FLUIDS: Gases and Liquids  Chapter 5 of text

Introduction:

There are three “phases” of matter: Solid, liquid and gas

Solids: Have form, constituents (atoms and molecules) are in fixed positions (though they can vibrate and perform other motions) have well defined density etc.

Liquids: They can flow and assume the shape of their container. Their constituents, although they stay close together, can move in bulk or flow Liquids have well defined density and other properties.

Gases: They expand to fill the space they are in – air in the room. Their constituents move about freely unless they collide with each other.
With water we can illustrate all three phases:

At low temperature (below its freezing point) water is a solid = ice

At room temperature (or above 0 degrees Centigrade or above its melting point and below its boiling point) it is a liquid = water

Above its boiling point (around 100 degrees centigrade) it is a gas = water vapor.

Melting point (MP) and Boiling point (BP) are characteristics which vary from substance to substance and are properties that find their explanation in atomic structure.
Section 5.1 (pages 140-144)
We want to discuss balloons so we must start with understanding the properties of a Gas: Air is a gas (of mainly diatomic molecules of Nitrogen and Oxygen – in proportion 80% and 20% respectively.

• Air is a gas
  – Consists of individual atoms and molecules
  – Particles kept separate by their thermal energy
  – Particles bounce around in free fall
Its molecules are moving about madly, randomly. There is kinetic energy in this random motion (and molecules individually have momentum too) which is related to its temperature. Air exerts pressure because of this motion on any imaginary surface in it.

• Air has pressure
  - Air particles exerts forces on container walls
  - Average force is proportional to surface area
  - Average force per unit area is called “pressure”

Force is $F = \text{Pressure} \times \text{Area} = PA$

Hence $P = \frac{F}{A}$ which is $\frac{\text{Newtons}}{m^2}$

which is also $P = \frac{\text{Newton} \times \text{meters}}{m^3}$

which is $\frac{\text{Joules}}{\text{m}^3}$ or Energy density
In a static fluid (fluid at rest) there are no preferred directions. Hence pressure in any direction is the same. Pressure is not a vector.
Air and Density

Air has density

Air particles have mass

Each volume of air has a certain amount of mass

Average mass per unit volume is called “density”

Its units are kg per cubic meter.

Its dimensions are

\[ \rho_{\text{air}} = \frac{M}{L^3} \]
Gas and its density: (continued)

Suppose there are $N$ molecules of air in a volume $V$. It consists of 80% $N_2$ and 20% $O_2$.

If the mass of nitrogen atom is $M_N$ and the mass of oxygen atom is $M_O$.

Then the mass of $N$ molecules of air is: $M_{\text{air}} = (0.8 \times 2 M_N + 0.2 \times 2 M_O) \times N$

Its density or Mass per unit volume is $\rho_{\text{air}} = \frac{M_{\text{air}}}{V}$

With a good balance, one can measure the density of cubic meter of air: Density at sea level under normal conditions of temperature and pressure it is 1.29 kg / cubic meter.

How many molecules of air in 1 cubic meter does this correspond to?

We must use the value of atomic masses:

mass of oxygen atom: $M_O = 16 \times 1.67 \times 10^{-27} \text{ kg}$

mass of nitrogen atom: $M_N = 14 \times 1.67 \times 10^{-27} \text{ kg}$

We can calculate $N$ by: $N_{\text{air}} = \frac{1.29 \text{ kg/m}^3}{4.27 \times 10^{-26}} = 3.02 \times 10^{25} \text{ molecules/m}^3$
Table 14.1

Densities of Some Common Substances at Standard Temperature (0°C) and Pressure (Atmospheric)

<table>
<thead>
<tr>
<th>Substance</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>Substance</th>
<th>$\rho$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.29</td>
<td>Ice</td>
<td>$0.917 \times 10^3$</td>
</tr>
<tr>
<td>Aluminum</td>
<td>$2.70 \times 10^3$</td>
<td>Iron</td>
<td>$7.86 \times 10^3$</td>
</tr>
<tr>
<td>Benzene</td>
<td>$0.879 \times 10^3$</td>
<td>Lead</td>
<td>$11.3 \times 10^3$</td>
</tr>
<tr>
<td>Copper</td>
<td>$8.92 \times 10^3$</td>
<td>Mercury</td>
<td>$13.6 \times 10^3$</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>$0.806 \times 10^3$</td>
<td>Oak</td>
<td>$0.710 \times 10^3$</td>
</tr>
<tr>
<td>Fresh water</td>
<td>$1.00 \times 10^3$</td>
<td>Oxygen gas</td>
<td>1.43</td>
</tr>
<tr>
<td>Glycerin</td>
<td>$1.26 \times 10^3$</td>
<td>Pine</td>
<td>$0.373 \times 10^3$</td>
</tr>
<tr>
<td>Gold</td>
<td>$19.3 \times 10^3$</td>
<td>Platinum</td>
<td>$21.4 \times 10^3$</td>
</tr>
<tr>
<td>Helium gas</td>
<td>$1.79 \times 10^{-1}$</td>
<td>Seawater</td>
<td>$1.03 \times 10^3$</td>
</tr>
<tr>
<td>Hydrogen gas</td>
<td>$8.99 \times 10^{-2}$</td>
<td>Silver</td>
<td>$10.5 \times 10^3$</td>
</tr>
</tbody>
</table>
Air Pressure and Density

Air pressure is proportional to:

Density

Denser particles hit surface more often

Denser air $\rightarrow$ more pressure

Pressure is proportional to density

We write: $P \propto \rho$
What is Temperature?

It measures how “hot” an object is.

In physics it has a mechanical explanation. It is a measure of the random motion of molecules of a gas (or for that matter random motion of atomic units of any other material, liquid or a solid). In a gas, when molecules move about randomly, each molecule has its own speed, some moving slowly others moving fast. Each molecule will have a different kinetic energy which is

\[ KE = \frac{1}{2} M v^2 \]

Now calculate the average kinetic energy of a molecule by adding the KE of the molecules and dividing by N

\[ \sum \left( \frac{1}{2} M v^2 \right) \]

which is symbolically: \[ \langle KE \rangle = \frac{1}{2} \frac{M v^2}{N} \]
Temperature is a measure of the average kinetic energy of molecules.

which is \( T \propto \langle KE \rangle \)

Now let us ask how is the Pressure related to KE? We saw earlier that Pressure is a measure of energy density. The energy in a gas is due to the kinetic energy of its random motion. If there are \( N \) molecules in a volume \( V \), each with an average KE given by \( \langle KE \rangle \) then the total energy in \( V \) is

Total Energy = \( N \langle KE \rangle \propto N T \)

Pressure is proportional to energy density

Hence \( P \propto \frac{N T}{V} = \rho_{\text{particle}} T \)

The ideal gas law is: \( P = k \rho_{\text{particle}} T \)
k is called the Boltzmann constant.

Units of Pressure: As pressure is force per unit area, we define its units as:
If \( F = 1 \) Newton and \( A = 1 \) square meter, then \( P = 1 \) Newton per 1 square meter
This unit is called Pascal: \( 1 \text{ Pa} = 1 \text{ N/m}^2 \)
Pressure of the atmosphere on your ear drum at sea level is \( 10^5 \text{ Pa} \)

In these units the value of \( k \) is

remember that \( k = \frac{P}{\rho_{\text{particle}} T} \)

Pressure is given in Pascals or Pa
the density is in particles per cubic meter
Hence \( k \) has units of \( k = 1.381 \times 10^{-23} \frac{\text{Pa m}^3}{\text{particle}(\text{degree K})} \)
or in terms of energy \( k = 1.381 \times 10^{-23} \frac{\text{Joules}}{\text{particle}(\text{degree K})} \)
Why do balloons float? pages 145 - 149

Lifting force on a balloon or any object submerged in a fluid is given by the Archimedes Principle:

An object, wholly or partially immersed in a fluid is acted upon by an upward buoyant force equal to the weight of the fluid it displaces.
Float to top

(b)  
sink to bottom
When the ice melts, will the water surface rise?
Which balloon will float?  
Which balloon will rise?  
Which balloon will sink?

Net force on the balloon is (downward is positive) \( F_{\text{net}} = W_B + W_{\text{gas}} - W_{\text{air}} \)

If the volume of the balloon is \( V \) then \( W_{\text{gas}} = V \rho_{\text{gas}} g \); \( W_{\text{air}} = V \rho_{\text{air}} g \)

So if the magnitude of \( (\rho_{\text{gas}} - \rho_{\text{air}}) V g \) is greater than \( W_B \)

\[
(\rho_{\text{air}} - \rho_{\text{gas}}) V g = W_R \quad \text{or} \quad \rho_{\text{air}} V g = \rho_{\text{gas}} V g + W_R
\]
How hot air balloons work.

Hot air has a lower density, so for a given volume of the balloon its weight is less than when it is filled with cold air. If the balloon has fixed size the upward buoyant force remains the same. Balloon rises.
Density of helium is less than that of air as helium atoms are lighter than air molecules.

Hot air balloon compared to Helium filled balloon.