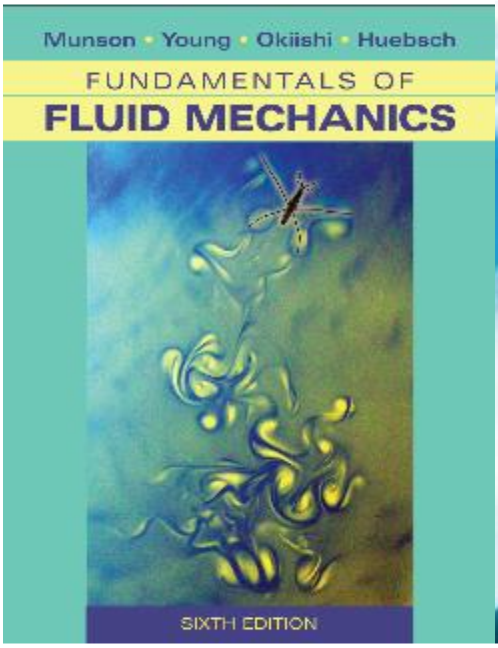
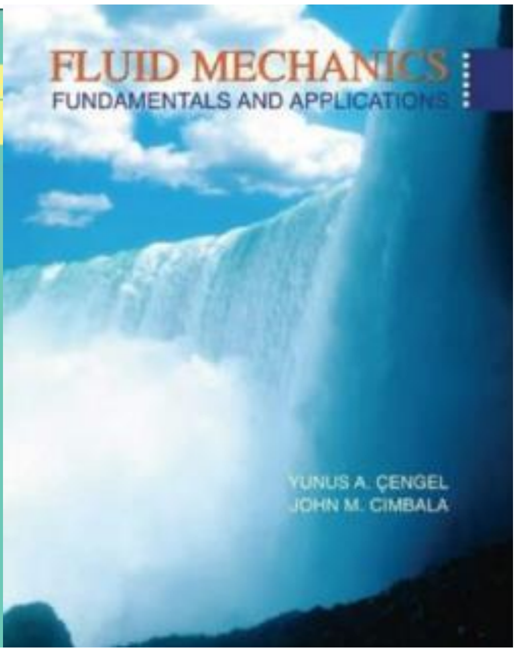
FLUID MECHANICS





PROF. DR. METİN GÜNER
COMPILER

ANKARA UNIVERSITY
FACULTY OF AGRICULTURE
DEPARTMENT OF AGRICULTURAL MACHINERY AND TECHNOLOGIES ENGINEERING

1. INTRODUCTION

Mechanics is the oldest physical science that deals with both stationary and moving bodies under the influence of forces.

Mechanics is divided into three groups:

a) Mechanics of rigid bodies,
b) Mechanics of deformable bodies,
c) Fluid mechanics

Fluid mechanics deals with the behavior of fluids at rest (*fluid statics*) or in motion (*fluid dynamics*), and the interaction of fluids with solids or other fluids at the boundaries (Fig.1.1.).

Fluid mechanics is the branch of physics which involves the study of fluids (liquids, gases, and plasmas) and the forces on them.

Fluid mechanics can be divided into two.

a)Fluid Statics
b)Fluid Dynamics

Fluid statics or **hydrostatics** is the branch of **fluid mechanics** that studies fluids at rest. It embraces the study of the conditions under which fluids are at rest in stable equilibrium

Hydrostatics is fundamental to hydraulics, the engineering of equipment for storing, transporting and using fluids.

Hydrostatics offers physical explanations for many phenomena of everyday life, such as why atmospheric pressure changes with altitude, why wood and oil float on water, and why the surface of water is always flat and horizontal whatever the shape of its container.

Fluid dynamics is a subdiscipline of fluid mechanics that deals with **fluid flow**—the natural science of fluids (liquids and gases) in motion.

It has several subdisciplines itself, including **aerodynamics** (the study of air and other gases in motion) and **hydrodynamics** (the study of liquids in motion).

Figure 1.1. Fluid mechanics deals with liquids and gases in motion or at rest.

1.1. What is a Fluid?

You will recall from physics that a substance exists in four primary phases:

a) Solid
b) Liquid
c) Gas
d) Plasma (at very high temperatures, it also exists as plasma.)

A substance in the liquid or gas phase is referred to as a fluid.

Distinction between a solid and a fluid is made on the basis of the substance's ability to resist an applied shear (or tangential) stress that tends to change its shape.

A solid can resist an applied shear stress by deforming, whereas a fluid deforms continuously under the influence of shear stress, no matter how small.

In solids stress is proportional to strain, but in fluids stress is proportional to strain rate.

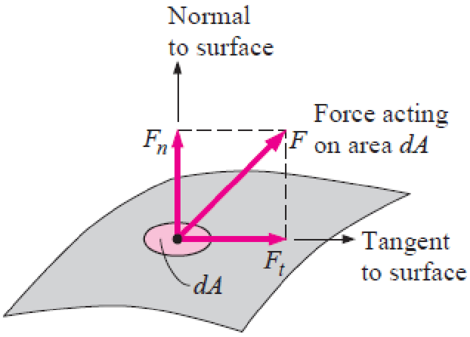
Strain describes relative deformation or change in shape and size of elastic, plastic, and fluid materials under applied forces**.** ***Strain*** is the definition of how much a material has been stretched (or compressed) when compared to its original length.

When a constant shear force is applied, a solid eventually stops deforming, at some fixed strain angle, whereas a fluid never stops deforming and approaches a certain rate of strain.

Shear Force: A force acting in a direction parallel to a surface or to a planar cross section of a body.

Stress is defined as force per unit area and is determined by dividing the force by the area upon which it acts.

The normal component of the force acting on a surface per unit area is called ***the normal stress,*** and the tangential component of the force acting on a surface per unit area is called ***shear stress*** (Fig 1.2.).



$$\text{Normal stress: } \sigma = \frac{F_n}{dA}$$

$$\text{Shear stress: } \tau = \frac{F_t}{dA}$$

Figure 1.2.The normal stress and shear stress at the surface of a fluid element. For fluids at rest, the shear stress is zero and pressure is the only normal stress.

In a fluid at rest, the normal stress is called ***pressure***. The supporting walls of a fluid eliminate shear stress, and thus a fluid at rest is at a state of zero shear stress. When the walls are removed or a liquid container is tilted, a shear develops and the liquid splashes or moves to attain a horizontal free surface.

In a liquid, chunks of molecules can move relative to each other, but the volume remains relatively constant because of the strong cohesive forces between the molecules. As a result, a liquid takes the shape of the container it is in, and it forms a free surface in a larger container in a gravitational field.

A gas, on the other hand, expands until it encounters the walls of the container and fills the entire available space. This is because the gas molecules are widely spaced, and the cohesive forces between them are very small. Unlike liquids, gases cannot form a free surface (Fig.1.3).

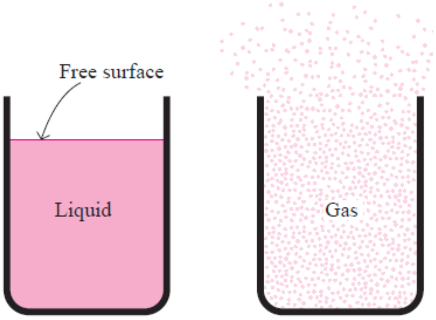


Figure 1.3. Unlike a liquid, a gas does not form a free surface, and it expands to fill the entire available space.

Although solids and fluids are easily distinguished in most cases, this distinction is not so clear in some borderline cases. For example, asphalt appears and behaves as a solid since it resists shear stress for short periods of time. But it deforms slowly and behaves like a fluid when these forces are exerted for extended periods of time.

Intermolecular bonds are strongest in solids and weakest in gases. One reason is that molecules in solids are closely packed together, whereas in gases they are separated by relatively large distances (Fig.1.4)

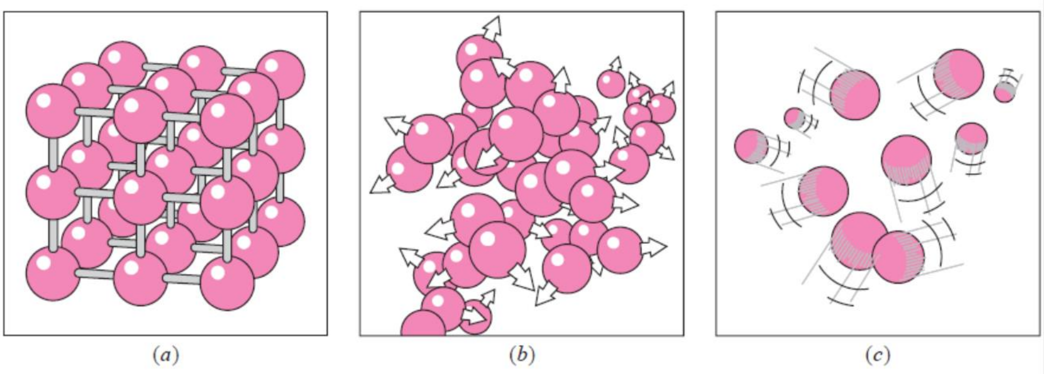


Figure 1.4.The arrangement of atoms in different phases: a) molecules are at relatively fixed positions in a solid, b) groups of molecules move about each other in the liquid phase, and c) molecules move about at random in the gas phase.

The molecules in a solid are arranged in a pattern that is repeated throughout. Because of the small distances between molecules in a solid, the attractive forces of molecules on each other are large and keep the molecules at fixed positions.

The molecular spacing in the liquid phase is not much different from that of the solid phase, except the molecules are no longer at fixed positions relative to each other and they can rotate and translate freely.

In a liquid, the intermolecular forces are weaker relative to solids, but still strong compared with gases. The distances between molecules generally increase slightly as a solid turns liquid, with water being a notable exception.

In the gas phase, the molecules are far apart from each other, and a molecular order is nonexistent. Gas molecules move about at random, continually colliding with each other and the walls of the container in which they are contained.

Particularly at low densities, the intermolecular forces are very small, and collisions are the only mode of interaction between the molecules. Molecules in the gas phase are at a considerably higher energy level than they are in the liquid or solid phase. Therefore, the gas must release a large amount of its energy before it can condense or freeze.

Gas and vapor are often used as synonymous words. The vapor phase of a substance is customarily called a gas when it is above the critical temperature. Vapor usually implies a gas that is not far from a state of condensation.

1.2. Application Areas of Fluid Mechanics

Fluid mechanics is widely used both in everyday activities and in the design of modern engineering systems from vacuum cleaners to supersonic aircraft.

To begin with, fluid mechanics plays a vital role in the human body. The heart is constantly pumping blood to all parts of the human body through the arteries and veins, and the lungs are the sites of airflow in alternating directions. Needless to say, all artificial hearts, breathing machines, and dialysis systems are designed using fluid dynamics.

An ordinary house is, in some respects, an exhibition hall filled with applications of fluid mechanics.

The piping systems for cold water, natural gas, and sewage for an individual house and the entire city are designed primarily on the basis of fluid mechanics. The same is also true for the piping and ducting network of heating and air-conditioning systems.

A refrigerator involves tubes through which the refrigerant flows, a compressor that pressurizes the refrigerant, and two heat exchangers where the refrigerant absorbs and rejects heat. Fluid mechanics plays a major role in the design of all these components. Even the operation of ordinary faucets is based on fluid mechanics.

We can also see numerous applications of fluid mechanics in an automobile. All components associated with the transportation of the fuel from the fuel tank to the cylinders—the fuel line, fuel pump, fuel injectors, or carburetors— as well as the mixing of the fuel and the air in the cylinders and the purging of combustion gases in exhaust pipes are analyzed using fluid mechanics.

Fluid mechanics is also used in the design of the heating and air-conditioning system, the hydraulic brakes, the power steering, automatic transmission, and lubrication systems, the cooling system of the engine block including the radiator and the water pump, and even the tires. The sleek streamlined shape of recent model cars is the result of efforts to minimize drag by using extensive analysis of flow over surfaces.

On a broader scale, fluid mechanics plays a major part in the design and analysis of aircraft, boats, submarines, rockets, jet engines, wind turbines, biomedical devices, the cooling of electronic components, and the transportation of water, crude oil, and natural gas.

It is also considered in the design of buildings, bridges, and even billboards to make sure that the structures can withstand wind loading. Numerous natural phenomena such as the rain cycle, weather patterns, and the rise of ground water to the top of trees, winds, ocean waves, and currents in large water bodies are also governed by the principles of fluid mechanics (Figs.1.5, 1.6, and 1.7).

Figure 1.5. Natural flows, boats aircrafts

Figure 1.6. Power plant, human body cars

Figure 1.7. Wind turbines, piping and plumbing systems industrial applications

1.3. Dimensions, Dimensional Homogeneity, and Units

Any physical quantity can be characterized by ***dimensions***. The magnitudes assigned to the dimensions are called units.

Some basic dimensions such as mass M, length *L*, time T, and temperature θ are selected as ***primary or fundamental dimensions***, while others such as area velocity *V*, density ρ, and volume $\forall$ are expressed in terms of the primary dimensions and are called ***secondary dimensions, or derived dimensions, or basic dimensions.***

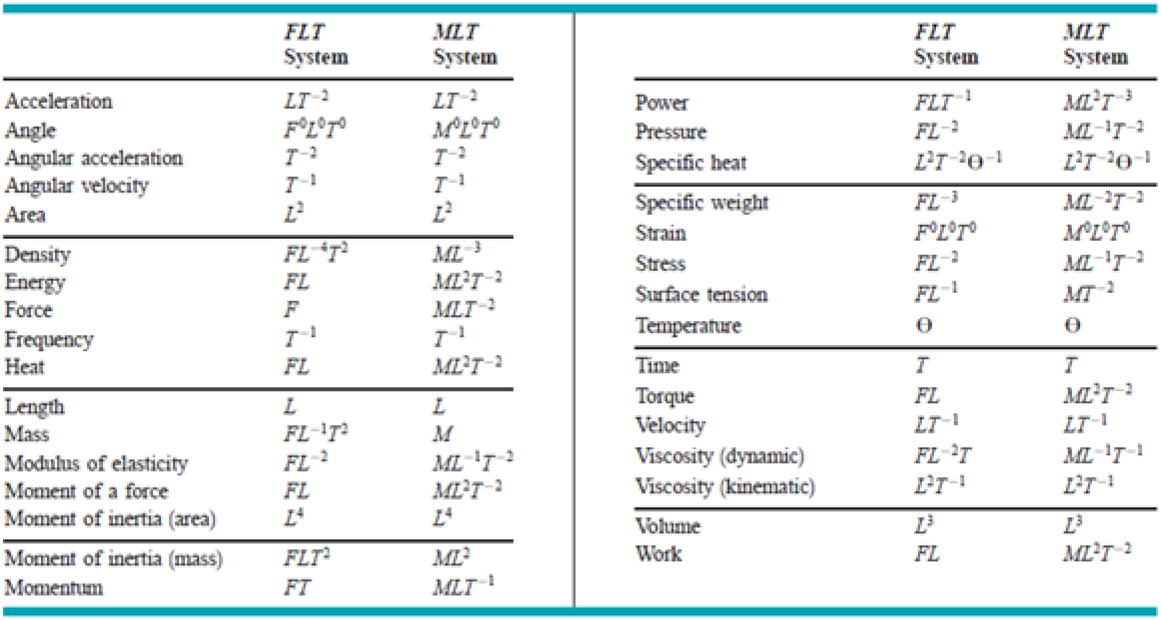
The dimensions of area equal length times length, Area=L^2.
The dimensions of velocity equal length divided by time, Velocity=LT^{-1}.
The dimensions of density equal mass divided by volume cubic, density=ML^{-3}

There are two dimension systems; ***MLT*** and ***FLT***. For a wide variety of problems involving fluid mechanics, only the three basic dimensions, *L*, *T*, and *M* are required. Alternatively, *L*, *T*, and *F* could be used, where *F* is the basic dimensions of force. Since Newton's law states that force is equal to mass times acceleration, it follows that

$$F = MLT^{-2}$$
$$M = FL^{-1}T^{2}$$

or thus, secondary quantities expressed in terms of *M* can be expressed in terms of *F* through the relationship above. For example, stress, is a force per unit area, so that $\sigma = FL^{-2}$but an equivalent dimensional equation is $\sigma = ML^{-1}T^{-2}$. Table 1.1. provides a list of dimensions for a number of common physical quantities

Table 1.1.Dimensions associated with common physical quantities



	FLT System	MLT System
Acceleration	LT^{-2}	LT^{-2}
Angle	$F^0L^0T^0$	$M^0L^0T^0$
Angular acceleration	T^{-2}	T^{-2}
Angular velocity	T^{-1}	T^{-1}
Area	L^2	L^2
Density	$FL^{-4}T^2$	ML^{-3}
Energy	FL	ML^2T^{-2}
Force	F	MLT^{-2}
Frequency	T^{-1}	T^{-1}
Heat	FL	ML^2T^{-2}
Length	L	L
Mass	$FL^{-1}T^2$	M
Modulus of elasticity	FL^{-2}	$ML^{-1}T^{-2}$
Moment of a force	FL	ML^2T^{-2}
Moment of inertia (area)	L^4	L^4
Moment of inertia (mass)	FLT^2	ML^2
Momentum	FT	MLT^{-1}
Power	FLT^{-1}	ML^2T^{-3}
Pressure	FL^{-2}	$ML^{-1}T^{-2}$
Specific heat	$L^2T^{-2}\Theta^{-1}$	$L^2T^{-2}\Theta^{-1}$
Specific weight	FL^{-3}	$ML^{-2}T^{-2}$
Strain	$F^0L^0T^0$	$M^0L^0T^0$
Stress	FL^{-2}	$ML^{-1}T^{-2}$
Surface tension	FL^{-1}	MT^{-2}
Temperature	Θ	Θ
Time	T	T
Torque	FL	ML^2T^{-2}
Velocity	LT^{-1}	LT^{-1}
Viscosity (dynamic)	$FL^{-2}T$	$ML^{-1}T^{-1}$
Viscosity (kinematic)	L^2T^{-1}	L^2T^{-1}
Volume	L^3	L^3
Work	FL	ML^2T^{-2}

In engineering, all equations must be *dimensionally homogeneous*. That is, every term in an equation must have the same unit.

All theoretically derived equations are dimensionally *homogeneous*—that is, the dimensions of the left side of the equation must be the same as those on the right side, and all additive separate terms must have the same dimensions.

We accept as a fundamental premise that all equations describing physical phenomena must be dimensionally homogeneous. If this were not true, we would be attempting to equate or add unlike physical quantities, which would not make sense. For example, the equation for the velocity, *V*, of a uniformly accelerated body is

$$V = V_0 + at$$

Where; V_0 is the initial velocity, *a is* the acceleration, and *t is* the time interval. In terms of dimensions the equation is

$LT^{-1} = LT^{-1} + LT^{-1}$ and this Equation is dimensionally homogeneous.

Some equations that are known to be valid contain constants having dimensions. The equation for the distance, *d*, traveled by a freely falling body can be written as

$$d = 16.2{\times}t^2$$

and a check of the dimensions reveals that the constant must have the dimensions of LT^{-2} if the equation is to be dimensionally homogeneous. Actually, The last equation is a special form of the well-known equation from physics for freely falling bodies,

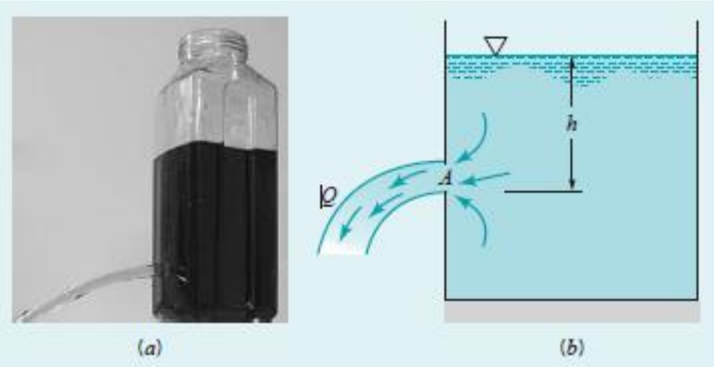
$$d = \frac{gt^2}{2}$$

Equation is dimensionally homogeneous and valid in any system of units.

Example: A liquid flows through an orifice located in the side of a tank as shown in Fig. A commonly used equation for determining the volume rate of flow, *Q*, through the orifice is

$$Q = 0.61\, A\sqrt{2gh}$$

Where; *A* is the area of the orifice, *g* is the acceleration of gravity, and *h* is the height of the liquid above the orifice. Investigate the dimensional homogeneity of this formula.



Solution: The dimensions of the various terms in the equation are *Q*=volume/time = L^3T^{-2}, A=area=L^2, g= acceleration of gravity=LT^{-2}, and h=height=L. These terms, when substituted into the equation, yield the dimensional form:

$$(L^3T^{-1})=0.61L^2\sqrt{2}\,(LT^{-2})^{1/2}\,(L)^{1/2} \quad \text{or} \quad L^3T^{-1}=0.61\sqrt{2}\,(L^3T^{-1})$$

It is clear from this result that the equation is dimensionally homogeneous (both sides of the formula have the same dimensions of L^3T^{-1}), and the numbers 0.61 and $\sqrt{2}$ are dimensionless.

1.3.1. Systems of Units

Two sets of units are still in common use today:

The ***English system,*** which is also known as the *United States Customary System* (USCS), and ***The metric SI*** (from *Le Système International d' Unités),* which is also known as the *International System.*

The SI is a simple and logical system based on a decimal relationship between the various units, and it is being used for scientific and engineering work in most of the industrialized nations, including England.

In SI the unit of length is the meter (m), the time unit is the second (s), the mass unit is the kilogram (kg), and the temperature unit is the kelvin (K). Note that there is no degree symbol used when expressing a temperature in kelvin units. The kelvin temperature scale is an absolute scale and is related to the Celsius (centigrade) scale through the relationship

$$K = °C + 273.15$$

Although the Celsius scale is not in itself part of SI, it is common practice to specify temperatures in degrees Celsius when using SI units.

The force unit, called the newton (N), is defined from Newton's second law as

$$1\ N = (1\ kg)(\frac{m}{s^2})$$

Thus, a 1-N force acting on a 1-kg mass will give the mass an acceleration of 1 m/s^2. Standard gravity in SI is 9.807 m/s^2 (commonly approximated as 9.81 m/s^2) so that a 1-kg mass weighs 9.81 N under standard gravity.

The unit of *work* in SI is the joule (J), which is the work done when the point of application of a 1-N force is displaced through a 1-m distance in the direction of a force.

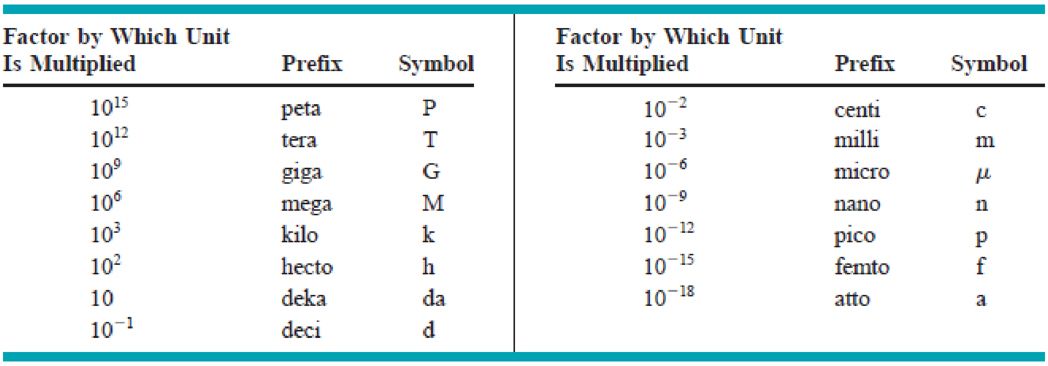
$$1\ \mathrm{J} = 1\ \mathrm{N\ m}$$

The unit of *power* is the watt (W) defined as a joule per second. Thus,

$$1\ \mathrm{W} = 1\ \mathrm{J/s} = 1\ \mathrm{N\ m/s}$$

Prefixes for forming multiples and fractions of SI units are given in Table 1.2. For example, the notation kN would be read as "kilonewtons" and stands for 1000 N. Similarly, mm would be read as "millimeters" and stands for 10^{-3} m. The centimeter is not an accepted unit of length in the SI system, so for most problems in fluid mechanics in which SI units are used, lengths will be expressed in millimeters or meters.

Table 1.2. Prefixes for forming multiples and fractions of SI units



Factor by Which Unit Is Multiplied	Prefix	Symbol	Factor by Which Unit Is Multiplied	Prefix	Symbol
10^{15}	peta	P	10^{-2}	centi	c
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10	deka	da	10^{-18}	atto	a
10^{-1}	deci	d			

Example: A tank is filled with oil whose density is $\rho = 900$ kg/m^3. If the volume of the tank is $\forall = 3$ m^3, determine the amount of mass m in the tank.

$$m = \rho \forall = 900 \times 3 = 2700\ kg$$