

Chapter 1

Fluid properties

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1.2.1 Density (ρ)

Density is a fundamental physical quantity that characterizes the mass of a substance per unit volume. It is defined by the following expression:

$$\rho = \frac{\text{Mass}}{\text{Volume}} \quad [\text{kg} / \text{m}^3] \quad \text{or} \quad [\text{g} / \text{cm}^3] \quad (1-1)$$

Here is the density of some substances:

Fluid	[k (g/m ³)]	Fluid	ρ [kg / m ³]
Air	1.29	Iron (Fe)	7860
Hydrogen (H ₂)	0.09	Copper (Cu)	8920
Helium (He)	0.18	Silver (Ag)	10500
Oxygen (O ₂)	1.43	Lead (Pb)	11300
Water	1000	Gold (Au)	19300
Sea water	1025	Mercury (Hg)	13600
Blood	1050	Ice cream (T° < 0)	917

Table 1.1: Density of some substances
(under atmospheric pressure (P) and normal temperature (T) of 4°C).

- For a fluid: $\rho_{\text{gas}} = f(P, T^\circ)$ and $\rho_{\text{liquid}} \approx g(T^\circ)$ with low pressure dependence (P)

For water at T = 20° C and P = atmospheric pressure, the density (ρ) is 998 kg/m³.

If the pressure changes at P = 10⁷ Pa, the density (ρ) changes slightly by 1003 kg/m³.

Figure 1.2 illustrates the variation in the density (ρ) of water as a function of temperature and under atmospheric pressure.

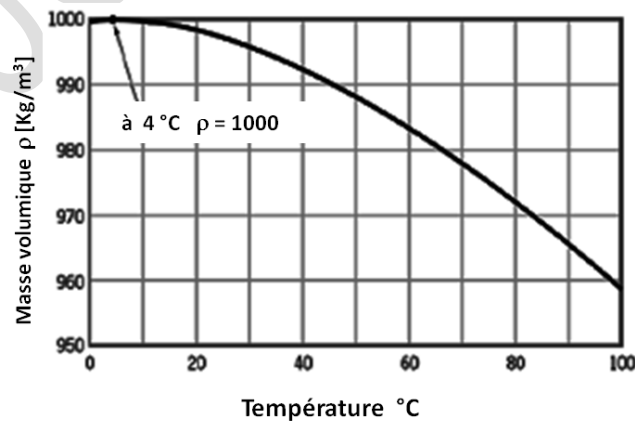


Figure 1.2: Variation in the density of water as a function of T° under atmospheric pressure.

- For ideal gases, the density can be calculated from its equation of state:

$$\rho = \frac{P}{R.T} \quad (1-2)$$

With: P is the absolute pressure [Pa], ρ is the density [kg/m^3], T is the temperature in [$^\circ\text{K}$] and R is the ideal gas constant.

$$\text{Where: } R = \frac{r}{M} = \frac{\text{Molar ideal gas constant}}{\text{molar mass}} = \frac{8,314}{M} \quad [\text{J/kg} \cdot \text{K}]$$

For air at T = 20° C and P = atmospheric pressure, the density (ρ) is 1.202 kg/m^3 . For other values of T°, the density of the air changes.

- The reciprocal of the density per unit mass is called the specific volume.

1.2.2 Specific weight (ϖ)

The specific weight *represents the weight per unit of volume*:

$$\varpi = \rho \cdot g \quad [\text{N/m}^3] \quad (1 - 3)$$

Where: g is the acceleration of gravitation in [m/s^2], ρ is the density in [kg/m^3].

The specific weight of water is generally equal to $1000 \times 9.81 \approx 10000 \text{ N/m}^3$.

1.2.3 Relative Density (d)

The relative density of a substance is the ratio between its density and the reference density under standard conditions.

- For a liquid:

$$d_{\text{liquid}} = \frac{\rho_{\text{solid ou liquid}}}{\rho_{\text{water}}} \quad [\text{unitless}] \quad (1-4)$$

- For a gas:

$$d_{\text{gaz}} = \frac{\rho_{\text{gas}}}{\rho_{\text{air}}} \quad [\text{unitless}] \quad (1 - 5)$$

The relative density of water is 1.00 and that of mercury is 13.6

- The relative density of liquids tells us about the buoyancy of the substance.
 - If ($d_{\text{liquid}} > 1$), the substance flows in water (Case of Mercury);
 - If ($d_{\text{liquid}} < 1$), the substance floats (partially) on water (Case of cooking oil).
- The same for gases:
 - If ($d_{\text{gaz}} > 1$), the substance descends to the ground (Case of Oxygen);
 - If ($d_{\text{gaz}} < 1$), the substance rises into the atmosphere (Case of Hydrogen).

1.2.4 Viscosity of a fluid

1.2.4.1 Dynamic viscosity

Fluid viscosity is the molecular property that indicates the presence of internal resistance forces of a moving fluid.

To give more explanation to the concept of viscosity, we consider two large parallel plates separated by a fluid of thickness e , see figure 1.3. The fluid in contact with the upper plate will adhere to it and moves at speed V , while the fluid in contact with the fixed plate will have zero speed.

Couette's experiment shows that the frictional (resisting) force F is proportional to the surface area of the plate S , to the speed V and inversely proportional to the distance e . That is, $F \approx S \cdot \frac{V}{e}$

Couette showed that there exists a coefficient μ which depends only on the fluid, such that the relation of the friction force becomes : $F = \mu \cdot \frac{S \cdot V}{e}$



Figure 1.3: Fluid movement between two plates.

To explain the phenomenon inside the liquid, we consider two contiguous fluid layers separated by Δy . The friction force F which is exerted at the separation surface of these two layers opposes the sliding of one layer over the other. It is proportional to the difference in speed of the layers, i.e. ΔV , to their surface S and inversely proportional to Δy :

For a small distance $\Delta y \rightarrow \partial y$ and the difference in speed $\Delta V \rightarrow \partial V$, in this case, the formula for friction constraints becomes:

$$\frac{F}{S} = \mu \frac{\partial V}{\partial y} \quad \text{Or} \quad \mu = \frac{F/S}{\partial V / \partial y} \quad [\text{Ns} / \text{m}^2] \quad (1 - 6)$$

μ : is the dynamic viscosity, in SI system, the unit is Poiseuille (Pa.s), or (Ns / m²)

In the (CGS) system, the unit is the poise, such as 1 poise \approx 0.1 Ns / m².

For water at 20 °C, the dynamic viscosity is $\mu \approx 10^{-3}$ Ns / m². See Table A.1.

1.2.4.2 Kinematic viscosity:

This parameter ν is the dynamic μ viscosity quotient by the density ρ fluid. It represents the particle retention capacity of the fluid and quantifies its capacity to flow.

$$\nu = \frac{\mu}{\rho} \quad [\text{m}^2 / \text{s}] \quad (1-7)$$

In system (CGS), the unit is the stokes. One stokes is equal to 10^{-4} m²/s.

For water at 20 °C, the kinematic viscosity is $\nu \approx 10^{-6} \text{ m}^2/\text{s}$. For other fluids, see Table A.1.

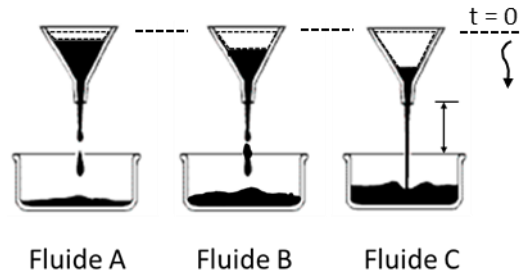


Figure 1.4: Simple experiment showing the effect of kinematic viscosity on the flow of a fluid.

Some viscosity values (μ) at 20°C.

Substance	μ [NS/m ²]	ν [m ² /s]
Water	$1.005 \cdot 10^{-3}$	$1.007 \cdot 10^{-6}$
Air	$18.5 \cdot 10^{-6}$	$15.6 \cdot 10^{-6}$

Table 1.2: Dynamic and kinematic viscosity of water and air.

1.2.5 Newtonian fluid:

For which the strain rate of a fluid ($\frac{v}{e} \approx \frac{\partial v}{\partial y}$) is proportional to the shear stress ($\tau = \frac{F}{S}$) is called Newtonian fluid.

The following figure shows the laws of behavior of Newtonian and non-Newtonian fluids.

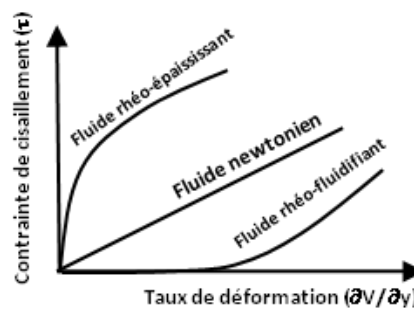


Figure 1.5: Relationship between stress and strain rate for different fluids.

Figure 1.6 allows us to determine the dynamic viscosity coefficient for some Newtonian fluids.

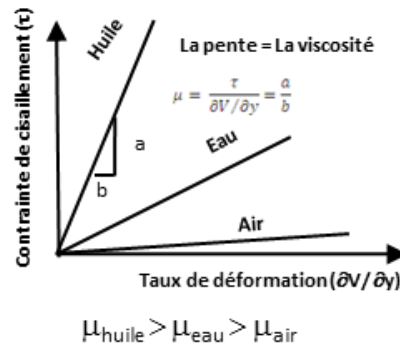


Figure 1.6: Evolution of the stress as a function of the strain rate making it possible to determine the viscosity coefficient of certain Newtonian fluids.

Various viscosity values are shown in Table A.3.

Noticed

The dynamic viscosity of liquids decreases as temperature increases. Unlike that of liquids, the viscosity of gases increases with temperature, see Figure 1.7.

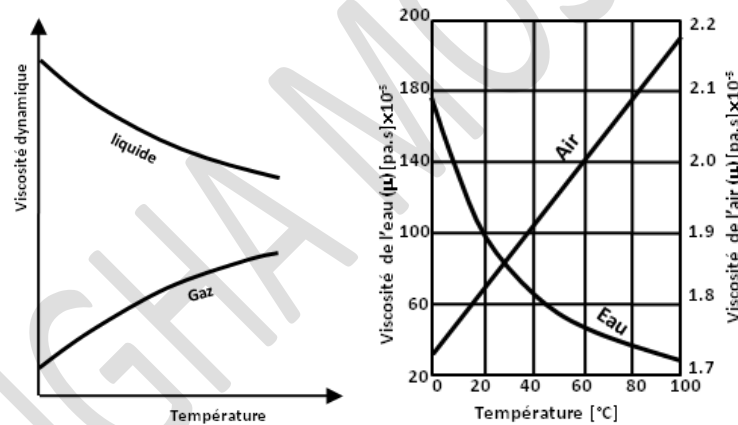


Figure 1.7: Variation of dynamic viscosity as a function of temperature (T°).

Noticed

In what follows, we particularly consider Newtonian fluids.

1.2.5 Surface tension (σ)

Surface tension is the force per unit length which is exerted on any line element forming part of the separation surface between two immiscible fluid media. Surface tension results from differences between the interactions between the molecules of the liquid located under the interface and those between the molecules located within the liquid. This is energy per unit area or force per unit length.

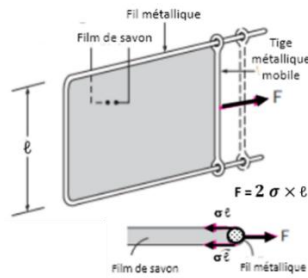


Figure 1.8: Surface tension creates a force normal to the rod.

The phenomenon causes surface tension whose direction is perpendicular to the separation surface. Generally, we designate the surface tension (σ) per unit length of any line of the separation surface.

$$\sigma = F / \ell \quad [N/m] \quad (1 - 8)$$

In this formula F is the elastic force perpendicular to any element ℓ of the surface, see figure 1.8.

In Table 1.3, values of σ for some substances are given.

Liquid	Liquid surface	Surface tension [N/m]
Mercury	Air	476×10^{-3}
Mercury	Water	373×10^{-3}
Water	Air	72.8×10^{-3}
Chlorine	Air	34×10^{-3}
Ethanol	Air	23×10^{-3}
Nitrogen	Air	9×10^{-3}
Glycerin	Air	63×10^{-3}

Table 1.3: The surface tension of some substances (under the temperature of 20°C).

- Case of a bubble on a flat surface:

Considering the balance of forces, see Figure 1.9.

Pressure Force = capillary Force

$$\Delta P \times \pi R^2 = 2 \times 2\pi R\sigma \quad \Delta P = 4\sigma \left(\frac{1}{R}\right) \quad (\text{Laplace's law})$$

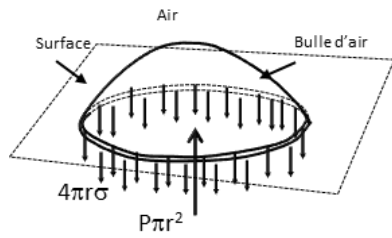


Figure I.9: Presence of the surface tension force on a gas bubble

- Case of a liquid droplet on a flat surface
Same principle to apply, see figure 1.10.

$$\Delta P = \frac{2\sigma}{R} \quad (\text{Laplace's law})$$

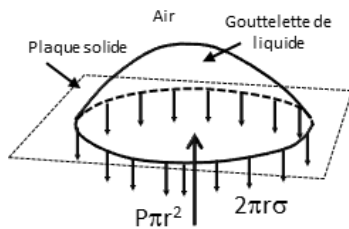


Figure I.10: Presence of the surface tension force on a liquid droplet

- Case of a surface with different curvatures in the two perpendicular directions (for example, case of an ellipsoid), the Laplace expression is rewritten as follows:

$$\Delta P = \sigma \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

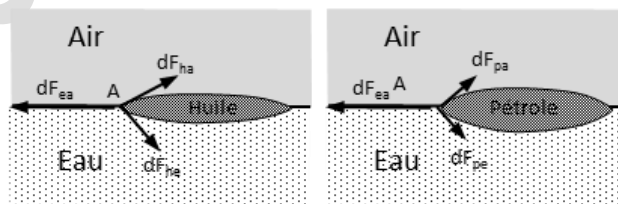


Figure I.11: Presence of oil/oil droplet on the free surface water in contact with air.

- The following figure shows the relationship between surface tension and the cleanliness of the glass plate in the presence of a water droplet .

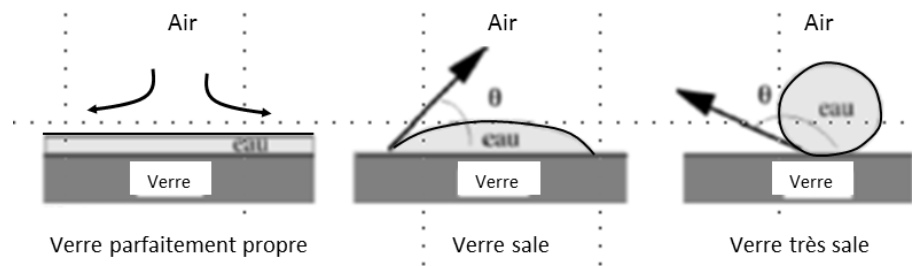


Figure 1.12: Surface tension of water on a glass plate.

- The following photos show the phenomenon of surface tension on insects and objects.

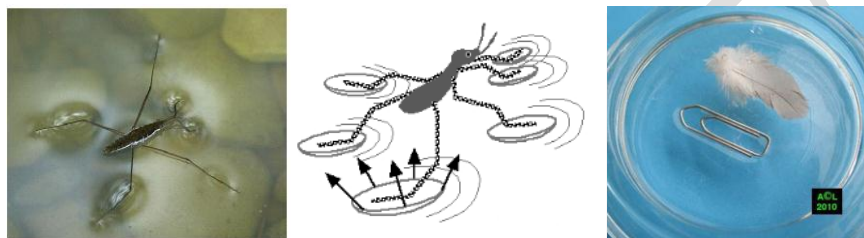


Figure 1.9: Surface tension creates a force normal to the rod.

1.2.6 Capillarity (h)

The rise of a liquid in a capillary tube is caused by surface tension and depends on the relative magnitudes of the cohesion of the liquid and its adhesion to the walls of the container.

Liquids rise in tubes they wet (adhesion force greater than cohesive force) and sink in tubes they do not wet (cohesion greater than adhesion).

Capillarity is important when using tubes with a diameter of less than 10 mm.

Capillarity is negligible for tubes with a diameter greater than 12 mm.

We have approximately:

$$h = \frac{2\sigma}{\varpi \cdot r} \cdot \cos(\theta) \quad [\text{m}] \quad (1 - 9)$$

With: σ is the surface tension $[N/m]$, θ is the connection or wetting angle $[^\circ]$, r is the radius of the tube $[m]$, and ϖ is the density of the liquid $[N/m^3]$.

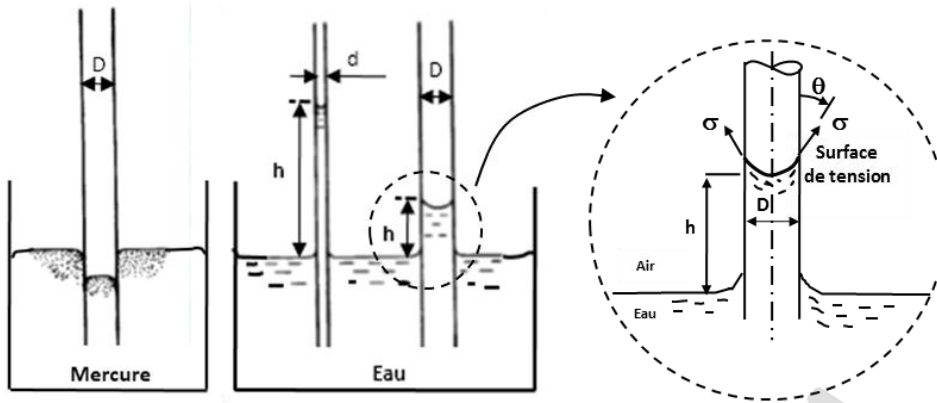


Figure 1.13: The capillarity of a circular glass tube which contains a liquid.

- Application: Hair rise or depression

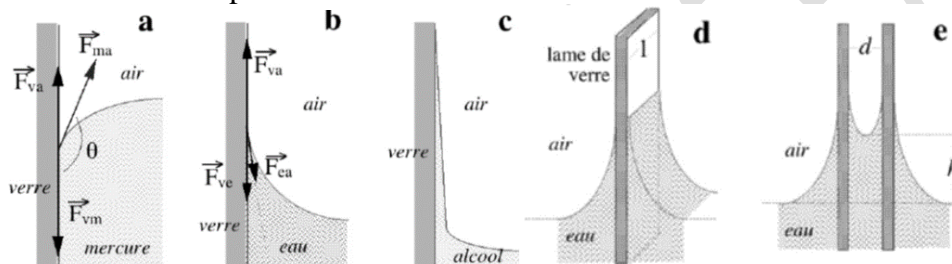


Figure 1.14: Surface tension phenomenon in the presence of a blade immersed in a liquid.

1.2.7 Water vapor pressure (hv)

Vapor pressure is the pressure that vapor exerts in a confined environment. The saturation vapor pressure increases with temperature and becomes equal to atmospheric pressure at the boiling point.

The atmosphere that surrounds us exerts a pressure on us of the order of 10^5 Pa. We can measure this pressure using a simple device. A tube filled with mercury is immersed in a basin, see Figure 1.15. After a certain time the equilibrium in the tube is achieved, i.e., we begin to see the vacuum from 760 mm from the free surface. The column of mercury which remains in the tube therefore compensates for the atmospheric pressure applied to the free surface.

The following figure explains the link between the mercury column and atmospheric pressure which varies with altitude.

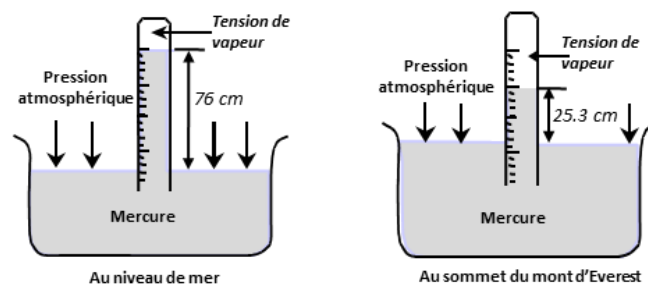


Figure 1.15: Experiment indicating the principle of the barometer to measure atmospheric pressure.

1.2.8 Compressibility (χ)

This parameter reflects the flexibility of a fluid with respect to compression.

Compressibility is the ratio of relative change in volume $\frac{\Delta V}{V}$ to change in pressure ΔP , see Figure 1.16.

$$\chi = -\frac{\Delta V/V}{\Delta P} \quad \text{at } T^\circ = \text{Cte} \quad [m^2/N] \quad (1-10)$$

With :

$$\frac{\Delta V}{V} = \frac{V_2 - V_1}{V_1} ; \Delta p = p_2 - p_1$$

The fluid can be considered as an elastic medium, the presence of a pressure difference can compress fluids and the compressed volumes return to their initial volumes once the applied pressure is removed. The minus sign expresses the decrease in volume.

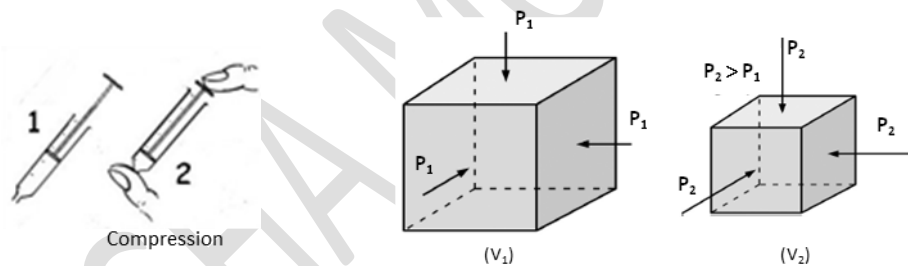


Figure 1.16: Phenomenon of compressibility of fluids.

For water, a pressure change of $22 \times 10^9 \text{ N/m}^2$ will cause a volume change of approximately 1%.

For air at $T^\circ = 15^\circ$: $\chi = 0.885 \times 10^{-5} \text{ N/m}^2$, see table A.4.

Noticed

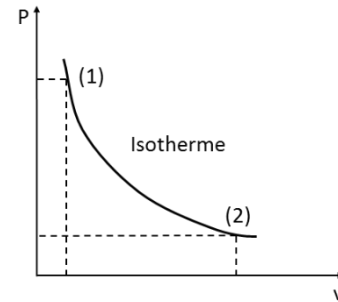
The coefficient of elasticity (E) of a fluid represents the reciprocal of compressibility $E = 1/\chi$

1.2.9 Isothermal condition

For an ideal gas in an isothermal medium ($T^\circ = Cte$), the product $P \times V$ remains constant.

During a transformation from state (1) to state (2), the condition is:

$$p_1 \times V_1 = p_2 \times V_2 \quad \text{And} \quad \frac{p_1}{\rho_1} = \frac{p_2}{\rho_2} = Cte \quad (1-11)$$



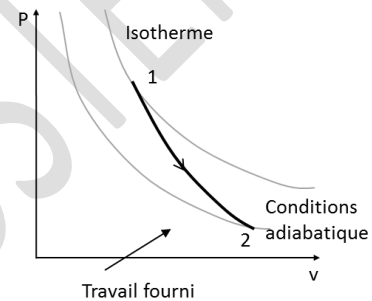
1.2.10 Adiabatic conditions

In the case of no heat exchange between the gas and its external environment, the equations are thus modified:

$$p_1 \times V_1^k = p_2 \times V_2^k \quad \text{Or} \quad \frac{p_1}{\rho_1^k} = \frac{p_2}{\rho_2^k} = Ct \quad (1-12)$$

$$\text{With:} \quad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{(k-1)/k} \quad ; \quad k = \frac{C_P}{C_V}$$

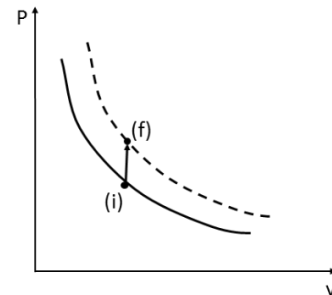
C_P , are the C_V specific heat coefficients for $P = Cte$ and $V = Ct$ respectively. k is the adiabatic exponent, see Table A.5.



1.2.11 Isochoric condition (Isovolume)

In the case of an ideal volume of gas in a confined medium and which satisfies the following condition:

$$\text{Work (W)} = \int_{V_i}^{V_f} P \cdot dV = \int_{V_f}^{V_i} P \cdot dV = 0 \quad (1-13)$$



1.2.12 Speed of propagation of a pressure wave

The possibility of compressing a fluid is initially a wave (of overpressure or depression) in the medium considered. The speed of propagation of the wave is called celerity. The value of this speed in the fluid depends on the value of its compressibility by the following formula:

$$c = \frac{1}{\sqrt{\rho \chi}} \quad (1-14)$$

In an ideal gas: $c = \sqrt{k \cdot R \cdot T}$, R : ideal gas constant, T : temperature.

For water it is $c_{\text{water}} \approx 1470$ m/s and for air $c_{\text{air}} \approx 300$ m/s.

1.3 Summary of important formulas in the chapter

Density $\rho = \frac{\text{Masse de matière}}{\text{Volume de matière}}$ (1-1)

Ideal gas law $\rho = \frac{P}{R.T}$ (1-2)

Fluid Newtonian $\frac{F}{S} = \mu \frac{\partial V}{\partial y}$ (1 - 6)

Tube capillarity $h = \frac{2\sigma}{\rho \cdot r} \cdot \cos(\theta)$ (1 - 9)

Compressibility $\chi = -\frac{\Delta V/V}{\Delta P}$ (1-10)
