

Chapter 1

INTRODUCTION TO FLUID MECHANICS

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1. Introduction

Fluid mechanics is the science of the laws governing the flow of fluids, whether liquids or gases. This branch of physics is essential for understanding and modeling systems in which fluids play a crucial role, particularly in autonomous systems. These systems, whether used in robotics, aeronautics, or naval engineering, often interact with fluids and require a deep understanding of fluid dynamics to optimize their behavior and performance.

Autonomous systems, equipped with sensors and complex algorithms, often need to make real-time decisions based on surrounding fluid conditions, whether it's adjusting the speed of a drone flying through changing air masses (aerodynamics), regulating flow in pipelines (hydrodynamics), or maintaining the stability of an underwater vehicle in response to ocean currents. Fluid mechanics, and particularly computational fluid dynamics (CFD), allows for modeling these interactions and providing autonomous systems with the necessary data to adjust their behavior in real time.

Thus, the applications of fluid mechanics and autonomous systems intersect significantly, whether in the automatic control of flow, energy optimization in complex fluid environments, or the autonomous navigation of vehicles subjected to fluid forces.

2. Definition of a Fluid

A fluid can be defined as a substance composed of a very large number of material particles, extremely small, that are free to move relative to one another.

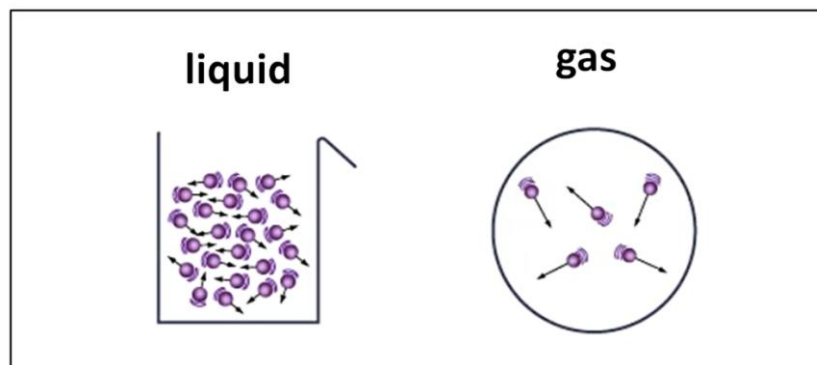


Figure 1. Movement of liquid and gas particles

A fluid is a continuous material medium, without rigidity, that can deform and flow. Due to the weakness of the cohesive forces between its particles, a fluid has no inherent shape and takes the shape of the container holding it. For example, molten metals, cast to form complex parts, are fluids.

It is essential to understand that even on a very small scale, a fluid is considered a continuous medium. A mist droplet, though tiny to us, is immense at the molecular scale, allowing it to be studied as a continuum. Finally, fluids are divided into two categories based on their physical state: liquids and gases.

3. Different Types of Fluids

3.1. Perfect Fluid

Let there be a fluid system, that is, a volume bounded by a closed surface Σ , whether fictitious or not.

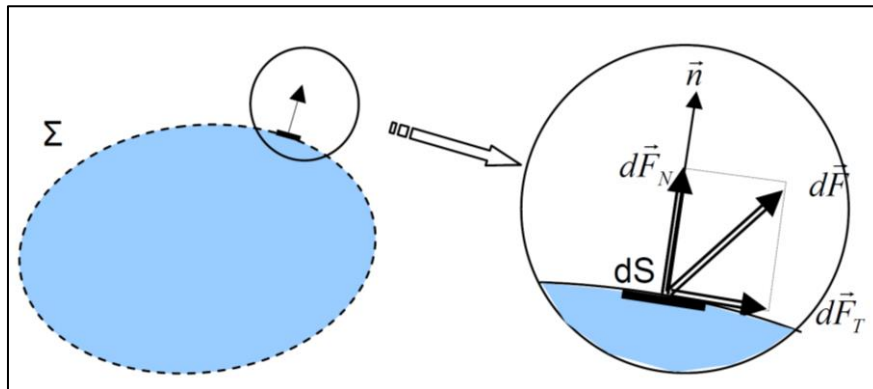


Figure 2. Decomposition of Forces Acting on a Surface Element of a Fluid

Figure 2 illustrates an infinitesimal surface element d at the interface between a fluid and the external medium, as well as the forces acting on this surface. The force exerted on this element is represented by \vec{dF} and can be decomposed into two components: a normal component \vec{dF}_N and a tangential component \vec{dF}_T .

The normal component \vec{dF}_N is perpendicular to the surface dS and corresponds to the pressure exerted by the fluid on the interface. This force acts in the direction perpendicular to the surface, influencing the variation of pressure within the fluid.

The tangential component $\overrightarrow{dF_T}$, on the other hand, is parallel to the surface dS . It is associated with shear stress (friction) and, therefore, with the viscosity of the fluid.

In the case of a perfect fluid, which is an ideal model, the tangential component $\overrightarrow{dF_T}$ is neglected because there are no frictional effects between fluid layers. In this situation, only the normal component $\overrightarrow{dF_N}$ is considered, making the force \overrightarrow{dF} purely perpendicular to the surface ds .

In other words, in a perfect fluid, only the normal force, perpendicular to the fluid surface, is taken into account, with no tangential forces related to friction. This type of fluid does not exhibit energy dissipation in the form of heat during its flow, and it is often used to simplify calculations in fluid dynamics. While real fluids always have some viscosity, the perfect fluid assumption is useful in situations where frictional effects are negligible compared to other forces, such as in high-speed flows or low-density gases.

3.2. Real Fluid

Unlike a perfect fluid, which is merely a model to simplify calculations and practically non-existent in nature, in a real fluid, the tangential frictional forces that oppose the relative sliding of fluid layers are taken into account.

This phenomenon of viscous friction occurs when the fluid is in motion. It is only when at rest that a real fluid is assumed to behave like a perfect fluid, and it is assumed that the contact forces are perpendicular to the surface elements on which they act. The statics of real fluids is thus identical to the statics of perfect fluids.

3.3. Incompressible fluid

A fluid is considered incompressible when the volume occupied by a given mass remains constant, regardless of external pressure. Liquids, such as water or oil, are typically regarded as incompressible fluids.

3.4. Compressible fluid

A fluid is considered compressible when the volume occupied by a given mass changes based on external pressure. Gases are compressible fluids. For example, air, hydrogen, and methane in their gaseous state are classified as compressible fluids.

4. *Physical Properties of Fluids*

Fluids possess a set of physical properties that define their behavior during flow or under the influence of forces. Here are the main physical properties of fluids:

4.1. *Density*

Density, also known as mass density, is defined as the amount of mass contained in a given volume of a substance. It is expressed by the relation:

$$\rho = \frac{m}{v}$$

where:

ρ : Density (kg/m³),

m : Mass (kg),

V : Volume (m³).

Density characterizes the concentration of a material, indicating how much matter is present per unit volume. It varies depending on the nature of the material and its conditions (pressure and temperature). The dimensional formula for density is ML^{-3} .

In the International System of Units (SI), it is expressed in kilograms per cubic meter (kg/m³). Examples: $\rho_{water} = 1000 \text{ kg/m}^3$, $\rho_{air} = 1,293 \text{ kg/m}^3$.

4.2. *Specific Weight*

The specific weight of a substance is defined as the weight (gravitational force) exerted by a unit volume of that substance. It is expressed by the relation:

$$\varpi = \frac{P}{V} = \frac{mg}{V} = \rho g$$

ϖ : Specific weight (N/m³).

m : mass (kg),

g : gravitational acceleration (m/s²),

V : volume en (m³).

Specific weight measures the gravitational force acting on a certain volume of a material, while density measures the amount of matter in that same volume.

Example: Water

Density of water: The density of water is approximately $\rho=1000 \text{ kg/m}^3$. This means that each cubic meter of water contains a mass of 1000 kilograms.

Specific weight of water: To obtain the specific weight of water, we use the relation $\varpi = \rho g$ is the acceleration due to gravity.

$$\varpi = 1000 \text{ kg/m}^3 \times 9,81 \text{ m/s}^2 = 9810 \text{ N/m}^3$$

This means that each cubic meter of water exerts a weight of 9810 newtons (N) due to the gravitational force.

4.3. Relative density

The density of a fluid, also known as specific density, is defined as the ratio of the density of a given fluid to the reference density of a substance, typically water (at 4°C and standard atmospheric pressure). It is a dimensionless quantity, meaning it has no unit.

It is defined by the equation::

$$d = \frac{\rho_{liq}}{\rho_{water}} \quad \text{Ou} \quad d = \frac{\rho_{gas}}{\rho_{air}}$$

Density allows us to compare the density of a fluid to that of water. If the density of a fluid is greater than 1, it means the fluid is denser than water; otherwise, it is less dense. The same applies to gases.

4.4. Viscosity

The viscosity of a fluid is its property of resisting tangential forces that tend to make the layers of the liquid move relative to each other. Viscosity is a fundamental property of fluids that measures their resistance to flow. It reflects the internal adhesion of the fluid layers, which tend to oppose relative movement between them. In other words, viscosity characterizes the internal friction force between fluid particles as they slide over each other.

Example:

If we consider a viscous fluid placed between two plates, P1 and P2, where plate P1 is stationary and plate P2 moves with a velocity \vec{V}_2 .

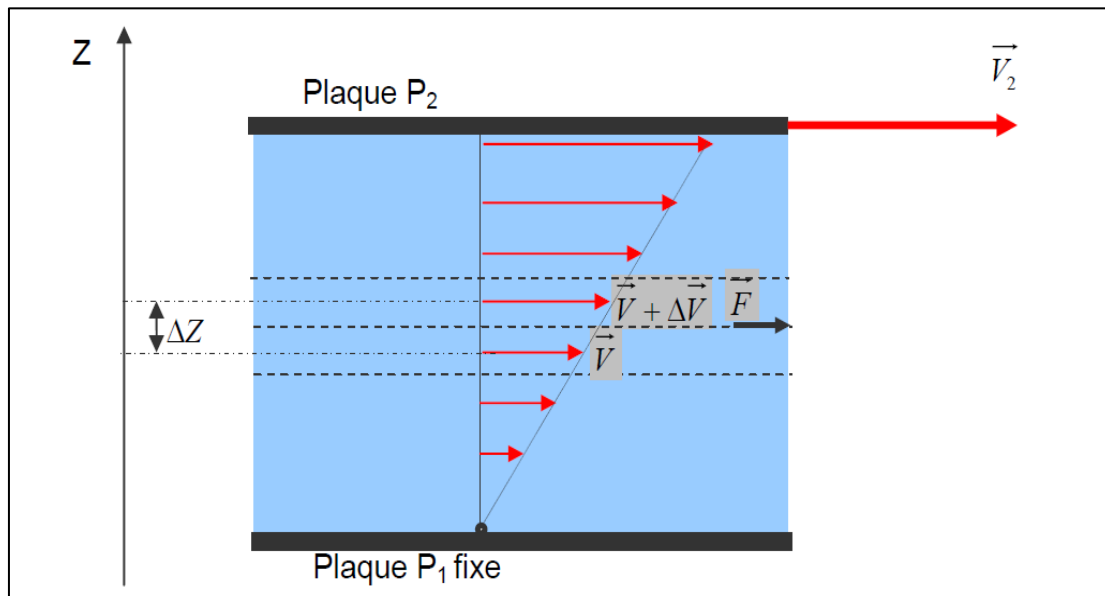


Figure 3. Velocity Profile for Free Surface Flow

In the figure above, we observe fluid flow between two parallel plates. The lower plate is stationary, while the upper plate moves with a velocity \vec{V}_2 . The fluid adheres to both plates, creating a velocity gradient across the fluid: the velocity is zero near the stationary plate and maximal near the moving plate. This velocity gradient generates a shear force acting on the fluid. Viscosity is responsible for this internal resistance to motion. We distinguish between dynamic viscosity and kinematic viscosity.

4.4.1. *Dynamic Viscosity (or Absolute Viscosity)*

Dynamic viscosity, denoted by μ , is a physical property of fluids that measures their internal resistance to flow under the influence of an external force. It describes a fluid's ability to resist movement when its layers slide past each other. The higher the dynamic viscosity, the "thicker" the fluid is and the more difficult it is to move.

Dynamic viscosity is related to shear stress (τ) and the velocity gradient $\frac{dv}{dy}$ between fluid layers. The relationship between these quantities is given by Newton's law of viscosity.

$$\tau = \mu \frac{dv}{dy}$$

where :

- τ is the shear stress,
- μ is the dynamic (or absolute) viscosity of the fluid,,
- $\frac{dv}{dy}$ is the velocity gradient perpendicular to the flow.

Dynamic (or absolute) viscosity μ represents a fluid's ability to resist deformation under the effect of a shear force. This force, or more precisely the shear stress, is proportional to the rate of change in velocity between two adjacent fluid layers.

4.4.2. *Kinematic viscosity*

Kinematic viscosity is a measure of a fluid's ability to flow under the influence of gravity, taking into account the fluid's internal resistance (dynamic viscosity) and its density. It is defined as the ratio of dynamic viscosity (μ) to the fluid's density (ρ):

$$V = \frac{\mu}{\rho}$$

In the SI system, the unit of dynamic viscosity, μ , is (kg/m.s) or (N.s/m²). In the CGS system, the unit is the poise, where 1 poise = 1 g/cm.s.

Kinematic viscosity, ν , has the unit m^2/s in the SI system. In the CGS system, the unit is the stokes, where $1 \text{ stokes} = 1 \text{ cm}^2/\text{s}$.

However, the kinematic viscosity of liquids varies with temperature but is not significantly affected by pressure under normal conditions. The relationship between the kinematic viscosity of water and temperature is given by Poiseuille's empirical formula, which allows for the calculation of water's kinematic viscosity at various temperatures.

$$\nu = \frac{0.0178}{1 + 0.03377T + 0.0002217T^2}$$

- ν is the kinematic viscosity in stokes.
- T is the temperature in degrees Celsius.

This formula shows that the kinematic viscosity of water decreases as the temperature increases.

4.5. Surface Tension

The molecules in a liquid are mutually attracted by forces known as cohesive forces. The attractive forces between molecules of two different, non-miscible liquids (or liquid-material) are called adhesive forces.

A liquid molecule at rest is subject to surface contact forces exerted by neighboring molecules, and their average value is zero.

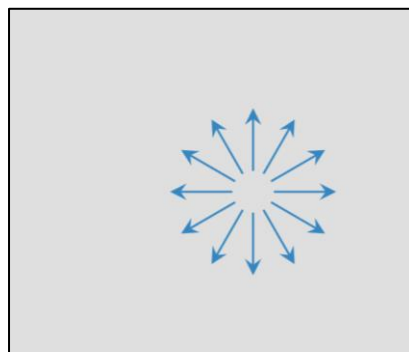


Figure 4. Fluid interaction

A molecule at the free surface of a liquid or at the interface between two liquids (Figure 5) is no longer subject to symmetrical forces, as it is no longer symmetrically surrounded by other molecules of the same type. As a result, the net molecular forces are no longer zero. This imbalance creates surface tension, with a direction that is normal to the interface.

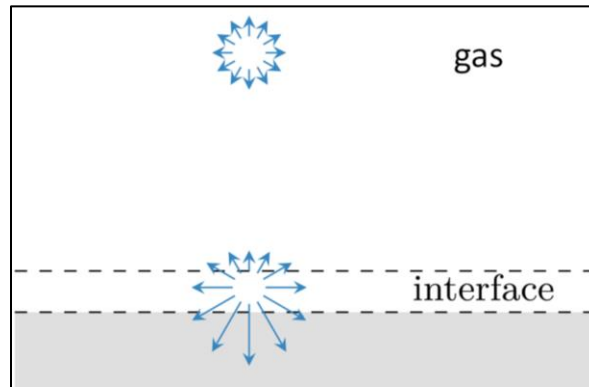


Figure 5. Distribution of Molecular Forces at the Interface Between a Liquid and a Gas.

A molecule located at the free surface or in the separation zone between two fluids possesses energy corresponding to the work done by the molecule to position itself at the surface. The free surface behaves like a stretched membrane.

Surface tension is given by :

$$\sigma = \frac{F}{L}$$

Where:

- σ is the surface tension (N/m),
- F is the force acting on the surface of the liquid (N),
- L is the length of the line on which the force acts (m).

4.6. Capillarity

Capillarity is a physical phenomenon observed when liquids rise or fall in very thin tubes, called capillary tubes, due to the attraction forces between the liquid molecules and the molecules of the tube walls. It results from the interaction of two types of forces:

- **Adhesive forces** : these are the forces that attract the liquid molecules to the surface of the solid, i.e., the tube wall.
- **Cohesive forces**: these are the forces that hold the liquid molecules together.

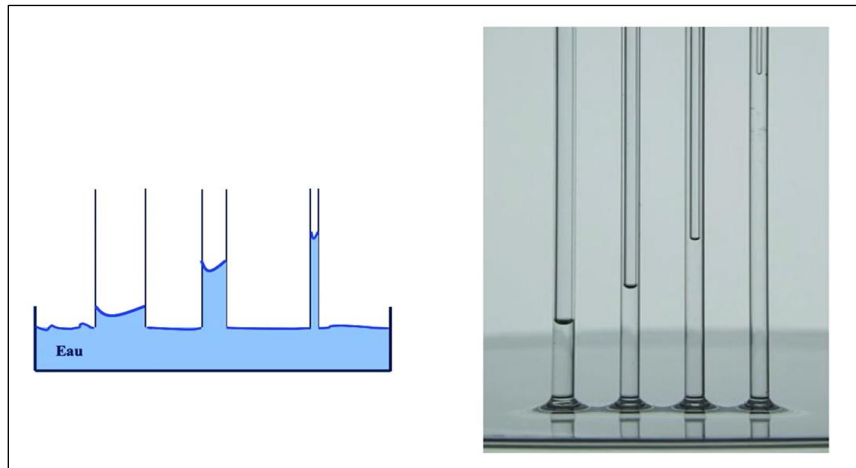


Figure.6 Capillary action in tubes of different diameters immersed in water

Practical example: considering the case of water and mercury (Figure 7).

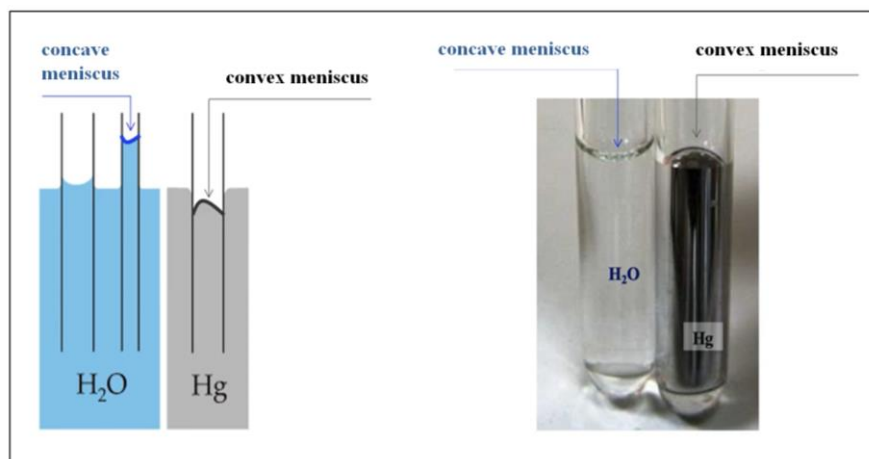


Figure.7 Comparison of Concave and Convex Meniscus for Water and Mercury in Capillary Tubes.

Water in a glass tube: Water wets the walls of the glass tube because the adhesive forces between the water molecules and the glass are stronger than the cohesive forces between the water molecules. This causes the water to rise in the tube, forming a concave meniscus (curved surface dipping downward).

Mercury in a glass tube: Mercury does not wet the glass because the cohesive forces between mercury molecules are stronger than the adhesive forces between mercury and the glass. This results in capillary depression, where the mercury level falls in the tube, forming a convex meniscus (curved surface upward).

We can, for example, assume that the water stops rising in the tube at a certain point. However, this phenomenon does not continue indefinitely, as there comes a point where the forces pulling the water upward are counterbalanced by its own weight.

Indeed, the vertical component of the force due to surface tension, defined by $T\cos\theta$, which acts on the wetted length at the free surface (the tube's circumference), becomes equal to the weight of the vertical water column.

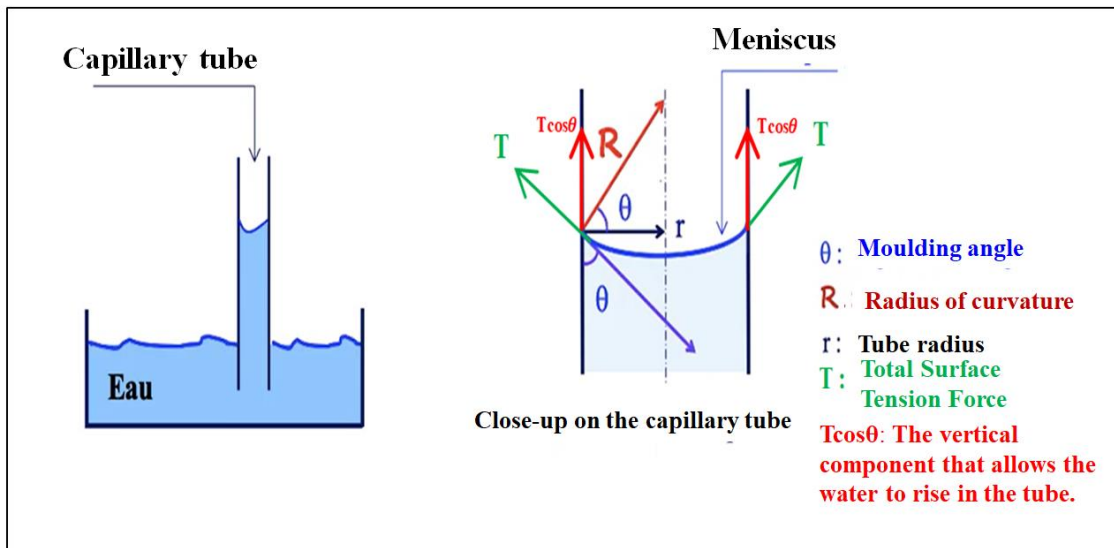


Figure.8 Superficial Tension Forces and their Vertical Component in a Capillary Tube.

In a capillary tube, water rises due to surface tension, which creates an upward force along the tube wall. The water will continue to rise until this force is balanced by the weight of the water column. At that point, the ascent stops.

For mercury, however, cohesive forces between the mercury molecules are stronger than the adhesive forces with the tube walls. As a result, mercury descends in the tube, forming a convex meniscus, with the surface tension acting downward. So:

$$T \cos \theta = \frac{\pi d^2}{4} h \varpi$$

Where

$$T = \sigma \pi d$$

- θ : the contact angle between the liquid and the solid surface.
- d : diameter of the capillary tube.
- h : the height of capillarity, which can be written in the following form:

$$h = \frac{(4 \cos \theta) \sigma}{\varpi d}$$

The height of capillary rise or fall in a glass tube with a diameter d (in mm), at 20°C, can be determined using the following empirical formulas:

Water: $h = \frac{30}{d} \quad (mm)$

Mercury : $h = \frac{10.15}{d} \quad (mm)$

Alcohol: $h = \frac{12}{d} \quad (mm)$

The height of capillary rise or fall is more pronounced in very thin tubes. The smaller the diameter of the tube, the more significant the capillary effect becomes.

4.7. Vapor pressure

All liquids tend to evaporate, transitioning from the liquid phase to the gaseous phase. The vapor (gas) molecules exert a pressure known as vapor pressure P_v . For example, the pressure of water vapor, which occupies a certain volume along with water, is equal to the pressure it would exert if it occupied the same volume alone. The total pressure of the mixture equals the sum of the pressures of the individual components. In the SI system, the units are N/m². Vapor pressure varies from one liquid to another and increases with temperature.

4.8. Compressibility

All solid, liquid, or gaseous materials are compressible, meaning the volume V of a given mass decreases to $V-dV$ when a force F is applied over the entire peripheral surface (force per unit area) and the pressure changes from p to $p+dp$. The relationship between the pressure variation and the volume variation depends on the compressibility modulus ϵ :

$$\frac{-dV}{V} = \frac{dp}{\varepsilon}$$

The increase in pressure results in a decrease in volume. It is necessary to introduce the negative sign (-) to ensure that ε remains positive. ε is expressed in pascals.

4.9. Expansion

The increase in the volume of a body due to a rise in temperature is characterized by a coefficient known as the thermal expansion coefficient.

The volumetric expansion coefficient β_t of a liquid is the increase in volume per unit when its temperature rises by 1°C, and it is expressed as:

$$\beta_t = \frac{1}{V} \frac{dV}{dT}$$

Where :

- β_t the volume expansion coefficient (in K^{-1}),
- V the initial volume of the fluid,
- dV the change in volume as a function of the change in temperature dT .

5. Properties of Gases

Gases are highly compressible fluids and are characterized by a change in density. This change can be caused by a change in pressure or temperature.

The mass density, or specific density, is defined by the relation $\frac{m}{v}$. The mass density of water is approximately 1000 kg/m³ at normal temperature. The mass density of a gas can be calculated using its equation of state:

$$p\vartheta_s = rT$$

Où :

p the absolute pressure,

ϑ_s The specific volume ($\frac{V}{m}$),

T The absolute temperature,

r the specific gas constant for the gas being studied:

$$r = \frac{R}{M} = \frac{\text{Universal gas constant for ideal gases}}{\text{Molar mass}} = \frac{8.31431 \text{ (j/k)}}{M}$$

6. Conclusion

Fluids can be classified as perfect fluids (frictionless), real fluids (with friction), incompressible fluids (liquids), and compressible fluids (gases). They are characterized by several fundamental properties, such as density, specific weight, viscosity, surface tension, capillarity, compressibility, expansion, as well as other characteristics that have not yet been addressed. These properties will be used later.

The mechanical behavior and physical properties of compressible fluids differ from those of incompressible fluids. In fact, the laws of fluid mechanics are not universal; they apply specifically to each type of fluid. In line with the classification presented, the laws pertaining to each fluid type will be covered separately in the remainder of the course.