Chapter 2 - Properties of a Pure Substance

Lecture 3
Sections 2.1-2.3

MEMS 0051 Introduction to Thermodynamics

Mechanical Engineering and Materials Science Department
University of Pittsburgh

Student Learning Objectives

At the end of the lecture, students should be able to:

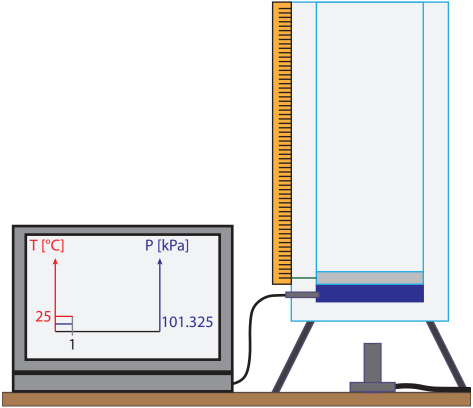
- Identify a pure substance
- Identify phase boundaries for solid, liquid and vapor phases
- Understand P-ν-T surface representing P-T, T-ν and P-ν diagrams
- Identify if a substance is a subcooled, compressed or saturated liquid, or a saturated or superheated vapor in terms of saturation pressure and temperature

Pure Substance

- A **pure substance** is homogeneous and has an invariable chemical composition
- It can exist in various phases either independently or simultaneously (solid, liquid, vapor), but the chemical composition must be the same in all phases (i.e. H_2O and not H_2O with H_2O_2)
- However, we may consider air (78% N_2, 20.9% O_2, 0.9% Ar, 0.03% CO_2 and CH_4) as a pure substance as long as there is no phase change

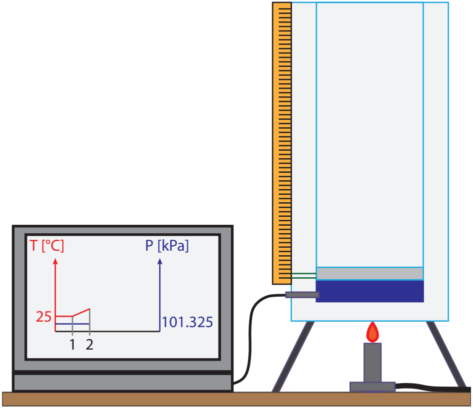
Vapor-Liquid-Phase Equilibrium

- Consider the following piston-cylinder system, with a weightless piston. The system is initially at State 1, at 25 °C and 101.325 [kPa], i.e. it is completely a liquid.



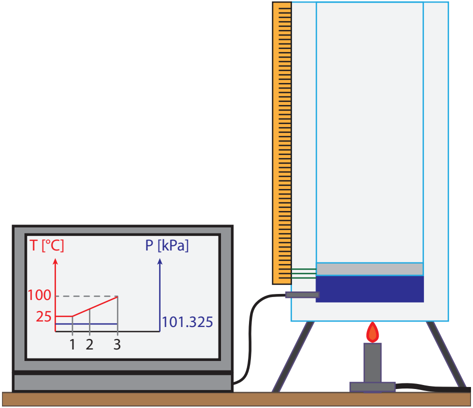
Vapor-Liquid-Phase Equilibrium

- As heat is added to the C.∀., the temperature will increase, as will the specific volume (marginally), whereas the pressure remains constant. This is shown as State 2.



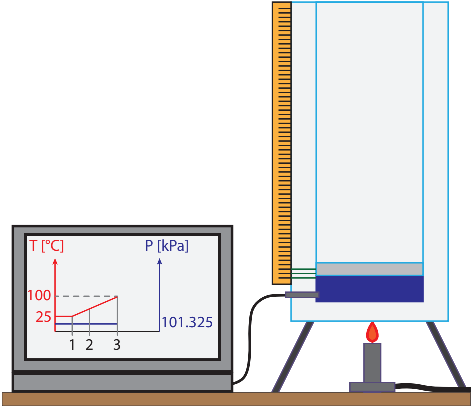
Vapor-Liquid-Phase Equilibrium

- The will be an increase in T and ν until the temperature reaches 100 °C. The pressure still remains constant. This is shown as State 3. The system is still completely liquid.



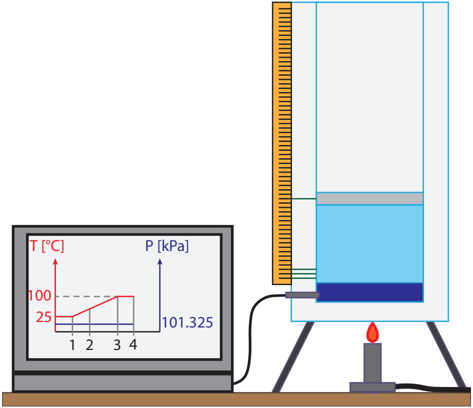
Vapor-Liquid-Phase Equilibrium

- Once the temperature reaches 100 °C (T_{sat}) at a pressure of 101.325 [kPa] (P_{sat}), additional heat is needed to change the phase of liquid to water, i.e. the **latent heat of vaporization**



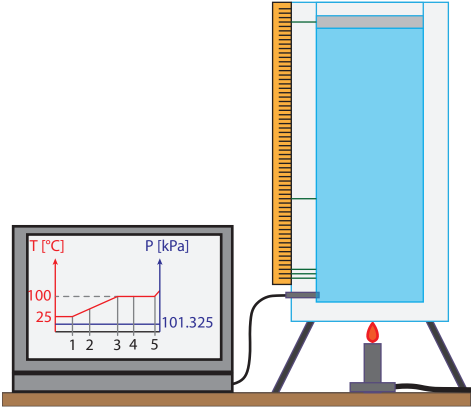
Vapor-Liquid-Phase Equilibrium

- During the process of phase change, both temperature and pressure remain constant, but ν increases appreciably as liquid water is turned into vapor. This is shown as State 4.



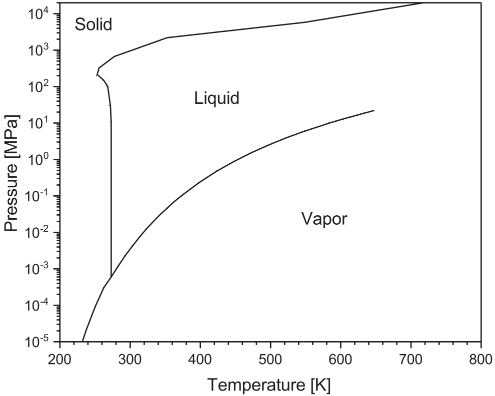
Vapor-Liquid-Phase Equilibrium

- Once all liquid is transformed to vapor (State 5), additional heat is required to increase the temperature and ν, as shown past State 5, however, in this set-up, pressure remains constant.



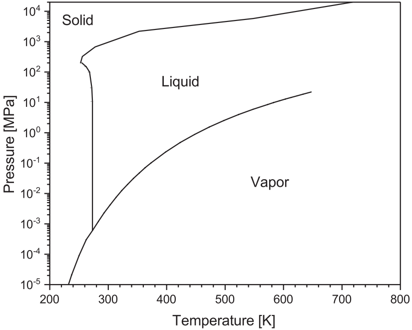
Vapor-Liquid-Phase Equilibrium

- The relationship between P_{sat} and T_{sat} is depicted by a *vapor-pressure curve* (P vs. T or vice versa is common), i.e. the interface between the solid, liquid and vapor regions on the phase diagram



Vapor-Liquid-Phase Equilibrium

- The vertical line between solid and liquid phases is the **fusion line**
- The line separating the water and vapor phases is the **vaporization line**
- The line separating the solid and vapor phases is the **sublimation line**



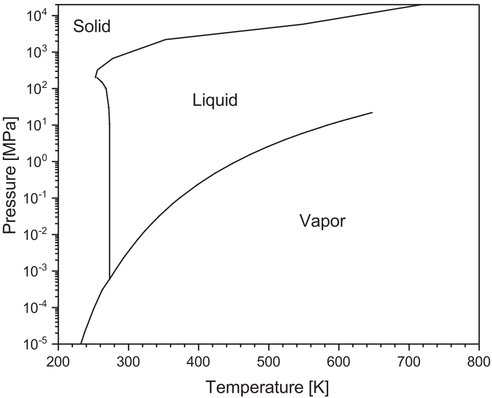
Vapor-Liquid-Phase Equilibrium

- Crossing the fusion line can be done via two processes:
  1. **Melting** - solid to liquid
  2. **Freezing** - liquid to solid
- Crossing the vaporization line can be done via two processes:
  1. **Boiling** - liquid to vapor
  2. **Condensation** - vapor to liquid
- Crossing the sublimation line can be done via two processes:
  1. **Sublimation** - solid to vapor
  2. **Deposition** - vapor to solid

Example #1 - P-T Diagram for H_2O

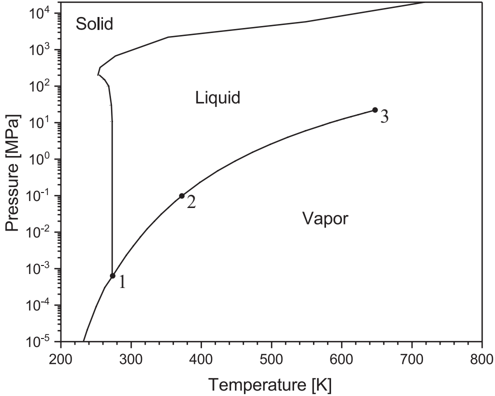
- What phase changes can water undergo if pressure is held constant at:

1. 50 [kPa]
2. 0.3 [kPa]



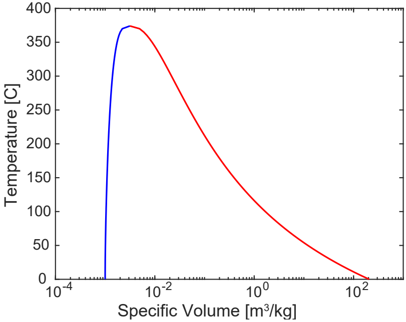
Vapor-Liquid-Phase Equilibrium

- 1 is the **triple point**
- 2 would be the **boiling point** at STSP
- 3 is the **critical point** - note there is no phase boundary past this point



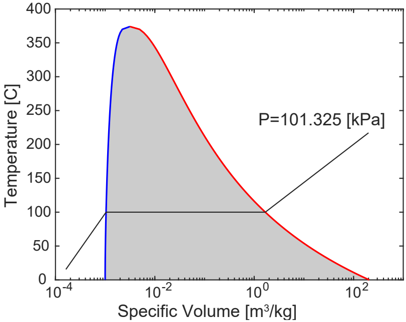
T-ν Diagram

- A $T-\nu$ diagram shows the relation between T and ν for lines of constant pressure
- The blue line represents a **saturated liquid**
- The red line represents a **saturated vapor**
- Everything constrained by these lines is the vapor dome



T-ν Diagram

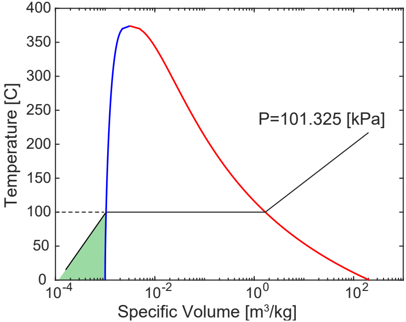
- At 100 °C, the P_{sat} is 101.325 [kPa]. That is to say, 100 °C is the T_{sat} corresponding to a pressure of 101.325 [kPa]. The substance is referred to as saturated, denoted by the shaded grey region, if existing at T_{sat} and P_{sat}



Note: lines outside the vapor dome are representative and do not reflect actual numeric values.

T-ν Diagram

- There are important classifications based upon relations to T_{sat} and P_{sat}
- If T is less than T_{sat} for a given P_{sat}, it is a **subcooled liquid**, i.e. the green shaded region.



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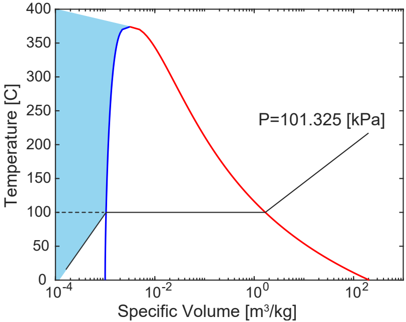
T-ν Diagram

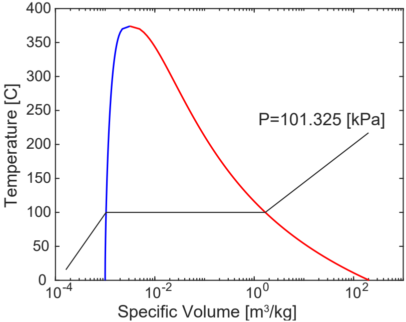
- If P is greater than P_{sat} for a given T_{sat}, it is a **compressed liquid**, as denoted by the shaded blue region.



Note: lines outside the vapor dome are representative and do not reflect actual numeric values.

T-ν Diagram

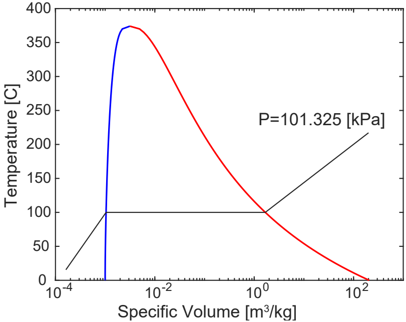
- If a substance exists as 100% liquid at T_{sat} and P_{sat}, it is a **saturated liquid**, as denoted by the blue line.



Note: lines outside the vapor dome are representative and do not reflect actual numeric values.

T-ν Diagram

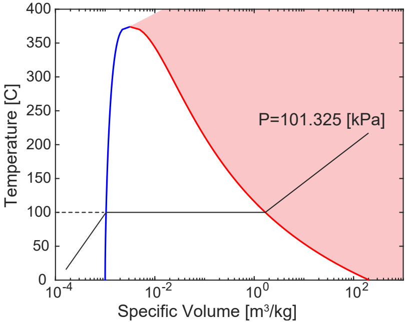
- If a substance exists as 100% vapor at T_{sat} and P_{sat}, it is a **saturated vapor**, as denoted by the red line.



Note: lines outside the vapor dome are representative and do not reflect actual numeric values.

T-ν Diagram

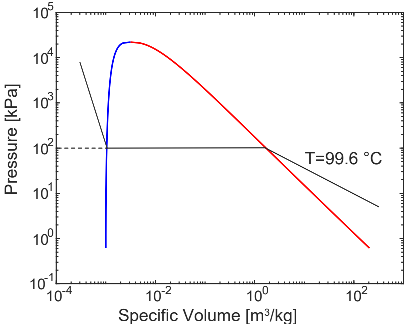
- If a substance exists as a vapor at T greater than T_{sat} for a given P_{sat}, it is a **superheated vapor**, as denoted by the shaded red region.



Note: lines outside the vapor dome are representative and do not reflect actual numeric values.

P-ν Diagram

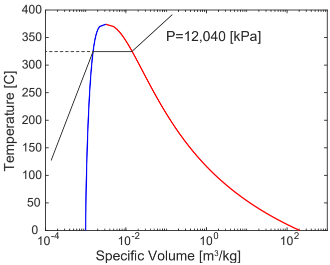
- We can also visualize states on the P-ν diagram
- Note the directionality of the lines of constant temperature

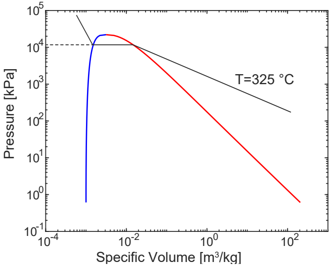


Note: lines outside the vapor dome are representative and do not reflect actual numeric values.

Example #2

- Given the $T - \nu$ and $P - \nu$ diagrams of water, and a temperature of 325 °C and a corresponding saturation pressure of 12,040 [kPa], determine the following classifications of the substance:





Note: lines outside the vapor dome are representative and do not reflect actual numeric values.

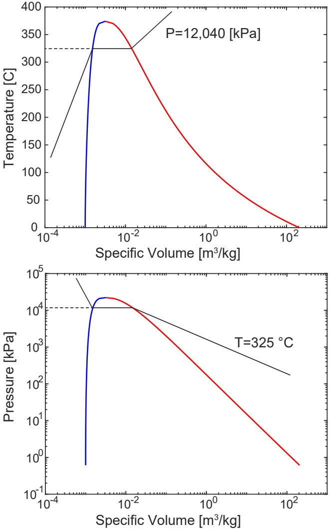
Example #2

1. T=325 °C, P=20,000 [kPa]

2. T=325 °C, P=8,000 [kPa]

3. T=200 °C, P=12,040 [kPa]

4. T=325 °C, P=12,040 [kPa]



Student Learning Objectives

At the end of the lecture, students should be able to:

- Identify t a pure substance
  - A pure substance is homogeneous with an invariable chemical composition.
- Identify phase boundaries for solid, liquid and vapor phases
  - The fusion line separates the solid and liquid regions, the vaporization line separates the liquid and vapor regions, and the sublimation line separates the solid and vapor regions.
- Understand P-ν-T surface representing P-T, T-ν and P-ν diagrams
  -
- Identify if a substance is a subcooled, compressed or saturated liquid, or a saturated or superheated vapor in terms of saturation pressure and temperature

Student Learning Objectives

- Understand P-ν-T surface representing P-T, T-ν and P-ν diagrams
  - A $P-T$ diagram, also known as a phase diagram, indicates what phase (solid, liquid vapor) the substance is existing in. The $T-\nu$ diagram gives a relation between T and ν with respect to lines of constant pressure. The $P-\nu$ diagram gives a relation between P and ν with lines of constant temperature. The latter two allow us see phase transformation processes in terms of T, P and ν. If all three are assembled with shared axes, we create at $P-\nu-T$ diagram.

Student Learning Objectives

- Identify if a substance is a subcooled, compressed or saturated liquid, or a saturated or superheated vapor in terms of saturation pressure and temperature
  - A substance is subcooled if T is less than T_{sat} for a given P_{sat}
  - A substance is compressed if P is less than P_{sat} for a given T_{sat}
  - A substance is a saturated liquid if T equals T_{sat}, P equals P_{sat}, and the substance is 100% liquid
  - A substance is a saturated vapor if T equals T_{sat}, P equals P_{sat}, and the substance is 100% vapor
  - A substance is superheated if T is greater than T_{sat} for a given P_{sat}

Suggested Problems

- 2.19, 2.20, 2.21, 2.25