

47201 – Engineering Thermodynamics

Lecture 1b:

Thermodynamic system

properties (Ch 3)



Describing a thermodynamic system

Once the system is defined, it is important to inspect it and determine what the state of the system is.

- Is it a solid, liquid or gas?
- Is it a single substance or a mixture? Are there multiple phases (gas/liquid/solid)?
- How much mass is in the system? Is there a mass flow into and out of the system?
- What are properties such as temperature, pressure and volume? Is the system at steady state or will the temperature, volume, etc. Change?



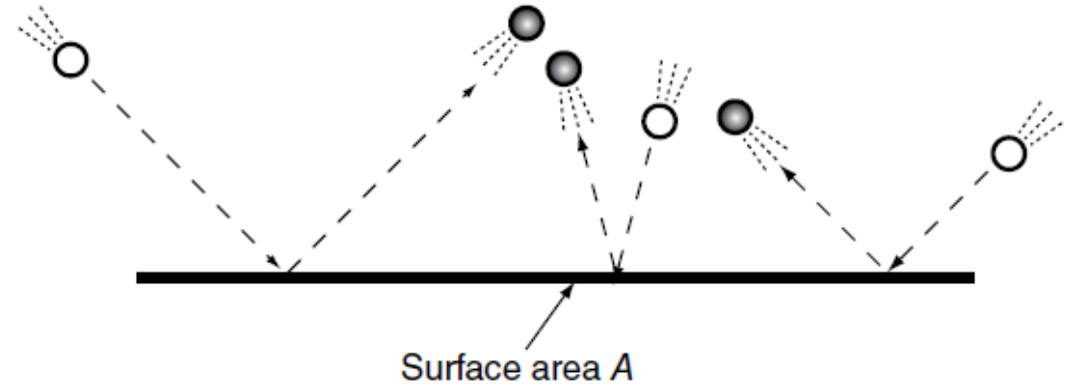
In this course mass will be given in both kg and mol

- Remember that 1 mol contains Avogadro's number (N_A) molecules, $6.022 \cdot 10^{23}$, and molar mass is given in grams
- A kmol has molecular mass in kg
- The mass corresponding a number of moles is
$$m [\text{kg}] = N [\text{kmol}] M [\text{kg} / \text{kmol}]$$
- Molecular masses of common gases are given in Appendix 1 of the book. Otherwise, the molecular mass can be calculated from the chemical composition and a periodic table



Pressure is the force exerted by molecules on a wall

$$P = \frac{F}{A}$$



- Units N/m^2 is Pa. 1 bar is 10^5 Pa and atmospheric pressure is 1.01325 bar
- When there is an atmosphere, the entire system is under some background pressure (P_{atm}). So on Earth we have an absolute pressure of 1.01325 bar. Since we don't "feel" this pressure, we can also call ambient pressure a gage pressure of 0 bar.

$$P_{abs} = P + P_{atm}$$

- The pressure is a function of the height of a fluid column, h , and the relation is

$$P_{abs} - P_{atm} = \rho g h$$



Temperature

We will deal only with SI units in this course. However we will need to take care when dealing with temperature scales for some calculations.

- The Celsius scale defines 0 °C as the freezing point of water
- However, it is also important to consider that there is a lowest possible temperature, absolute zero. This occurs when there is no kinetic energy in the molecules. For this reason an absolute temperature scale has been introduced, called the Kelvin scale. Absolute zero has been estimated for gases and is defined as 0 K. To convert between temperature scales

$$T [\text{K}] = T [^{\circ}\text{C}] + 273.15$$

- It is important to use absolute temperature when using the ideal gas equation or, in the future, calculating the Carnot efficiency



Ideal gas law background

Equations that give relations between intensive properties are known as *equations of state*. The ideal gas law is an equation of state for a specific set of materials, in this case gases that are not close in temperature to being liquids and not at very high pressure.

The assumptions used to derive the ideal gas law are:

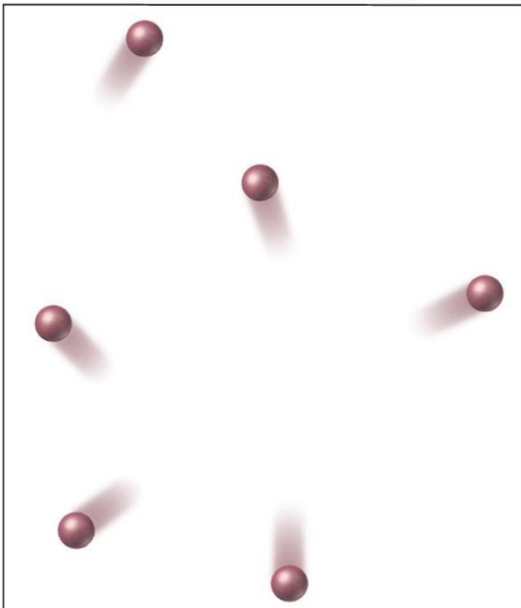
1. The gas is made of a very large number of elementary particles called molecules that are in constant, random motion. All molecules have the same mass (m_e).
2. The total number of molecules (n) is very large.
3. Molecules collide perfectly elastically with each other and with the walls of the container. They obey Newton's laws during collisions.
4. There is no force acting on molecules except during collisions.
5. The volume of molecules is negligible – they are considered to be point masses.



Deviation from ideality

Ideal gas conditions

- High temperature
- Low pressure

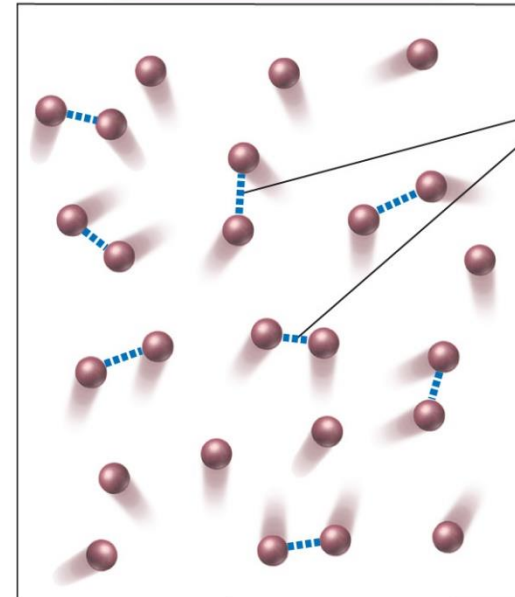


- Particle size small compared to space between particles.
- Interactions between particles are insignificant.

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Non-ideal gas conditions

- Low temperature
- High pressure



Intermolecular Interactions

- Particle size significant compared to space between particles.
- Interactions between particles are significant.

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Ideal gas law

The **ideal gas law** describes the relation between properties of a gas. These properties are connected by a constant, the (universal) **ideal gas constant** R_u (often just R):

$$PV = nR_u T$$

P : Pressure

V : Volume

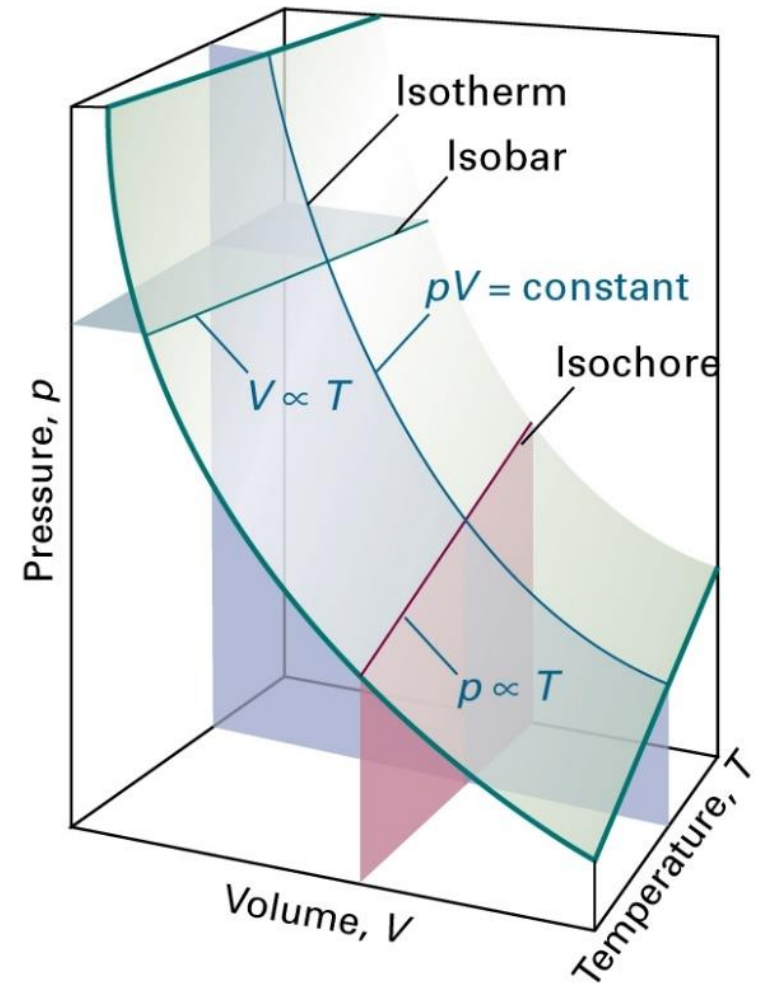
n : number of moles

T : Temperature

R_u : Universal gas constant = 8.314(47) J/(mol · K)

The ideal gas law is also often given in terms of a specific ideal gas constant defined as $R = R_u / M$ and then the ideal gas law can be stated as

$$P V = m R T$$



Energy implications of the ideal gas law

Section 3.8 and 3.9 give a derivation of the internal energy of an ideal gas based on the kinetic energy of all molecules. The conclusion is:

$$u_2 - u_1 = \frac{3}{2}R(T_2 - T_1)$$

Where u is the internal energy of an ideal gas. Note that is only for a “perfect” monatomic gas and many gases, such as air have a different relation.

- One important conclusion from this analysis is that the internal energy of an ideal gas is only dependent on its temperature and not pressure



A brief summary of energy

Gravitational potential energy

Energy stored in a body raised in a gravitational field

$$PE = E_p = mgz$$

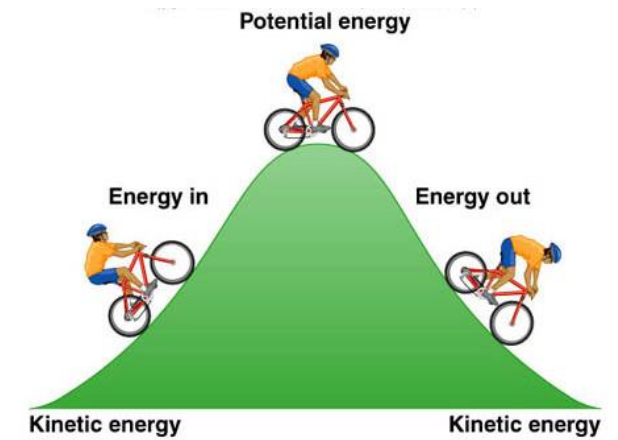
Kinetic energy

The energy stored in or possessed by an object due to motion

$$KE = E_k = \frac{1}{2}mV^2$$

Internal energy

The total microscopic energy of all atoms and molecules in a system



Specific Heats – Constant volume

We define the specific heat for **constant volume** systems as the change in internal energy with changing temperature:

$$c_v(T) \equiv \left(\frac{\partial u}{\partial T} \right)_v$$

For **ideal gasses** the **internal energy U** depends **only on T** (not P). Meaning we can integrate:

$$\Delta u = u_2 - u_1 = \int_{T_1}^{T_2} c_v(T) dT = c_v(T_2 - T_1)$$



Specific Heats of Liquids and Solids

We can assume liquids and solids to be practically incompressible, no volume change
(it takes roughly 200 x atmospheric pressure to compress water 1%)

Under this assumption one can show that:

$$c_v(T) = c_p(T) = c(T)$$

Incompressible substances have only one heat capacity. We call it c

It further follows that under these circumstances:

$$\Delta u = u_2 - u_1 = c(T_2 - T_1)$$

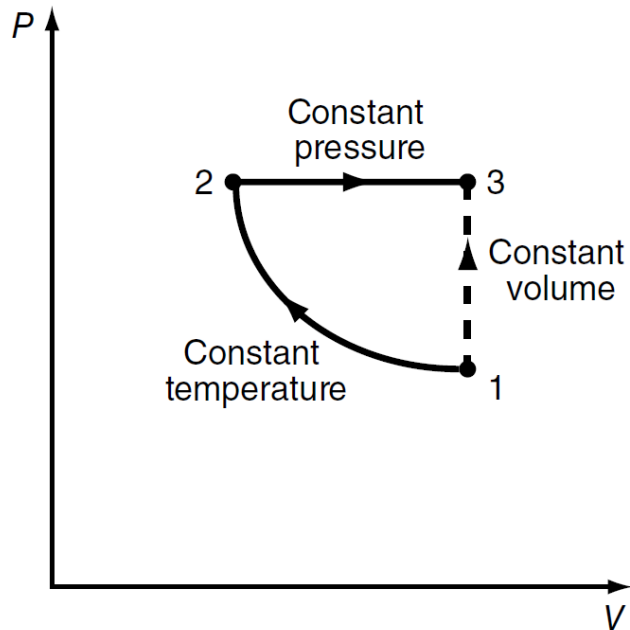
And

$$\Delta h = h_2 - h_1 = c(T_2 - T_1) + v(P_2 - P_1)$$



C_v or C_p – The path from initial to final state...

We can use internal energy (U) and enthalpy (H) for processes that are not at constant pressure, nor constant volume by noting that they are both state functions, and thus independent on path



Always hold for ideal gasses in thermodynamic processes

$$\Delta u = u_2 - u_1 = \int_{T_1}^{T_2} c_v(T) dT$$

$$\Delta h = h_2 - h_1 = \int_{T_1}^{T_2} c_p(T) dT$$

We can use C_v and C_p to calculate the changes in internal energy and enthalpy, respectively, for an ideal gas no matter the route getting there.

Example 3.8

How much energy does it take to raise the temperature of 1 kmol of argon by 1 K?

- Argon is a monatomic gas, so it follows Eq. (3.28)
- Then energy required to raise the temperature of the Argon is just the change in internal energy. So:

$$U_2 - U_1 = \frac{3}{2} N R_u (T_2 - T_1) = \frac{3}{2} 1 \text{ kmol } 8.314 \frac{\text{KJ}}{\text{kmol} \cdot \text{K}} 1 \text{ K} = 12.471 \text{ KJ}$$



Exercises – chapter 3

- 3.3
- 3.7
- 3.9
- 3.15
- 3.20
- 3.27 use 26 g of the gas, not 2.6 g. There is an error in the book.
- 3.39



Exercises – chapter 3 with solutions

- 3.3 ($m_{\text{O}_2} = 19.9 \text{ g}$, $m_{\text{CO}_2} = 13.7 \text{ g}$ and $m_{\text{H}_2\text{O}} = 11.2 \text{ g}$)
- 3.7 (3500 N)
- 3.9 (8632.8 Pa)
- 3.15 (22.4 L)
- 3.20 (0.728 mm)
- 3.27 (4.03 g/mol, helium)
- 3.39 ($c = 0.720 \text{ kJ/kg}$)

