higher the pressure the higher the temperature at which the water boils
- At higher pressure, the molecules need more energy (higher velocity) to escape the against the higher pressure
- High in the mountains at lower pressure, water boils at lower temperature

look at how few atoms are pressing down on the guy at the top of the mountain

lower pressure

look at all the atoms pressing down on the guy at the bottom of the mountain

higher pressure
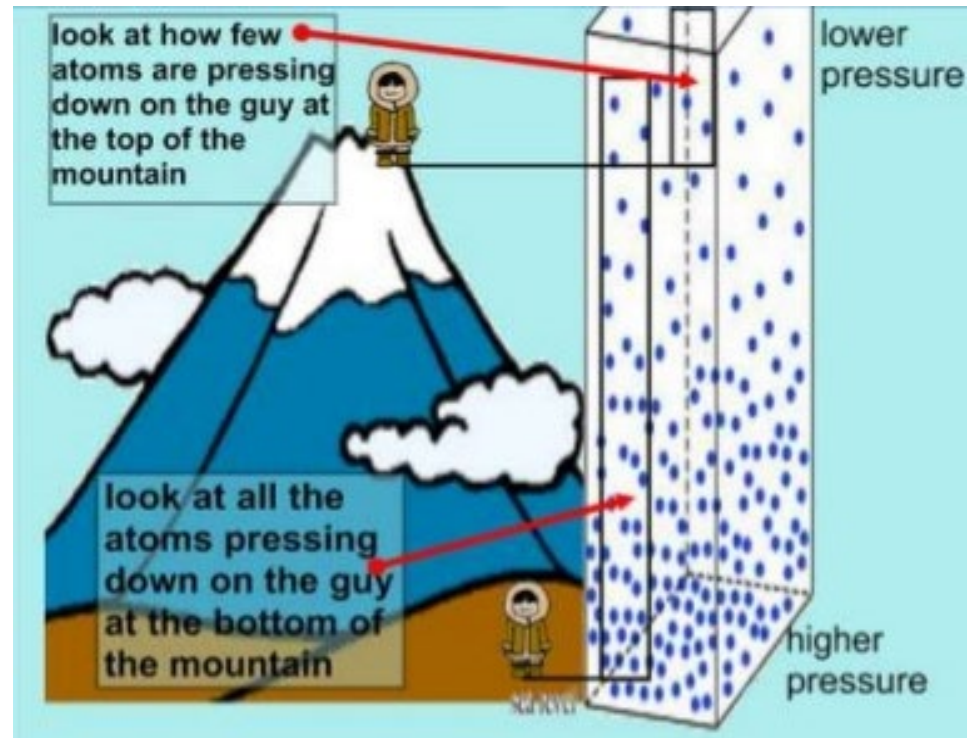
Saturation Temperature and Pressure

Some questions arise from the diagrams

2. Why are the lines in the vapor dome on the Tv and Pv - diagram horizontal, i.e. why does the temperature or pressure not increase inside the dome?

In the saturated liquid - vapor region pressure and temperature are dependent properties and do not increase because

- When a fluid is boiling the added heat is used to destroy the bounding's of the liquid molecules to turn them into vapor, once all liquid is vaporized the heat can be used to heat the vapor and the temperature of the vapor rises again

- It takes a large amount of energy to vaporize a liquid, the same amount of energy is released if vapor is condensed, this is called **latent heat**

- During a phase change process pressure and temperature are dependent properties $T_{sat} = f(P_{sat})$ (we need another second property !)
  - In the two-phase region → **saturated pressure P_{sat} and temperature T_{sat}**
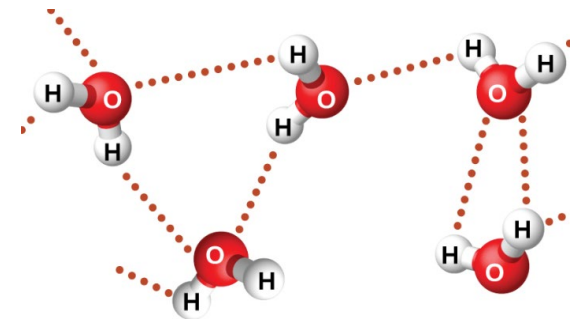
Saturation Temperature and Pressure

- During a phase change process pressure and temperature are dependent properties $T_{sat} = f(P_{sat})$
  - In the two-phase region: saturated pressure P_{sat} and temperature T_{sat}
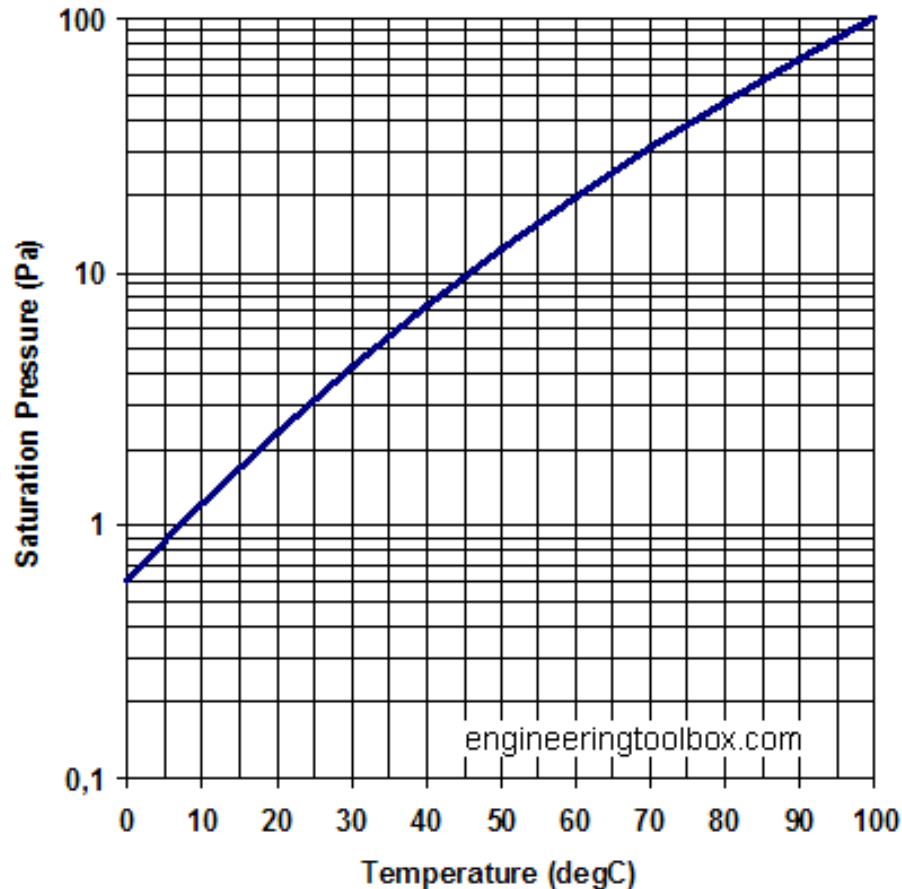
Temperature - t – (^{o}C)	Absolute Vapor Pressure p_v – (10^3 Pa, N/m^2)
0	0.6105
5	0.8722
10	1.228
20	2.338
30	4.243
40	7.376
50	12.33
60	19.92
70	31.16
80	47.34
90	70.10
100	101.3

Phase Change and P-v-T Surface

- **Three-dimensional P-v-T surface**

Region of the surface important in thermodynamics

Solid + liquid

Solid

Liquid

Gas

Pressure

Liquid + vapor

Triple-point line

Solid + vapor

Vapor

Volume

Temperature

ThermoNet John Wiley
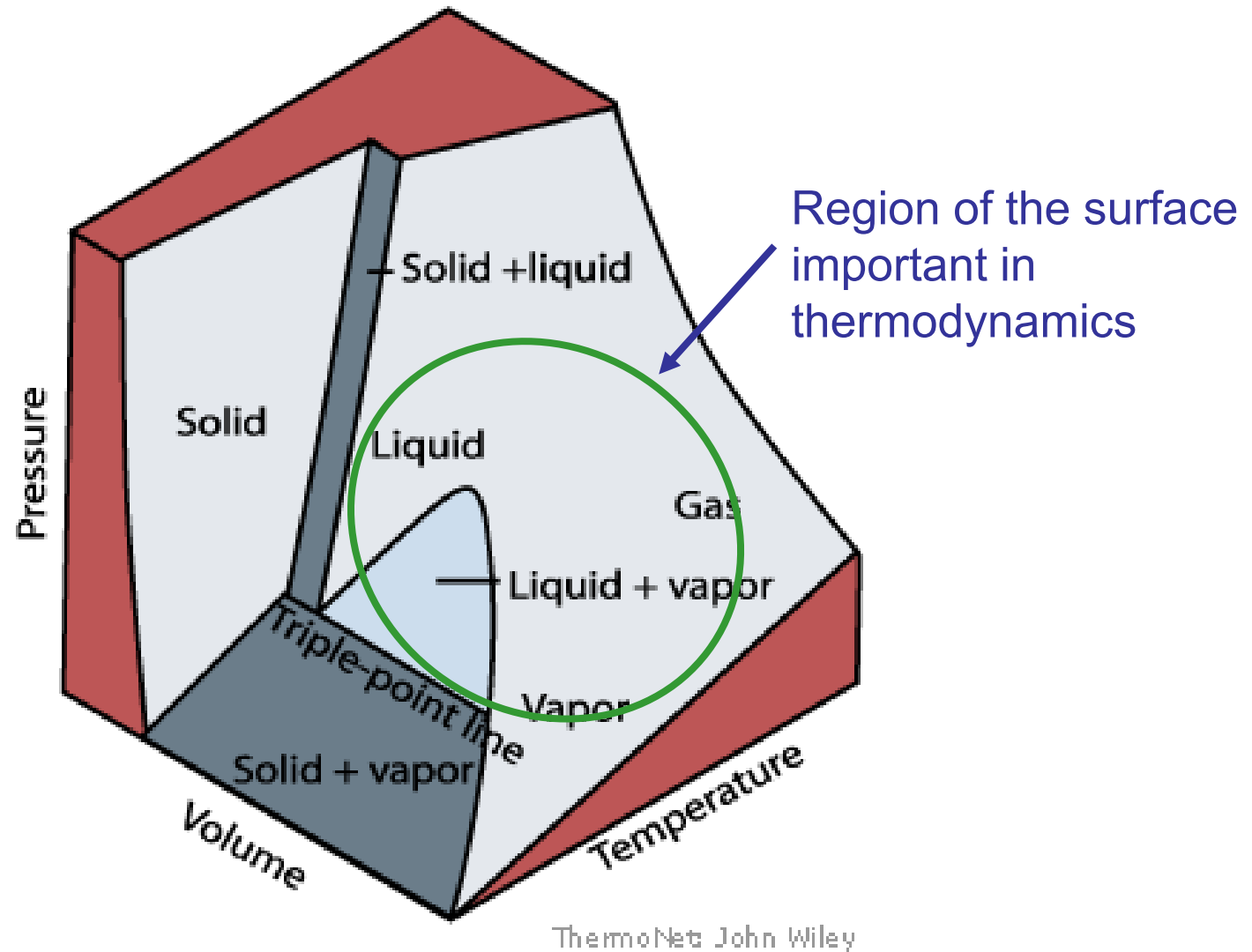
Example: Steam Cycle

Rankine Cycle
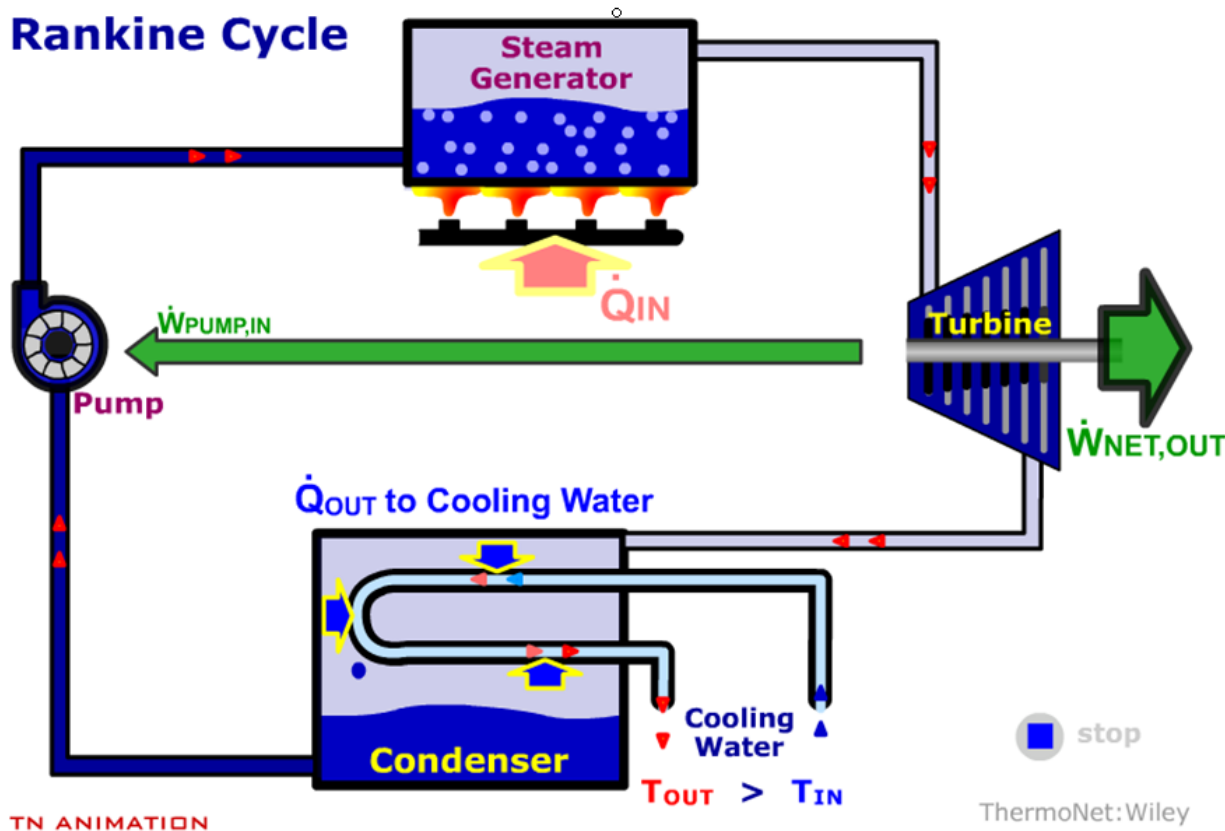
- Energy change steam generator
- $Q_{in} = E_{out} - E_{in}$
- Similar for the condenser
- $Q_{out} = E_{in} - E_{out}$
- E_{out} and E_{in} of the water and vapor depend on the temperature and pressure of the water and vapor

- In a steam cycle two times phase transitions occur
    1. From liquid to vapor in the steam generator
    2. From vapor to liquid in the condenser
- To analyze the system knowledge about the energy of water / vapor at different temperatures and pressures is necessary

Liquid-Vapor Tables

- To analyse a thermodynamic systems we need to know the energy values for water (or air) as a function of temperature and pressure

- Ideal would be to have simple equations to describe the relationships between properties (Equations of State)
  - For ideal gases very simple and accurate relation exist: $Pv = RT$, $du = c_v \, dT$, $dh = c_p \, dT$ (class 9)
  - For liquids, saturated liquid & vapor, vapor mixtures or superheated vapors such (simple) relations do not exist
  - Typically superheated vapers do not obey the ideal gas law

- Tables or diagrams are needed to find energy values

- Which tables and how to do that?

Table of Steam Properties

P (kPa)	T (^{0}C)	v (m^3/kg)
100	100	1.696
100	120	1.793
100	160	1.984

ThermoNet: John Wiley Publishers

Liquid-Vapor Tables

- **Tables**
  - Saturated liquid-vapor tables (A4 & A5)
  - Superheated vapor tables (A6)
  - Compressed liquid tables (A7)

- **Matlab** (MopPro 2)
  - Xsteam.m, returns steam and water properties based on tabulated data

Example: XSteam('h_pt',1,20) returns the enthalpy of water at 1 bar and 20 degC → 84.0118 kJ/kg

- **Diagram**
  - Mixture (partly)
  - Superheated vapor

Mollier diagram for water-steam

BREAK

https://www.cafepress.com/+thermodynamics+mugs
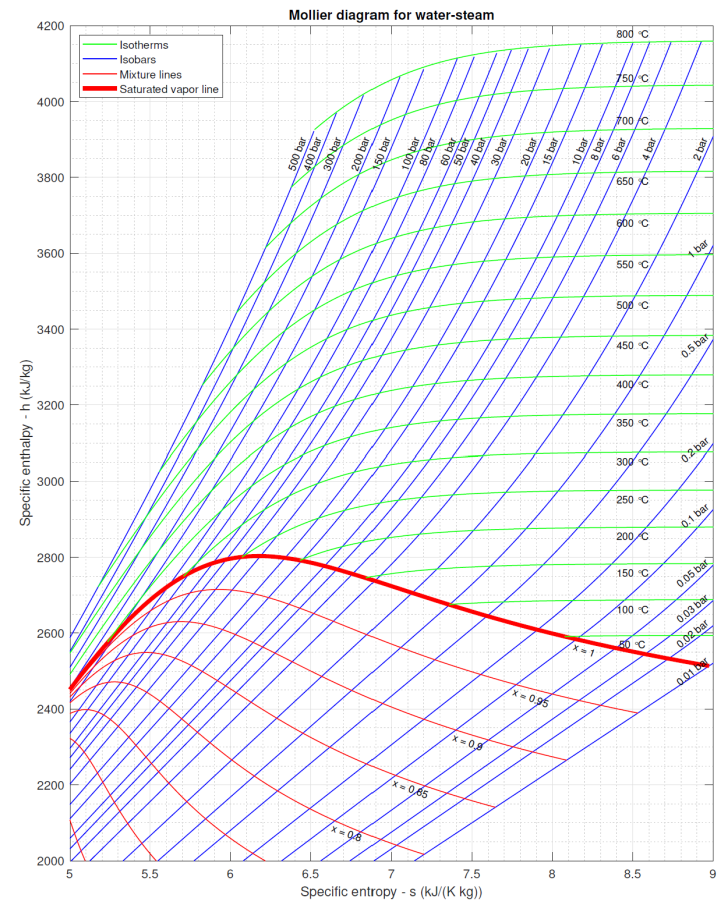
Saturated Liquid and Saturated Vapor Lines

- For **saturated values** use tables A4 and A5

- On the **saturated liquid and saturated vapor** lines
  - **Saturated liquid** denoted by **L** (e.g. v_L and u_L)   (also f (fluid) is used)
  - **Saturated vapor** denoted by **V** (e.g. v_V and u_V)   (also g (gas) is used)
  - **LV** = difference between saturated vapor and liquid values ($v_{LV} = v_V - v_L$)

- Under the dome in the **saturated liquid vapor** region
  - **Saturated mixture** denoted by **SAT** (T_{SAT} and P_{SAT})
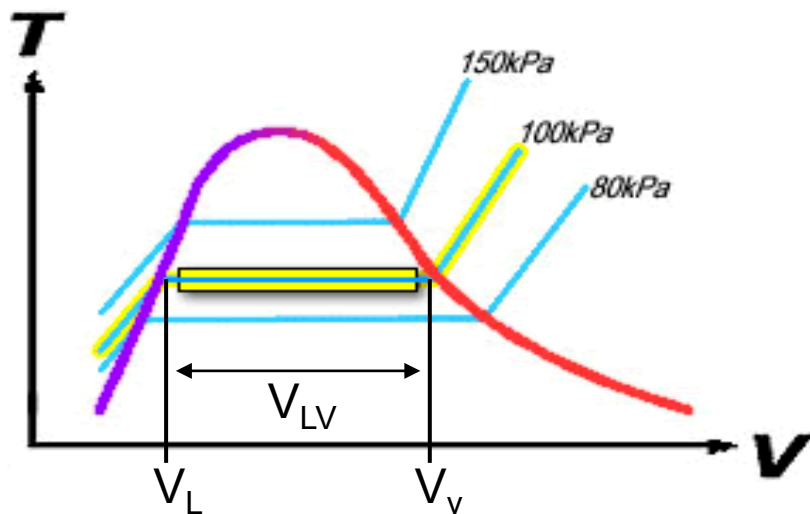
$$v_{LV} = v_V - v_L$$

Table A5

Properties of Saturated Water - Press. Table (SI)

P kPa	T ^{0}C	Specific Volume, m^3/kg v_L	v_{LV}	v_V
80	93.511	0.001038	2.0866	2.0876
100	99.632	0.001043	1.6933	1.6943
150	111.38	0.001053	1.1584	1.1595

Known P (for known T table A4)

Saturation and Quality

- Saturated liquid vapor region, this is under the vapor dome → liquid and vapor in equilibrium

- P and T are coupled (dependent) → extra parameter needed
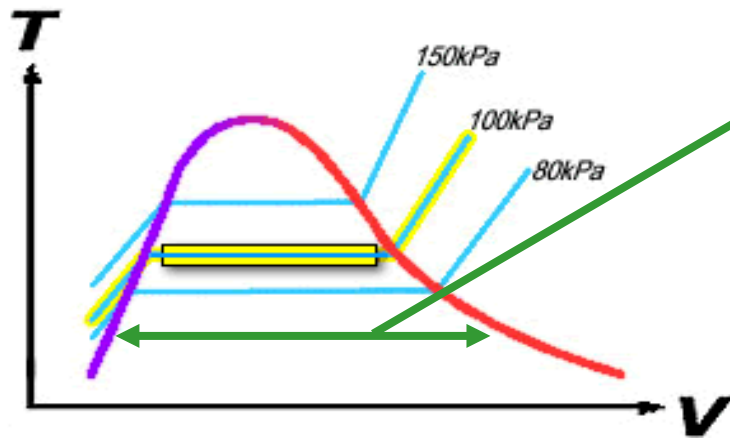
Saturated mixture, T & P coupled → extra parameter needed → x

- Total mass = mass liquid + mass vapor

$$m = m_l + m_v$$

- The ratio between mass of the vapor, m_v and total mass, m is denoted by the **quality (x):** Mass fraction of saturated vapor

$$x = Mass\ fraction\ of\ vapor = \frac{Mass\ of\ vapor}{Total\ mass\ of\ mixture} = \frac{m_v}{m}$$

$$1-x = Mass\ fraction\ of\ liquid = \frac{Mass\ of\ liquid}{Total\ mass\ of\ mixture} = \frac{m_l}{m}$$

Saturation and Quality

- Saturated mixture → extra parameter needed
- The ratio between the mass of the vapor and the total mass is denoted by the **quality (x):** Mass fraction of saturated vapor

$$x = Mass\ fraction\ of\ vapor = \frac{Mass\ of\ vapor}{Total\ mass\ of\ mixture} = \frac{m_v}{m}$$

$$1-x = Mass\ fraction\ of\ liquid = \frac{Mass\ of\ liquid}{Total\ mass\ of\ mixture} = \frac{m_l}{m}$$
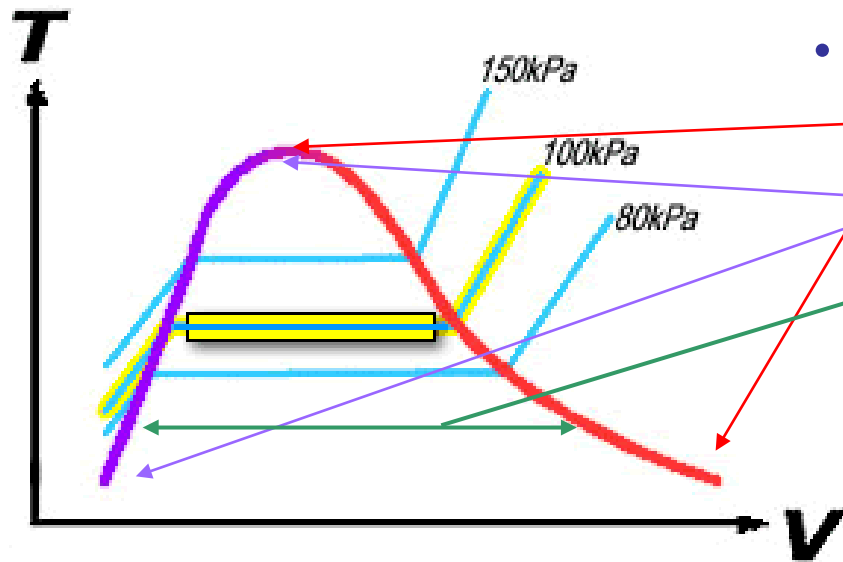
- Quality (x) of a saturated mixture
  - Saturated vapor line x = 1
  - Saturated liquid line x = 0
  - In between, a saturated mixture
    $$0 < x < 1$$
  - Outside the saturation area x is not defined!   x is never negative or > 1

Saturation and Quality

- Specific volume, v, of saturated liquid vapor mixture with quality, x:
$$v = v_L + x v_{LV} \quad \text{or specific enthalpy:} \quad h = h_L + x h_{LV}$$

- Quality of saturated liquid vapor mixture with specific volume, v

$$x = \frac{v - v_L}{v_V - v_L} = \frac{v - v_L}{v_{LV}} \qquad \text{or with enthalpy, h} \qquad x = \frac{h - h_L}{h_V - h_L} = \frac{h - h_L}{h_{LV}}$$

- These relations also held for specific internal energy u (and entropy, s)

Table A5

Properties of Saturated Water - Press. Table (SI)

P	T	Specific Volume, m^3/kg		
kPa	^{0}C	v_L	v_{LV}	v_V
80	93.511	0.001038	2.0866	2.0876
100	99.632	0.001043	1.6933	1.6943
150	111.38	0.001053	1.1584	1.1595

Example: Saturation and Quality

- Determine phase if:
  - P = 100 kPa and v = 0.001000 m^3/kg
  - P = 100 kPa and T = 100^{0}C
  - P = 100 kPa and v = 1.0000 m^3/kg

- v < v$_L$, liquid phase
- T > T$_{sat}$, vapor phase
- v$_L$ < v < v$_v$, saturated mixture

Table A5

Properties of Saturated Water - Press. Table (SI)

P	T	Specific Volume, m^3/kg		
kPa	^{0}C	v$_L$	v$_{LV}$	v$_V$
80	93.511	0.001038	2.0866	2.0876
100	99.632	0.001043	1.6933	1.6943
150	111.38	0.001053	1.1584	1.1595

Superheated Vapor

- For **superheated vapor** values use table A6
  - **Superheated vapor** denoted by **SV**, (e.g. v_{SV} and u_{SV})
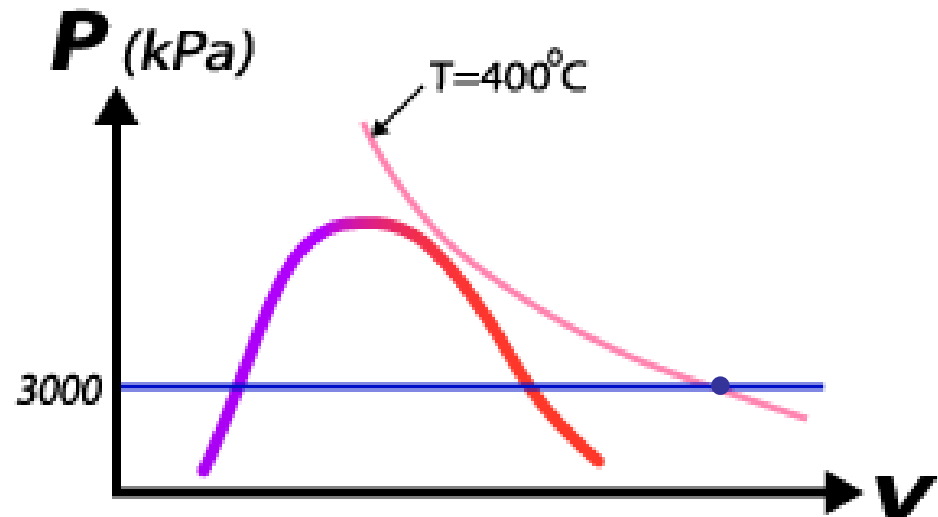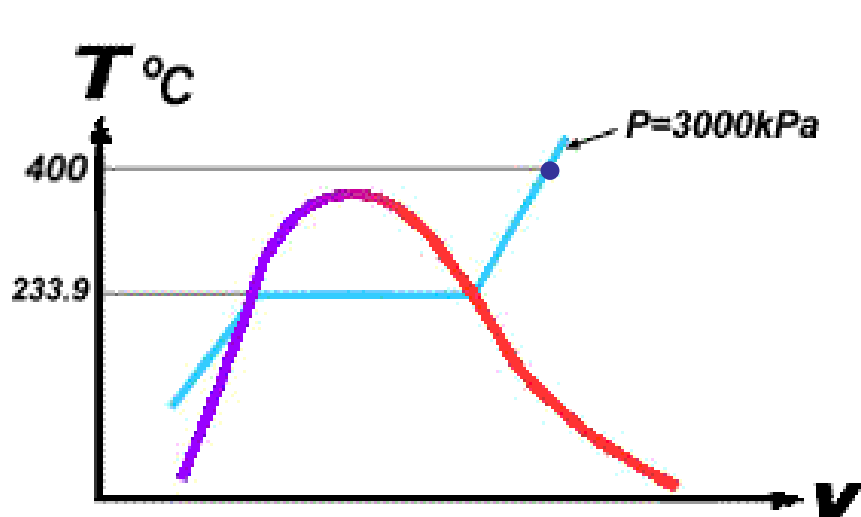
Steam entering the turbine is at
T = 400^0C & P = 3000 kPa
$T_{SAT@3000\ kPa}$ = 233.9^0C

Since T > T_{SAT}(P) → Superheated Vapor
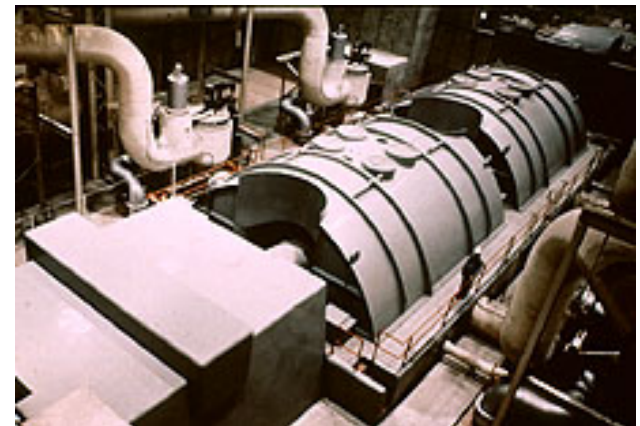
Superheated Vapor

- Superheated vapor with: P = 300 kPa and T = 200°C

Table A6

Properties of Water in the Superheated Vapor State (SI)

P kPa	T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/(kg·K)
200					
	(120.24)	(0.8859)	(2529.4)	(2706.5)	(7.1272)
	150	0.9597	2576.7	2768.6	7.2793
	200	1.0803	2653.9	2870.0	7.5059
	250	1.1988	2730.8	2970.5	7.7078
300					
	(133.56)	(0.6059)	(2543.5)	(2725.3)	(6.9921)
	150	0.6339	2570.7	2760.9	7.0779
	200	0.7163	2650.2	2865.1	7.3108
	250	0.7963	2728.2	2967.1	7.5157

Compressed (Subcooled) Liquids

- For **compressed liquid** values use table A7
  - **Compressed liquid** denoted by **CL**, (e.g. v_{CL} and u_{CL})
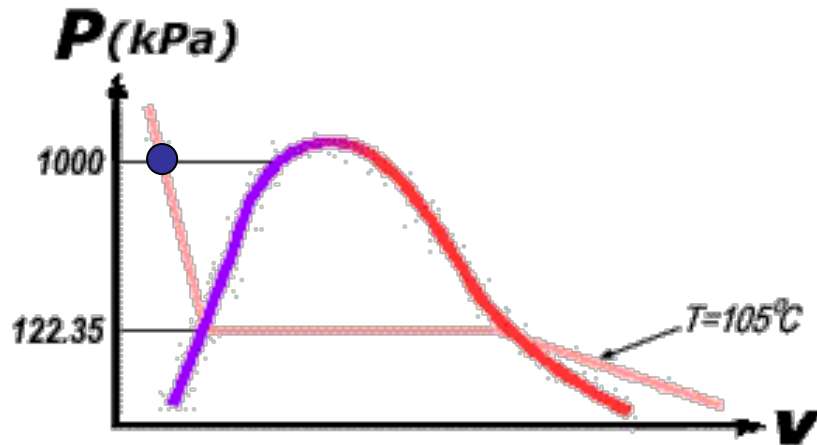
$P = 1000$ kPa & $T = 105^0$C

$P_{SAT@105^oC} = 122.35$ kPa

Since $P > P_{SAT}(T)$

$\rightarrow$ Compressed Liquid
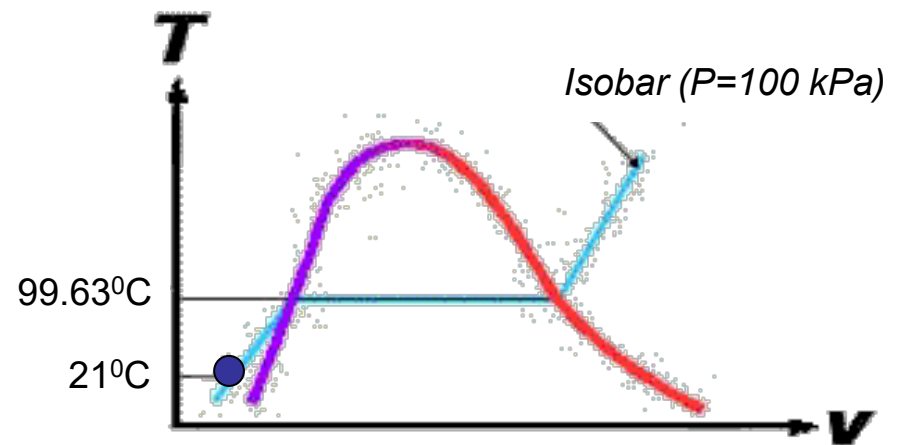
$T = 21^0$C & $P = 100$ kPa

$T_{SAT@100kPa} = 99.63^0$C

Since $T < T_{SAT}(P)$

$\rightarrow$ Subcooled Liquid

Incompressible Liquid Approx (ICL)

- Table A7 is only given for pressures above 5 MPa

- What to do for lower pressures?

- **Use incompressible liquid approximation**

- **Table A7**
  - $v_{CL}(70^0C, 5000\ kPa) = 0.001020\ m^3/kg$

- **Table A4**
  - $v_L(70^0C) = 0.00102\ m^3/kg$

- **Table A5**
  - $v_L(5000\ kPa) = 0.00129\ m^3/kg$

- **Conclusion**
  - ICL $\rightarrow v_{CL}(T,P) \cong v_L(T)$ (the volume depends mostly on T)

Table A7

Properties of Water in the Compressed Liquid State (SI)

P	T	v	u	h	s
kPa	°C	m³/kg	kJ/kg	kJ/kg	kJ/(kg·K)
5,000					
	50	0.001010	208.58	213.63	0.7014
	70	**0.001020**	291.97	297.07	0.9520

ThermoNet:Wiley

Table A4

Properties of Saturated Water (SI)

T	P	Specific Volume, m³/kg			Internal Energy, kJ/kg		
°C	kPa	v_L	v_{LV}	v_V	u_L	u_{LV}	u_V
70	31.18	**0.00102**	5.0437	5.045	292.98	2175.8	2468.8

Table A5

Properties of Saturated Water (SI)

T	P	Specific Volume, m³/kg			Internal Energy, kJ/kg		
°C	kPa	v_L	v_{LV}	v_V	u_L	u_{LV}	u_V
264	5000	**0.00129**	0.03815	0.039	1147.8	1448.7	2596.5

ThermoNet:Wiley

Incompressible Liquid Approx (ICL)

- $v_{CL}(T,P) \cong v_L(T)$

- **For all other properties**

- $u_{CL}(T,P) \cong u_L(T)$
- $h_{CL}(T,P) \cong h_L(T) + v_L(T) [P - P_{SAT}(T)]$
  - Recall $h = u + Pv \rightarrow$ h sensitive to P
  - If $P \cong P_{SAT}(T)$
    - $\rightarrow h_L(T) >> v_L(T) [P - P_{SAT}(T)]$
    - $\rightarrow h_{CL}(T,P) \cong h_L(T)$

- In conclusion: in order to find a property in the compressed liquid region (with too low pressure for the compressed liquid tables) use the value of the saturated liquid at **the right temperature**
  (Note: this is often forgotten)

Overview Liquid-Vapor Diagram & Tables

- **Regions in T-v diagrams and data tabulated**
  - Saturated liquid-vapor
  - Compressed liquid
  - Superheated vapor
- **Which region, which table?**
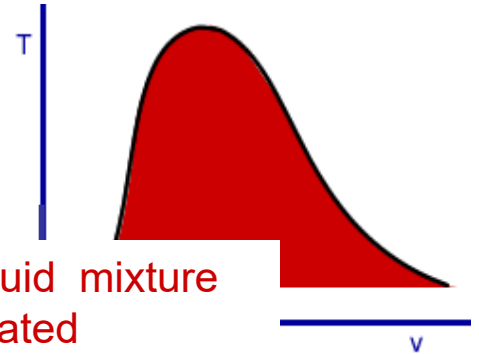
Phase: Saturated liquid mixture
Table 4 and 5: Saturated

Phase: Saturated liquid
Table 4 & 5: Saturated
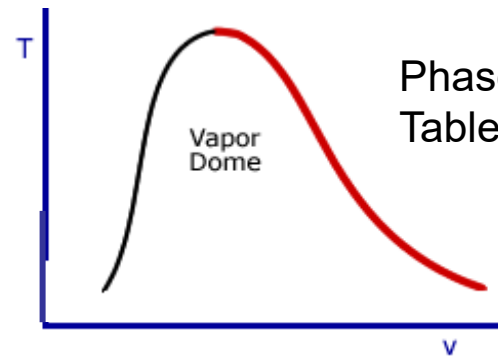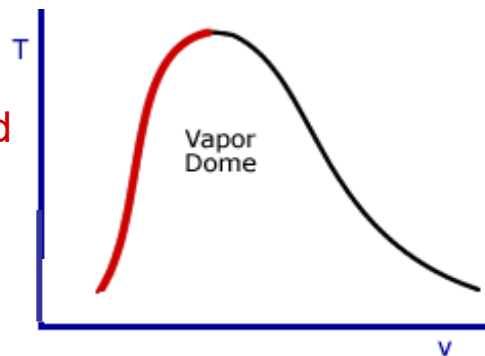
Phase: Saturated vapor
Table 4 & 5: Saturated

Phase: Compressed liquid
Table 7: Compressed liquid
(if not available use table
4 / 5 and ICL)
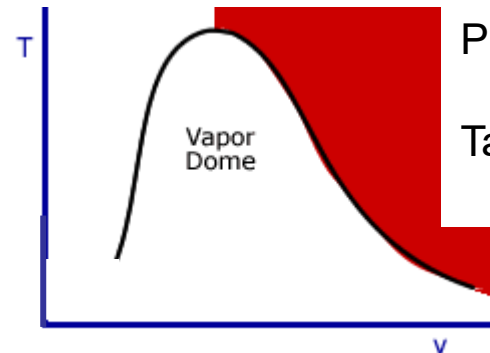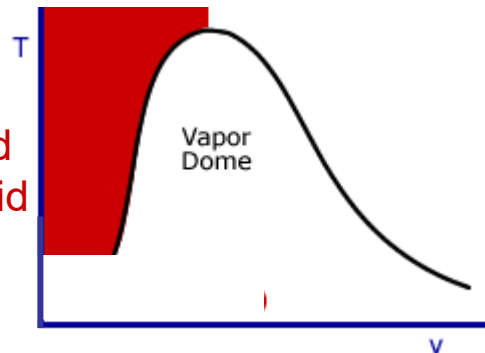
Phase: Superheated
        vapor
Table 6: Superheated
        vapor

Overview Liquid-Vapor Diagram & Tables

Region	Table nr refers to tables in Çengel and Boles
Compressed liquid	Properties of compressed liquid water (A7)
Saturated liquid line Saturated vapor line Saturated mixture	Properties of saturated water: temperature table (A4) Properties of saturated water: pressure table (A5) Quality x
Superheated vapor	Properties of superheated water (A6)
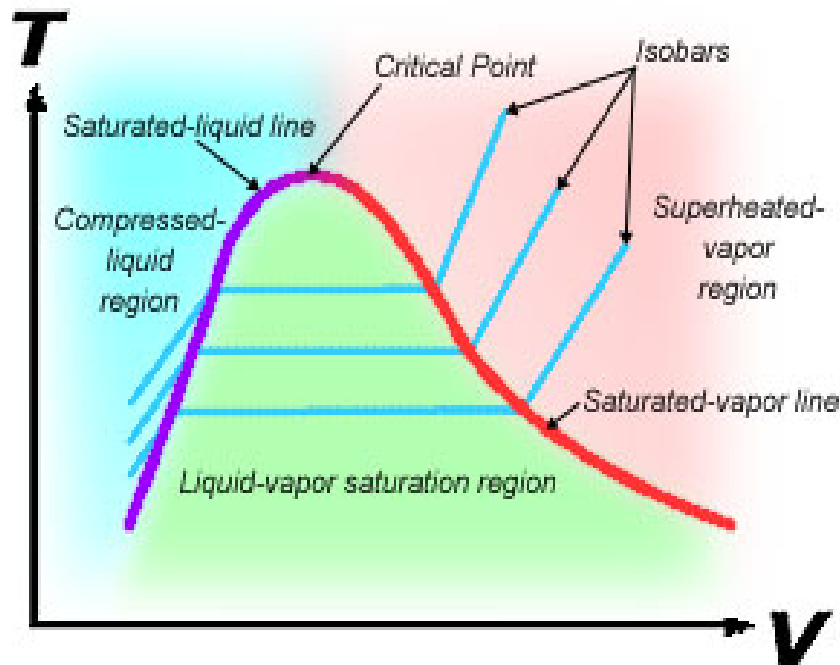
XSteam → ModPro2

Examples: Liquid-Vapor Diagram & Tables

- Water at 150 ^{0}C has a specific volume of 0.3928 m^3/kg

- Find the pressure and specific enthalpy

- Properties of saturated water: temperature table

Temp (^{0}C)	Pres (Bar)	Specific volume (m^3/kg)		Internal Energy (kJ/kg)		Enthalpy (kJ/kg)			Entropy (kJ/kgK)	
T	P	v_L x 10^3	v_v	u_L	u_v	h_L	h_{lv}	h_v	s_L	s_v
120	1.985	1.0603	0.8919	503.50	2529.3	503.71	2202.6	2706.3	1.5276	7.1296
130	2.701	1.0697	0.6685	546.02	2539.9	546.31	2174.2	2720.5	1.6344	7.0269
140	3.613	1.0797	0.5089	588.74	2550.0	589.13	2144.7	2733.9	1.7391	6.9299
150	4.758	1.0905	0.3928	631.68	2559.5	632.20	2114.3	2746.5	1.8418	6.8379
160	6.178	1.1020	0.3071	674.86	2568.4	675.55	2082.6	2758.1	1.9427	6.7502
170	7.917	1.1143	0.2428	718.33	2576.5	719.21	2049.5	2768.7	2.0419	6.6663
180	10.02	1.1274	0.1941	762.09	2583.7	763.22	2015.0	2778.2	2.1396	6.5857

- Answer: P = 4.758 Bar,   h = 2746.5 kJ/kg

Examples: Liquid-Vapor Diagram & Tables

- Water at 150 ^{0}C has a specific enthalpy (h) of 2800 kJ/kg.

- Find the pressure and specific volume.

- Properties of saturated water: temperature table

Temp (^{0}C)	Pres (Bar)	Specific volume (m^3/kg)		Internal Energy (kJ/kg)		Enthalpy (kJ/kg)			Entropy (kJ/kgK)	
T	P	v_L x 10^3	v_v	u_L	u_v	h_L	h_{lv}	h_v	s_L	s_v
120	1.985	1.0603	0.8919	503.50	2529.3	503.71	2202.6	2706.3	1.5276	7.1296
130	2.701	1.0697	0.6685	546.02	2539.9	546.31	2174.2	2720.5	1.6344	7.0269
140	3.613	1.0797	0.5089	588.74	2550.0	589.13	2144.7	2733.9	1.7391	6.9299
150	4.758	1.0905	0.3928	631.68	2559.5	632.20	2114.3	2746.5	1.8418	6.8379
160	6.178	1.1020	0.3071	674.86	2568.4	675.55	2082.6	2758.1	1.9427	6.7502
170	7.917	1.1143	0.2428	718.33	2576.5	719.21	2049.5	2768.7	2.0419	6.6663
180	10.02	1.1274	0.1941	762.09	2583.7	763.22	2015.0	2778.2	2.1396	6.5857

- Answer: P and v cannot be found from this table.
- h = 2800 kJ/kg > $h_{v@150c}$ = 2746.6 kJ/kg, therefore this is a superheated vapor; to find P and v we need the superheated vapor table

Examples: Liquid-Vapor Diagram & Tables

- Water at 15 MPa has a specific volume of 0.001006 m^3/kg. Find the temperature and enthalpy of the water.

- **Solution:**

1. **Determine the phase**

   P is given, table A5

   (properties of saturated water – pressure)

Examples: Liquid-Vapor Diagram & Tables

Water

P = 15 MPa

v = 0.001006 m³

Table A5

(properties
of saturated
water – pressure

$v_{L@15000kPa}$ =

0.001657m³/kg

TABLE 11s *Properties of Saturated Water — Pressure Table (SI)* *(continued)*

P kPa	T °C	SPECIFIC VOLUME, m³/kg			INTERNAL ENERGY, kJ/kg			ENTHALPY, kJ/kg			ENTROPY, kJ/(kg · K)		
		v_L	v_{LV}	v_V	u_L	u_{LV}	u_V	h_L	h_{LV}	h_V	s_L	s_{LV}	s_V
1400	195.08	0.001149	0.1397	0.1408	828.67	1763.6	2592.3	830.28	1959.1	2789.4	2.2842	4.1841	6.4683
1500	198.33	0.001154	0.1305	0.1317	843.12	1750.8	2593.9	844.85	1946.7	2791.5	2.3150	4.1288	6.4438
1600	201.41	0.001159	0.1225	0.1237	856.88	1738.4	2595.3	858.73	1934.6	2793.3	2.3441	4.0766	6.4207
1700	204.35	0.001163	0.1155	0.1167	870.02	1726.6	2596.6	872.00	1923.0	2795.0	2.3717	4.0272	6.3989
1800	207.15	0.001168	0.1092	0.1104	882.61	1715.1	2597.7	884.71	1911.7	2796.4	2.3980	3.9801	6.3781
1900	209.84	0.001172	0.1035	0.1047	894.70	1704.0	2598.7	896.92	1900.7	2797.6	2.4231	3.9353	6.3584
2000	212.42	0.001177	0.09841	0.09959	906.33	1693.2	2599.5	908.69	1890.0	2798.7	2.4471	3.8925	6.3396
2250	218.45	0.001187	0.08753	0.08872	933.70	1667.5	2601.2	936.37	1864.4	2800.8	2.5032	3.7926	6.2958
2500	223.99	0.001197	0.07875	0.07995	958.98	1643.3	2602.3	961.97	1840.2	2802.2	2.5544	3.7016	6.2560
2750	229.11	0.001207	0.07151	0.07272	982.53	1620.5	2603.0	985.85	1817.2	2803.0	2.6016	3.6178	6.2194
3000	233.89	0.001217	0.06544	0.06666	1004.6	1598.7	2603.3	1008.3	1795.0	2803.3	2.6454	3.5401	6.1855
3250	238.37	0.001226	0.06027	0.06150	1025.5	1577.7	2603.2	1029.5	1773.6	2803.1	2.6865	3.4673	6.1538
3500	242.60	0.001235	0.05582	0.05705	1045.3	1557.6	2602.9	1049.6	1753.0	2802.6	2.7251	3.3989	6.1240
3750	246.59	0.001244	0.05194	0.05318	1064.2	1538.1	2602.3	1068.8	1732.9	2801.7	2.7616	3.3341	6.0957
4000	250.39	0.001252	0.04852	0.04977	1082.2	1519.3	2601.5	1087.2	1713.4	2800.6	2.7962	3.2727	6.0689
5000	263.98	0.001286	0.03815	0.03944	1147.8	1448.7	2596.5	1154.2	1639.5	2793.7	2.9201	3.0524	5.9725
6000	275.62	0.001319	0.03112	0.03244	1205.4	1383.9	2589.3	1213.3	1570.6	2783.9	3.0266	2.8620	5.8886
7000	285.86	0.001352	0.02602	0.02737	1257.5	1322.7	2580.2	1267.0	1504.8	2771.8	3.1211	2.6919	5.8130
8000	295.04	0.001384	0.02214	0.02352	1305.5	1264.1	2569.6	1316.6	1441.2	2757.8	3.2066	2.5365	5.7431
9000	303.38	0.001418	0.01906	0.02048	1350.3	1207.3	2557.6	1363.1	1378.9	2742.0	3.2855	2.3916	5.6771
10,000	311.03	0.001452	0.01658	0.01803	1392.8	1151.4	2544.2	1407.3	1317.2	2724.5	3.3591	2.2548	5.6139
11,000	318.11	0.001488	0.01450	0.01599	1433.3	1096.2	2529.5	1449.7	1255.7	2705.4	3.4287	2.1238	5.5525
12,000	324.71	0.001526	0.01273	0.01426	1472.4	1041.0	2513.4	1490.7	1193.8	2684.5	3.4953	1.9968	5.4921
13,000	330.89	0.001566	0.01121	0.01278	1510.5	985.20	2495.7	1530.9	1130.9	2661.8	3.5595	1.8723	5.4318
14,000	336.70	0.001610	0.009870	0.01148	1547.9	928.40	2476.3	1570.4	1066.7	2637.1	3.6220	1.7491	5.3711
15,000	342.19	0.001657	0.008683	0.01034	1585.0	870.00	2455.0	1609.8	1000.3	2610.1	3.6837	1.6255	5.3092
16,000	347.39	0.001710	0.007600	0.009310	1622.1	809.20	2431.3	1649.5	930.80	2580.3	3.7452	1.4999	5.2451
17,000	352.34	0.001770	0.006603	0.008373	1659.9	744.90	2404.8	1690.0	857.10	2547.1	3.8073	1.3704	5.1777
18,000	357.04	0.001840	0.005665	0.007505	1698.9	675.70	2374.6	1732.0	777.70	2509.7	3.8714	1.2340	5.1054

→ v < v_L → compressed liquid ($T_{sat@15000kPa}$ = 342.19⁰C)

Up to now we know:

- Water

- Compressed liquid

- P = 15 MPa = 15000 kPa

- v = 0.001006 m^3/kg

- Compressed liquid table A7
- At 15000 kPa look for the volume and see:

T = 50^{0}C and h = 222.22 kJ/kg

TABLE 13s *Properties of Water in the Compressed Liquid State (SI)*

P kPa	T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/(kg · K)
5,000					
	10	0.000998	41.860	46.850	0.1505
	30	0.001002	125.21	130.22	0.4350
	50	0.001010	208.58	213.63	0.7014
	70	0.001020	291.97	297.07	0.9520
	90	0.001034	375.59	380.75	1.1890
	110	0.001049	459.63	464.88	1.4145
	130	0.001067	544.28	549.61	1.6301
	150	0.001087	629.68	635.12	1.8371
	170	0.001111	716.04	721.59	2.0367
	190	0.001138	803.64	809.33	2.2304
	210	0.001169	892.89	898.74	2.4193
	230	0.001206	984.40	990.43	2.6053
	250	0.001250	1079.0	1085.3	2.7901
10,000					
	10	0.000996	41.729	51.685	0.1500
	30	0.001000	124.75	134.75	0.4334
	50	0.001008	207.85	217.93	0.6991
	70	0.001018	290.98	301.16	0.9491
	90	0.001031	374.32	384.63	1.1855
	110	0.001046	458.07	468.53	1.4104
	130	0.001064	542.38	553.02	1.6253
	150	0.001084	627.41	638.25	1.8316
	170	0.001107	713.31	724.39	2.0305
	190	0.001133	800.37	811.70	2.2232
	210	0.001164	888.94	900.57	2.4111
	230	0.001199	979.55	991.54	2.5955
	250	0.001241	1073.0	1085.4	2.7784
	270	0.001292	1170.3	1183.2	2.9619
	290	0.001357	1273.5	1287.1	3.1497
15,000					
	10	0.000993	41.593	56.493	0.1494
	30	0.000998	124.30	139.27	0.4319
	50	0.001006	207.13	222.22	0.6968
	70	0.001016	290.01	305.25	0.9461
	90	0.001029	373.08	388.51	1.1820
	110	0.001044	456.54	472.20	1.4063
	130	0.001061	540.53	556.45	1.6206
	150	0.001081	625.19	641.41	1.8263
	170	0.001104	710.67	727.22	2.0244
	190	0.001129	797.20	814.14	2.2163

Examples: Liquid-Vapor Diagram & Tables

- Water at 15 Mpa has a specific volume of 0.001006 m^3 /kg.

- Find the temperature and enthalpy of the water

- **Solution:**

1. Determine the phase

   P is given, table A5 (properties of saturated water – pressure) gives:
   $v_{L@15000kPa}$ = 0.001657m^3/kg

   $v < v_L \rightarrow$ compressed liquid   ($T_{sat@15000kPa}$ = 342.19^{0}C)

2. Compressed liquid table A7, 15000 kPa and v = 0.001006 m^3/kg

   T = 50^{0}C and h = 222.22 kJ/kg

3. The water is in the compressed liquid phase, the temperature is 50^{0}Celsius which is indeed lower than the 342.19^{0}C which is the saturation temperature of water at 15 MPa
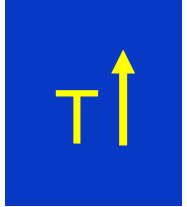
Specific heat

- **Specific heat, c [kJ/kgK]:** the amount of energy required to raise the temperature of a unit mass of a substance by one degree in a specified way

- Approximately specific is defined as: $c \approx \dfrac{de}{dT}$

- **The specific heat depends on:**
  - The substance (water, oil, air, helium, steel, wood,…)
  - The temperature
  - The process (constant pressure or constant volume)
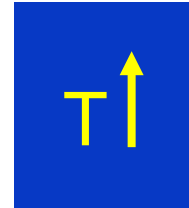
Specific heat

- Depending on the **process** different forms of heat capacity are defined (more about this when gases are studied in class 9)

  - **Specific heat at constant volume, c_v:** The energy required to raise the temperature of a unit mass of a substance by one degree as the volume is maintained constant

  - **Specific heat at constant pressure, c_p:** The energy required to raise the temperature of a unit mass of a substance by one degree as the pressure is maintained constant

Specific heat

- Depending on the process different forms of heat capacity are defined c_v **(constant volume)** and c_p **(constant pressure)**

- **Solids and liquids** are **incompressible,** volume does not change, therefore v = constant, no difference between specific heat for constant pressure and constant volume

- For solids and liquids: $c_P = c_V$ (sometimes denoted as c)

$$\triangle e \approx \triangle u \approx \triangle h = \int_{T_1}^{T_2} c \ \mathrm{d}T$$

- Values of c_p and c_v can be found in tables
- Tables A2 (gasses), A3 (liquids / solids) and A27 (fuels and hydrocarbons)

- Note: for gases c_p and c_v have different values, we will treat this later in class 9
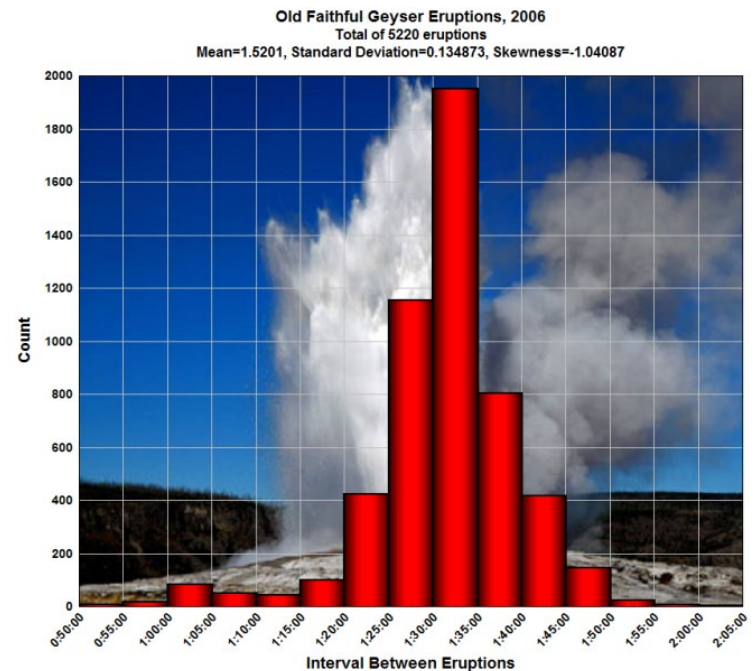
Old Faithful Geyser (Yellowstone Nat. Park)

Old Faithfull eruption
http://www.youtube.com/watch_popup?v=tShhZvvIM84&vq=medium#t=32

How does it work?
http://www.youtube.com/watch_popup?v=X4zA_YPCyHs&vq=medium#t=32

Old Faithful Geyser Eruptions, 2006
Total of 5220 eruptions
Mean=1.5201, Standard Deviation=0.134873, Skewness=-1.04087

How works a hot water geyser?

- For geyser to occur there must be heat, water, and a plumbing system. A magma chamber provides the heat, which radiates into surrounding rock. Water from rain and snow works its way underground through fractures in the rock.

- As the water reaches hot rock it begins to rise back to the surface, passing through rhyolite, which is former volcanic ash or lava rich in silica. The hot water dissolves the silica and carries it upward to line rock crevices. This forms a constriction that holds in the mounting pressure, creating a geyser's plumbing system.

- As superheated water nears the surface, its pressure drops, and the water flashes into steam as a geyser. Hot springs have unconstricted plumbing systems.
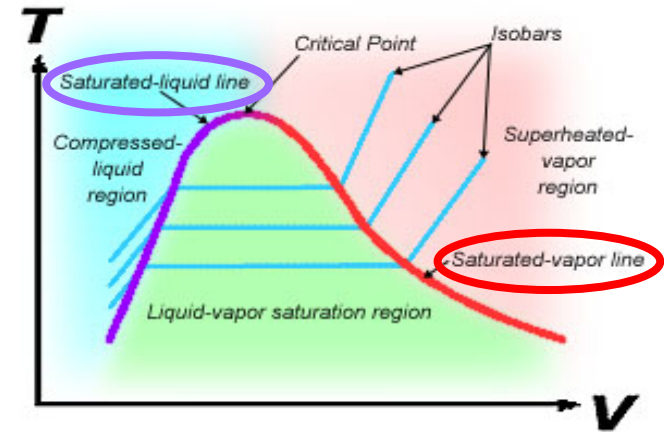

How Geysers Work

Hot Spring
← Cone Geyser
Plumbing System
Porous Rock
Heat Source
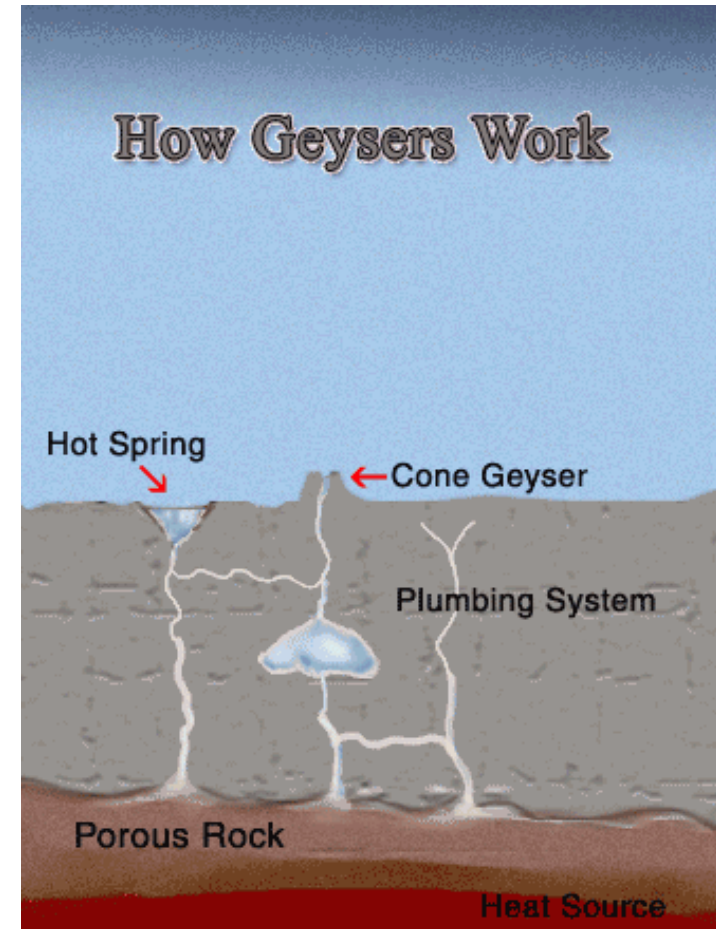
(Extra information, not part of the exam)

https://www.youtube.com/watch?v=x9UEKCYIM-I&feature=emb_rel_pause

Recapitulate class 3

- Pure substances change phases
  - Solid, liquid, gas phase
  - Saturated mixtures of them
- Different regions P – v – T diagram
  - Vapor dome, critical point
  - Saturated liquid and saturated vapor line
  - Liquid-vapor saturated region
    - Saturated mixture, constant dependent P_{sat} and T_{sat} in the mixture region
    - Quality of the mixture: $x = \dfrac{v - v_l}{v_v - v_l} \rightarrow v = v_l + x(v_v - v_l)$
  - Compressed liquid region
  - Superheated vapor region
- Tables to find values of v, u, s and h
- Specific heat of a liquid

T-v diagram of water showing the vapor dome and the different regions

Next Class 4: First law of Thermodynamics

- Energy balance of closed systems
- Conservation of mass and mass balances
- Flow work
- Total energy of a flowing fluid
- Energy balance of steady flow systems
- Applications of the first law of thermodynamics to
    - Turbines
    - Compressors
    - Pumps, blowers
    - Nozzles and diffusers
    - Throttling valves
    - Heat exchangers
    - Mixing device

Air being heated inside the cylinder shows energy transfer in a closed system

A rocket demonstrates some of the energy flows that can occur in an open system

Keep in mind: Important formulas

- Specific volume $v = V/m$ [m^3/kg] and density $\rho = 1/v = m/V$ [kg/m^3]

- Volume work $\delta w = Pdv$ or $\delta W = PdV$

- Enthalpy $h = u + Pv$, where u is internal energy, P is pressure
  v is volume (and not velocity!)

- Conservation of energy (first law) $E_{in} - E_{out} = \Delta E_{system}$

- Efficiency $\quad \eta_{thermal} = \dfrac{Net\ electrical\ power\ output}{Rate\ of\ fuel\ energy\ input} = \dfrac{\dot{W}_{net}}{\dot{Q}_{in}}$

- Different phases in phase diagrams

- Mixture fraction

$$x = \frac{v - v_l}{v_v - v_l} \rightarrow v = v_l + x(v_v - v_l)$$