LUT University

LAND OF THE CURIOUS

LES10A020 Engineering Physics

LES10A020

Engineering Physics
Lecture 2

by
Assoc. Prof. Jukka Paatero

LUT University

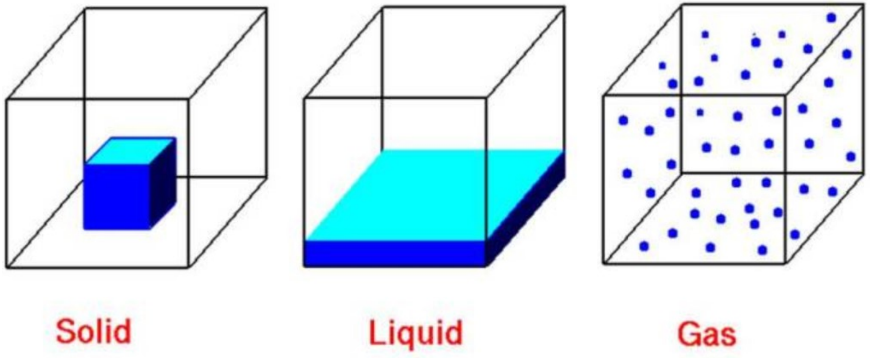
Energy and Changes in State and Phase

Changes in Internal Energy

- When the internal energy U of matter changes sufficiently, this can result in macroscopic changes
- In addition to the internal energy, the changes are also dependent on the pressure p and volume V of the matter.
- Naturally, any chemical reaction taking place within the matter also makes a major change, as the composition of matter changes significantly.

Three Common States of Matter

- **Solid** matter holds it shape even if internal energy changes
  - There can still be minor changes in its dimensions
- **Liquid** matter takes the form of the container
  - Also has an open surface
- **Gas** takes the form of container
  - Volume depends on container size



- How about **plasma**?

LUT University

Thermal Expansion

- Thermal expansion is dependent on the state of the matter
  - Expansion is fastest in gases and slowest in solids
- Thermal expansion of solids often results in quite linear change in the length of the solid, assuming the change in temperature remains small
- Assuming L_0 is the length of solid before temperature change, the length after temperature change ΔT is

$$L = L_0 + \alpha\ L_0 \Delta T$$

- Above α is the ***linear temperature expansion coefficient of length*** for that substance
- Correspondingly, for areal expansion of a square plate $\mathrm{A} = L^2$of solid we have

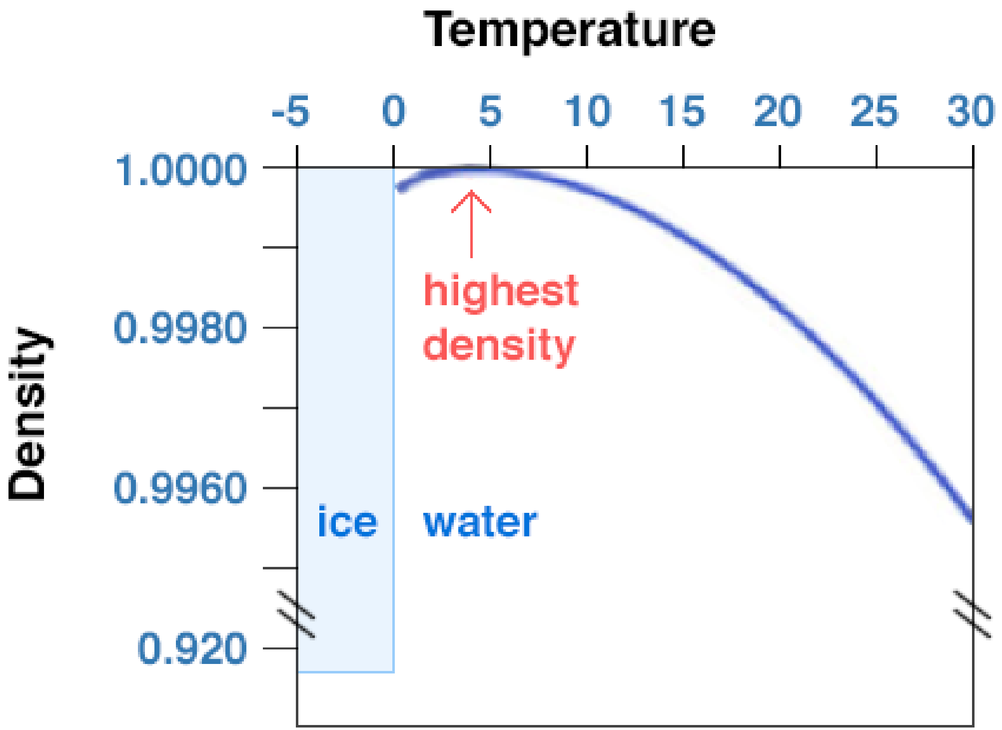
$$A = (L_0 + \alpha\ L_0 \Delta T)^2$$

LUT University

- When α is small, we can derive that $A \approx A_0 + 2\alpha\ A_0 \Delta T$
- Correspondingly, for a volume we get $V \approx V_0 + 3\alpha\ V_0 \Delta T$
- Thus, if you have the thermal expansion coefficient α for the solid, you can effectively also estimate the expansion of area and volume.
- For gases and liquids, a volumetric thermal expansion coefficient $\alpha_V = 3\alpha$ is typically used.
- Always check if you are using a linear or volumetric expansion coefficient of a matter!

Density of Water

- Water has some exceptional behavior, as its density behaves in non-linear way
- This also effects the way it expands when heated.
- When in temperatures above 10 degrees, linear estimates can often be applied.



Source: Mike Arthur and Demian Saffer from https://www.e-education.psu.edu/earth111/node/842

LUT University

Measuring Transfer of Heat Quantity

- Two ways are used to identify the ability of matter to absorb heat: heat capacity (or thermal capacity) and specific heat capacity

- Heat capacity C is the ratio of transferred heat quantity and the change in temperature:

$$C = \Delta Q / \Delta T$$

- Specific heat capacity expresses the heat capacity per mass unit:

$$c = \frac{\Delta Q}{\Delta T \cdot m}$$

LUT University

Amount of Matter

- When heat capacity is considered for a specific amount of mass, two different standards are used.
- Specific heat capacity can express the heat capacity per mass unit:

$$c = \frac{\Delta Q}{\Delta T \cdot m}, \quad [c] = \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}}$$

- Molar ~~specific~~ heat capacity expresses the heat capacity per amount of matter:

$$c_m = \frac{\Delta Q}{\Delta T \cdot n}, \quad [c] = \frac{\mathrm{kJ}}{\mathrm{mol} \cdot \mathrm{K}}$$

- Here $n = mM$, where M is the molecular mass of the matter.

Assumptions for Solids and Liquids

- For the above basic calculations, it was assumed that the volume of matter does not change and whole change in internal energy is expressed in change of temperature
  - Thus, all energy is transferred into movement of particles
- For solids and liquids, the change in volume is very small and thus it can often be ignored
- However, specific heat capacity is dependent on temperature, pressure, and volume of the matter at hand.

Heat Capacity of Gases

- When gases are heated or cooled, their volume or their pressure changes significantly
- When gas expands (or contracts) freely, its pressure remains constant
  - Then applies specific heat capacity for constant pressure c_p
- When gas is contained on a fixed volume, the energy change is expressed through change in pressure
  - Then applies specific heat capacity for constant volume c_V

LUT University

Gas and Temperature: The Ideal Gas Law

- In case of gases, the relationship between temperature, pressure and volume are captured by ideal gas law, also called as general gas equation.
- In empirical form, it is: $pV = nRT$
- Here p is pressure, V is volume, n is amount of substance, T is temperature, and R is the ideal gas constant:

$$R = 8.314510 \frac{\mathrm{Pa} \cdot \mathrm{m}^3}{\mathrm{mol} \cdot \mathrm{K}}$$

- Most gases follow this law quite well, main divergence occurring at extreme circumstances

LUT University

The Four Laws

- Based on the Ideal Gas Law, we have:

$$\frac{pV}{T} = constant \quad \Leftrightarrow \quad \frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

- In constant volume, we thus have $\frac{p_1}{T_1} = \frac{p_2}{T_2}$
- In constant pressure, we have $\frac{V_1}{T_1} = \frac{V_2}{T_2}$
- In constant temperature, we have $p_1V_1 = p_2V_2$
- These are called Gay Lussac's Law, Charles's Law and Boyle's Law, correspondingly.

Introducing Enthalpy

- Let us assume that totally cooled gas is heated up under constant pressure.
- Now, all the heated gas expands according to the Ideal Gas Law $V = nRT/p$
- When the gas expands, it does the work $W = F \cdot s = -pA\Delta s = -p\Delta V$
- Now we can define the Enthalpy as the inner energy of the matter when it only includes the energy resulting from heating the matter up:

$$H = U + pV$$

- Enthalpy is an extensive property; it is proportional to the size of the system (for homogeneous systems)

LUT University

Introducing Hydrostatic Pressure

- When something is immersed in liquid (or gas), the phenomenon called hydrostatic pressure manifests
- The deeper in the liquid one is, the more pressure one experiences due to earth gravity.
- More accurately, it can be shown that the pressure at depth z is equal to the weight of the liquid (gas) in the vertical column of unit cross-sectional area lying above that level.
- In practical terms, we have

$$p(z) = \rho g z + p_0$$

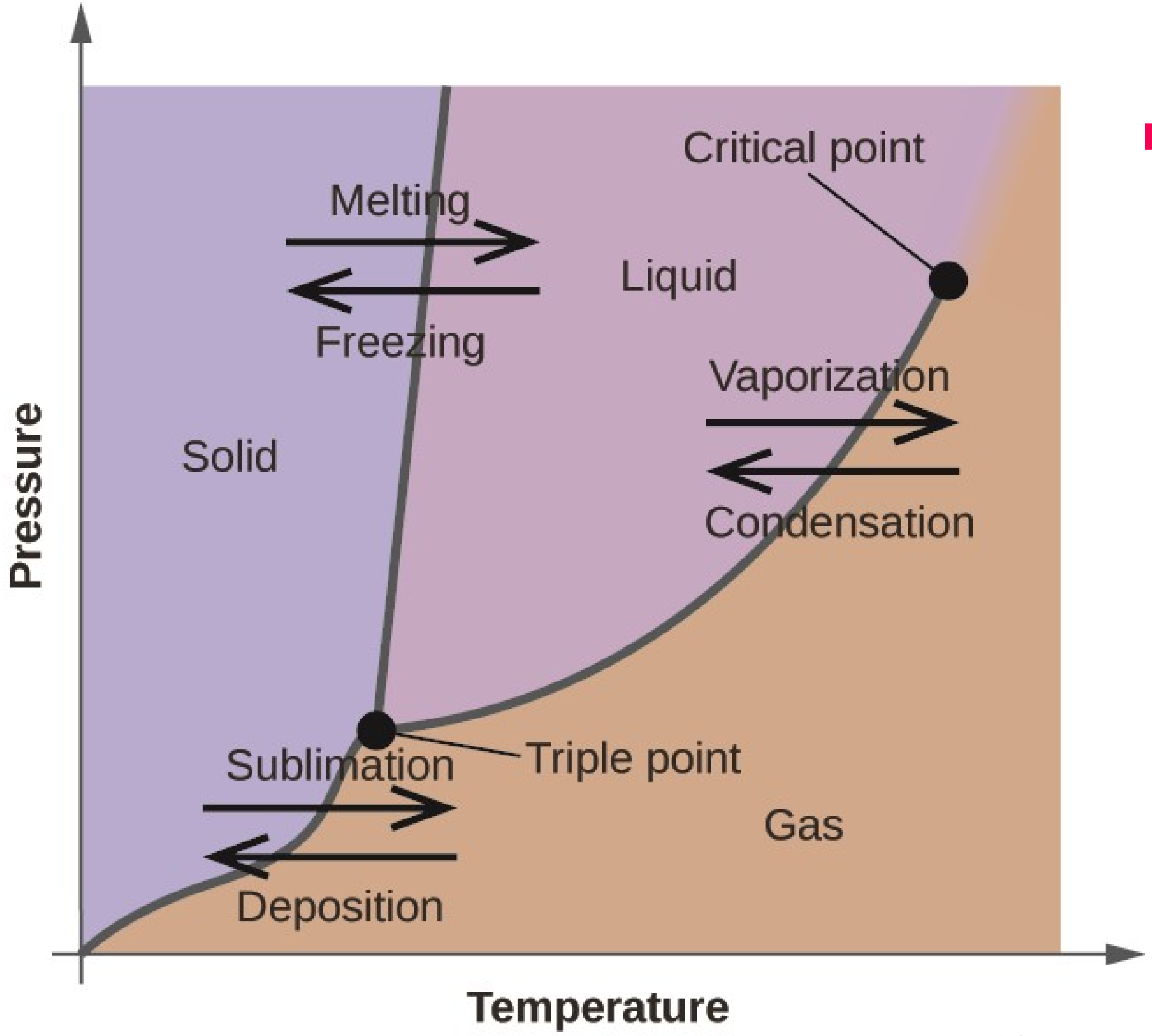
LUT University

Phase Transitions

LUT University

Phase Diagram

- We have regions for solid, liquid and gaseous regions separated by curves of melting, evaporation and sublimation
- The triple point is where these three regions meet.
- In addition, there is the supercritical area at high pressure and temperature
- The critical point defines the entry to supercritical region, where evaporation is not a clear transition anymore.



Source https://courses.lumenlearning.com/chemistryformajorsxmaster/chapter/phase-diagrams-2/

LUT University

Phase Diagram for Water

In case of water, the triple point is located at T = 273,16 K ja p = 611,7 Pa.

Correspondingly, the critical point is at T = 647,1 K ja p = 22,064 MPa.

For water, the melting curve is directed leftwards, while for most substances it turns toward right.

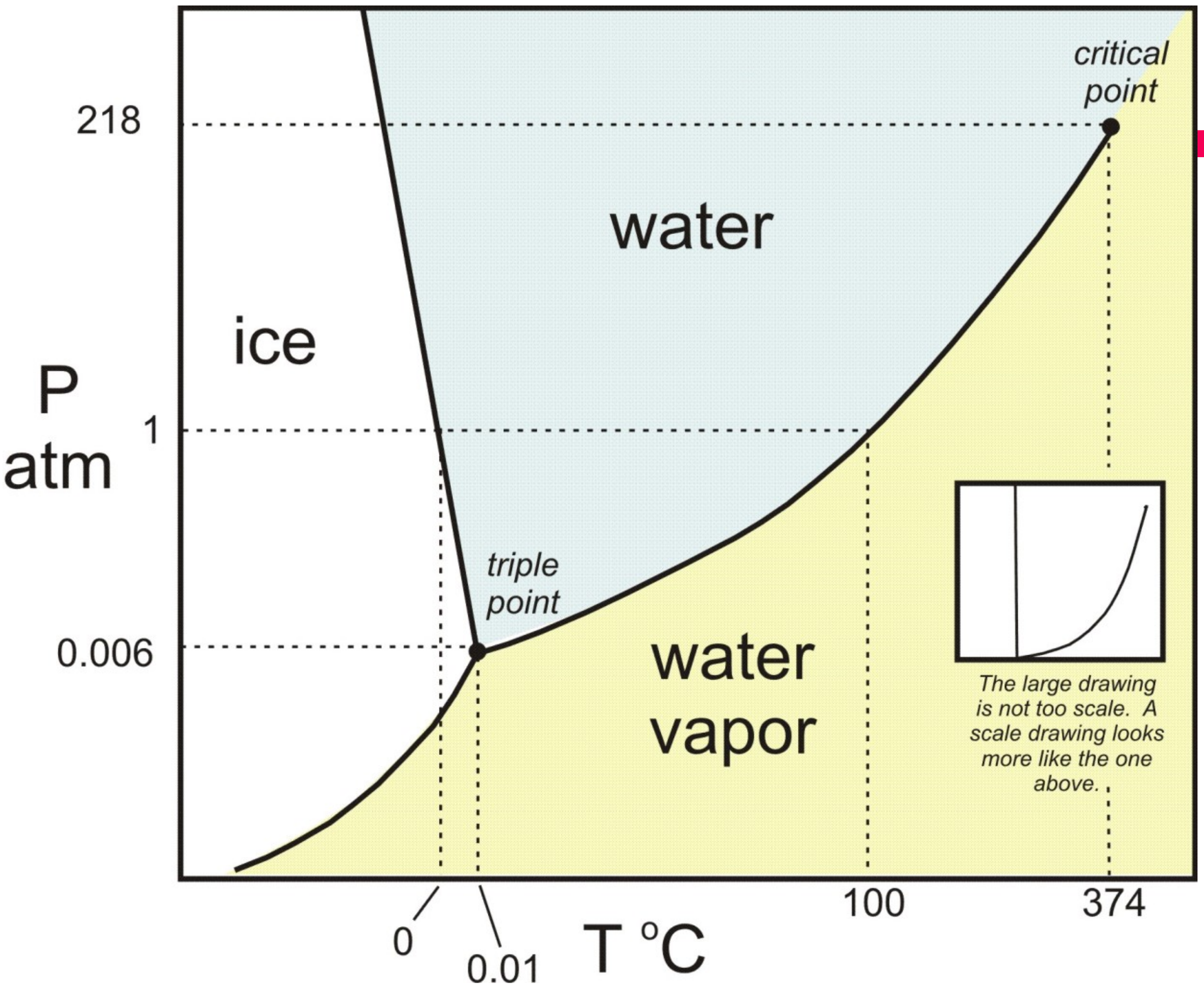


Figure source https://serc.carleton.edu/research_education/equilibria/phaserule.html

LUT University

Heat Quantity in Phase Transitions

- To evaporate matter, a significant amount of energy is required.
- The same energy is released, when the matter condensates back to liquid.
- Similarly, the melting and freezing also consumes and releases energy.
- Both the <u>latent heat of evaporation</u> (also enthalpy of evaporation) and <u>latent heat of fusion</u> (also enthalpy of fusion) carry the symbol of heat quantity Q and the amount of heat can be calculated using the specific heat of evaporation s and specific heat of fusion r as below

$$Q = sm, \text{or} \quad Q = rm$$

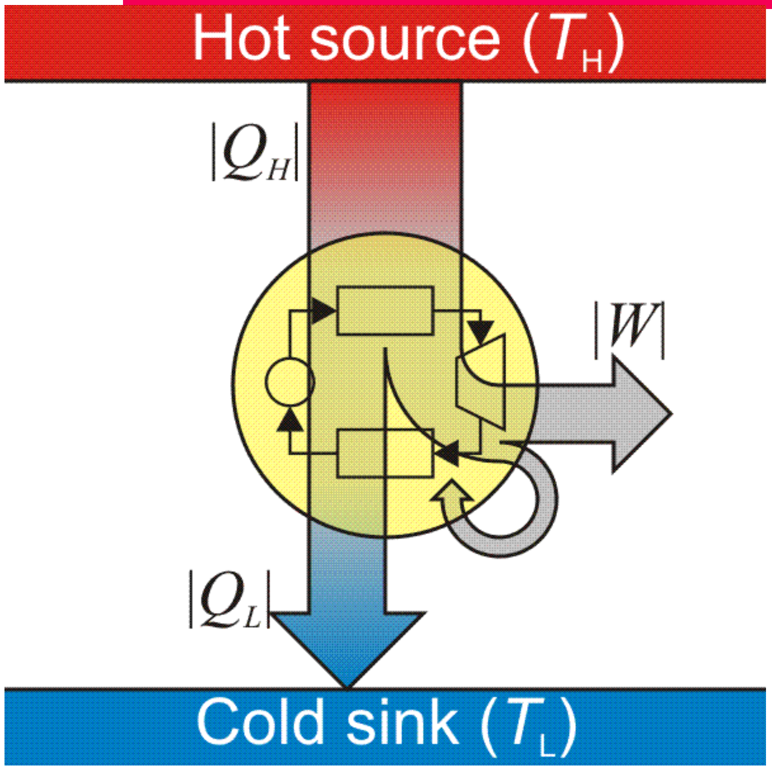
- Here m is the mass of the matter in question.

Thermal Engine

Heat Engine

- In Heat Engine, part of the heat from a source (Q_H) can be converted into work W
- Its efficiency is $(Q_H = Q_1)$

$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$



LUT University

Efficiency using Temperatures

- The theoretical efficiency of a heat engine can also be solved using the temperature of the hotter heat source (T_1) and the temperature at the heat cycle exhaust point (T_2):

$$\eta = 1 - \frac{T_2}{T_1}$$

LUT University

Thank you for your attention!