FLUID MECHANICS
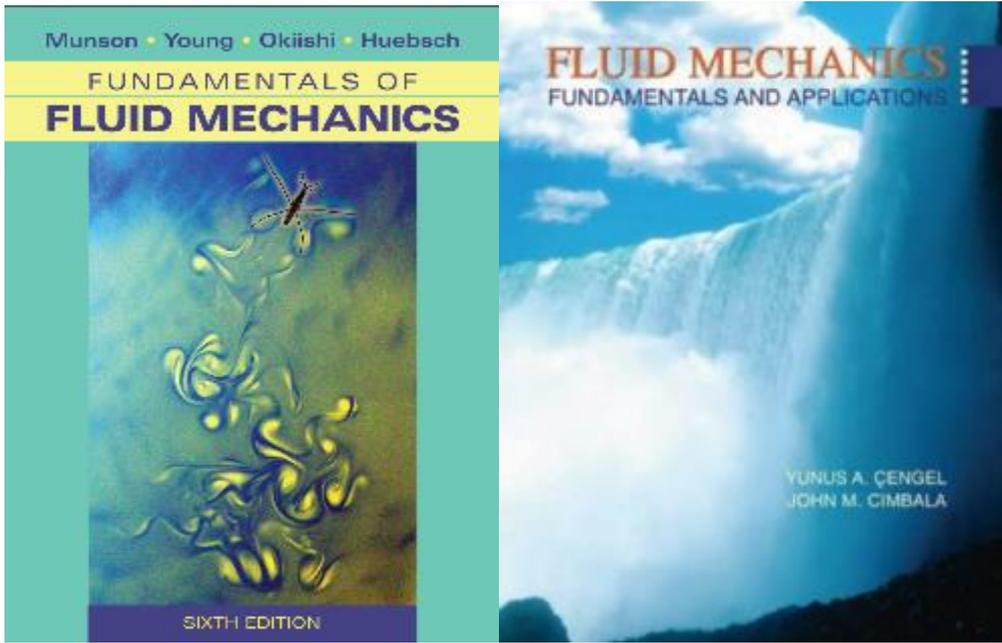

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2. PROPERTIES OF FLUIDS

2.1. Measures of Fluid Mass and Weight

Mass: Mass (m) is a scientific measure of the amount of matter an object is made up of. No matter where you are at given moment in time, mass is constant. So, whether you're walking on the world or on the moon, your mass is the same.

-Mass is indestructible. No matter where you are in the universe your mass will never change

-Mass can never be zero. What we mean by this is that everything in the universe has mass.

-Mass is not related to gravity, centrifugal force, etc and these forces have no effect whatsoever on your mass.

-Mass is commonly measured in kilograms and grams.

Weight: Weight (W) is a form of measurement that is dependent on gravity and, unlike mass, your weight can vary depending on where you are in the universe.

$$W=mg$$

-The weight of an object changes based on where it is. If you've decided to visit the moon to test out this theory then you'll find that, in a matter of hours, you will have reduced your weight by two thirds.

-Weight is a vector and its direction of pull is towards the centre of the planet you're stood on.

-The weight of any given object can go up or down depending on the amount of gravity acting on it. More gravity - the heavier the object. Less gravity - the lighter the object.

-Unlike mass, weight can be zero. An example of this is an astronaut floating in space - there's no gravity acting on his body and, therefore, he has no weight.

-Weight is commonly measured in Newtons.

2.1.1. Density

The ***density*** of a fluid, designated by the Greek symbol (ρ, rho), is defined as its mass per unit volume.

$$\rho = \frac{m}{\forall} \ (\frac{kg}{m^3})$$

Density is typically used to characterize the mass of a fluid system. In the SI system units of density are kg/m^3.

The value of density can vary widely between different fluids, but for liquids, variations in pressure and temperature generally have only a small effect on the value of ρ .

The small change in the density of water with large variations in temperature is illustrated in Fig. The density of water at 4 ^{0}C is 1000 kg/m^3. Table 2.1. lists values of density for several common liquids. Unlike liquids, the density of a gas is strongly influenced by both pressure and temperature.
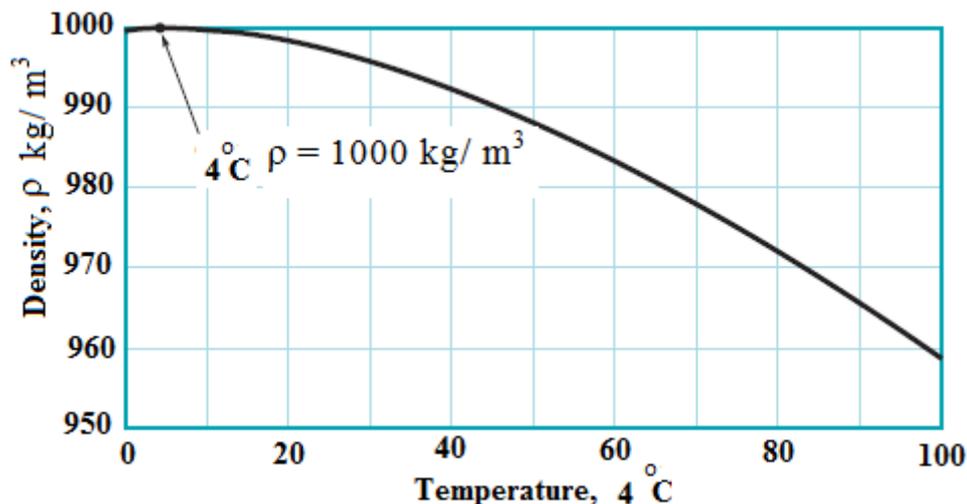

Figure 2.1. Density of water as a function of temperature.

The reciprocal of density is the ***specific volume v***, which is defined as *volume per unit mass*.

$$v = \frac{1}{\rho} \ (\frac{m^3}{kg})$$

The density of a substance, in general, depends on temperature and pressure.

The density of most gases is proportional to pressure and inversely proportional to temperature.

Liquids and solids, on the other hand, are essentially incompressible substances, and the variation of their density with pressure is usually negligible.

At 20°C, for example, the density of water changes from 998 kg/m^3 at 1 atm to 1003 kg/m^3 at 100 atm, a change of just 0.5 percent. The density of liquids and solids depends more strongly on temperature than it does on pressure. At 1 atm, for example, the density of water changes from 998 kg/m^3 at 20°C to 975 kg/m^3 at 75°C, a change of 2.3 percent, which can still be neglected in many engineering analyses.

2.1.2. Specific Weight

The ***specific weight*** of a fluid, designated by the Greek symbol (gamma), is defined as its *weight* per unit volume. Thus, specific weight is related to density through the equation.

$$\gamma = \rho g$$

Where; *g* is the local acceleration of gravity. Just as density is used to characterize the mass of a fluid system, the specific weight is used to characterize the weight of the system. In SI the units, γ has units of N/m^3. Under conditions of standard water has specific weight of 9810 N/m^3.

2.1.3. Specific Gravity

The ***specific gravity*** of a fluid, designated as *SG*, is defined as the ratio of the density of the fluid to the density of water at some specified temperature.

Usually the specified temperature is taken as 4 °C and at this temperature the density of water is 1000 kg/m^3. In equation form, specific gravity is expressed as

$$SG = \frac{\rho}{\rho_{H_2O \ at \ 4 \ °C}}$$

Since it is the *ratio* of densities, the value of *SG* does not depend on the system of units used. For example, the specific gravity of mercury at 20 °C is 13.55. Thus, the density of mercury can be readily calculated in SI units through the use of above Equation.

$$\rho_{Hg} = 13.55 \times 1000 \cong 13600 \ kg/m^3$$

It is clear that density, specific weight, and specific gravity are all interrelated, and from a knowledge of any one of the three the others can be calculated. Physical Properties of Some Common Liquids and gases are given in Table 2.1. and Table 2.2.

Table 2.1. Approximate Physical Properties of Some Common Liquids (SI Units)

Fluid	Density ρ (kg/m^3)	Specific Weight γ (kN/m^3)	Dynamic Viscosity μ (Pas)	Kinematic Viscosity ϑ (m^2/s)	Surface Tension (a) σ (N/m)	Vapor Pressure P_v (N/m^2) (mutlak)	Bulk Modulus (b) E_v (N/m^2)
Carbon Tetrachloride(20 ºC)	1590	15.6	9.58×10^{-4}	6.03×10^{-7}	2.69×10^{-2}	1.3×10^4	1.31×10^9
Ethyl alcohol (20 ºC)	789	7.74	1.19×10^{-3}	1.51×10^{-6}	2.28×10^{-2}	5.9×10^3	1.06×10^9
Gasoline (15.6 ºC)	680	6.67	3.1×10^{-4}	4.6×10^{-7}	2.2×10^{-2}	5.5×10^4	1.3×10^9
Glycerin(20 ºC)	1260	12.4	$1.50\times10^{+0}$	1.19×10^{-3}	6.33×10^{-2}	1.4×10^{-2}	4.52×10^9
Mercury (20 ºC)	13600	133	1.57×10^{-3}	1.15×10^{-7}	4.66×10^{-1}	1.6×10^{-1}	2.85×10^{10}
Oil (c) (SAE 30) (15.6 ºC)	912	8.95	3.8×10^{-1}	4.2×10^{-4}	3.6×10^{-2}	-	1.5×10^9
SeaWater (15.6 ºC)	1030	10.1	1.20×10^{-3}	1.17×10^{-6}	7.34×10^{-2}	1.77×10^3	2.34×10^9
Water (15.6 ºC)	999	9.80	1.12×10^{-3}	1.12×10^{-6}	7.34×10^{-2}	1.77×10^3	2.15×10^9

a: In contact with air; b: Isentropic bulk modulus calculated from speed of sound; c: Typical values. Properties of petroleum products vary

Table 2.2. Approximate Physical Properties of Some Common Gases at Standard Atmospheric Pressure (SI Units)

Gas	Density (ρ) (kg/m^3)	Specific Weight γ (N/m^3)	Dynamic Viscosity μ (Pas)	Kinematic Viscosity ϑ (m^2/s)	Gas Constant R * (J/kg.K)	Specific Heat Ratio (k)**
Air (Standard) (15 ºC)	1.23	$1.20.10^1$	$1.79.10^{-5}$	$1.46.10^{-5}$	$2.869.10^2$	1.4
Carbon dioxide (20 ºC)	1.83	$1.80.10^1$	$1.47.10^{-5}$	$8.03.10^{-6}$	$1.889.10^2$	1.30
Helium (20 ºC)	$1.66.10^{-1}$	1.63	$1.94.10^{-5}$	$1.15.10^{-4}$	$2.077.10^3$	1.60
Hydrogen (20 ºC)	$8.38.10^{-2}$	$8.22.10^{-1}$	$8.84.10^{-6}$	$1.05.10^{-4}$	$4.124.10^3$	1.41
Methane (natural gas) (20 ºC)	$6.67.10^{-1}$	6.54	$1.10.10^{-5}$	$1.65.10^{-5}$	$5.183.10^2$	1.31
Nitrogen (20 ºC)	1.16	$1.14.10^1$	$1.76.10^{-5}$	$1.52.10^{-5}$	$2.968.10^2$	1.40
Oxygen (20 ºC)	1.33	$1.30.10^1$	$2.04.10^{-5}$	$1.53.10^{-5}$	$2.598.10^2$	1.40

*: Values of the gas constant are independent of temperature. **: Values of the specific heat ratio depend only slightly on temperature

2.2. Density of Ideal Gases

Gases are highly compressible in comparison to liquids, with changes in gas density directly related to changes in pressure and temperature through the equation

$$\rho = \frac{P}{RT} \ \text{ or } \ P = \rho RT \text{ or } P\forall = mRT \text{ or } Pv = RT$$

Where; P is the absolute pressure, ρ is the density, *T is* the absolute temperature, υ is the specific volume, m is the mass, and *R* is a gas constant.

The above equation is commonly termed the ***ideal*** or *perfect **gas law,*** or the ***equation of state*** for an ideal gas.

The gas constant R is different for each gas and is determined from $R = R_u/M$, where *Ru* is the ***universal gas constant*** whose value is *Ru* = 8314 kJ/kmol · K. *M* is the molar mass (also called *molecular weight*) of the gas. The values of *R* and *M* for several substances are given in Table 2.3.

The pressure in the ideal gas law must be expressed as an ***absolute pressure,*** denoted (abs), which means that it is measured relative to absolute zero pressure (a pressure that would only occur in a perfect vacuum).

Standard sea-level atmospheric pressure (by international agreement) is 101.33 kPa (abs) or 101.325 kPa (abs). For most calculations these pressures can be rounded to 101 kPa, respectively.

In engineering it is common practice to measure pressure relative to the local atmospheric pressure, and when measured in this fashion it is called ***gage pressure.*** Thus, the absolute pressure can be obtained from the gage pressure by adding the value of the atmospheric pressure.

Table 2.3. Molar mass, gas constant, and ideal-gas specific heats of some substances

Substance	Molar Mass M, kg/kmol	Gas Constant R, kJ/kg · K*	Specific Heat Data at 25°C		
			c_p, kJ/kg · K	c_v, kJ/kg · K	$k = c_p/c_v$
Air	28.97	0.2870	1.005	0.7180	1.400
Ammonia, NH_3	17.03	0.4882	2.093	1.605	1.304
Argon, Ar	39.95	0.2081	0.5203	0.3122	1.667
Bromine, Br_2	159.81	0.05202	0.2253	0.1732	1.300
Isobutane, C_4H_{10}	58.12	0.1430	1.663	1.520	1.094
n-Butane, C_4H_{10}	58.12	0.1430	1.694	1.551	1.092
Carbon dioxide, CO_2	44.01	0.1889	0.8439	0.6550	1.288
Carbon monoxide, CO	28.01	0.2968	1.039	0.7417	1.400
Chlorine, Cl_2	70.905	0.1173	0.4781	0.3608	1.325
Chlorodifluoromethane (R-22), $CHClF_2$	86.47	0.09615	0.6496	0.5535	1.174
Ethane, C_2H_6	30.070	0.2765	1.744	1.468	1.188
Ethylene, C_2H_4	28.054	0.2964	1.527	1.231	1.241
Fluorine, F_2	38.00	0.2187	0.8237	0.6050	1.362
Helium, He	4.003	2.077	5.193	3.116	1.667
n-Heptane, C_7H_{16}	100.20	0.08297	1.649	1.566	1.053
n-Hexane, C_6H_{14}	86.18	0.09647	1.654	1.558	1.062
Hydrogen, H_2	2.016	4.124	14.30	10.18	1.405
Krypton, Kr	83.80	0.09921	0.2480	0.1488	1.667
Methane, CH_4	16.04	0.5182	2.226	1.708	1.303
Neon, Ne	20.183	0.4119	1.030	0.6180	1.667
Nitrogen, N_2	28.01	0.2968	1.040	0.7429	1.400
Nitric oxide, NO	30.006	0.2771	0.9992	0.7221	1.384
Nitrogen dioxide, NO_2	46.006	0.1889	0.8060	0.6171	1.306
Oxygen, O_2	32.00	0.2598	0.9180	0.6582	1.395
n-Pentane, C_5H_{12}	72.15	0.1152	1.664	1.549	1.074
Propane, C_3H_8	44.097	0.1885	1.669	1.480	1.127
Propylene, C_3H_6	42.08	0.1976	1.531	1.333	1.148
Steam, H_2O	18.015	0.4615	1.865	1.403	1.329
Sulfur dioxide, SO_2	64.06	0.1298	0.6228	0.4930	1.263
Tetrachloromethane, CCl_4	153.82	0.05405	0.5415	0.4875	1.111
Tetrafluoroethane (R-134a), $C_2H_2F_4$	102.03	0.08149	0.8334	0.7519	1.108
Trifluoroethane (R-143a), $C_2H_3F_3$	84.04	0.09893	0.9291	0.8302	1.119
Xenon, Xe	131.30	0.06332	0.1583	0.09499	1.667

* The unit kJ/kg · K is equivalent to kPa · m³/kg · K. The gas constant is calculated from $R = Ru/M$, where $Ru = 8.31447$ kJ/kmol · K is the universal gas constant and M is the molar mass.

Example: Determine the density, specific gravity, and mass of the air in a room whose dimensions are $2 \times 3 \times 4 \, m$ at 110 kPa and 25 °C (Fig.).
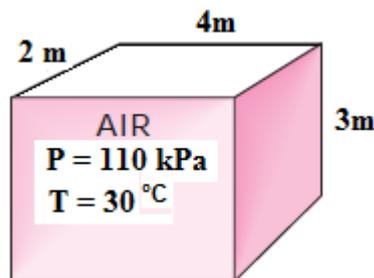
Solution: At specified conditions, air can be treated as an ideal gas. The gas constant of air is $R = 286.9$ kJ/kg K.

$$\rho = \frac{P}{RT} = \frac{110\,000\, Pa}{286.9\frac{kJ}{kgK} \times 303\, K} = 1.265 \, kg/m^3$$

The specific gravity of air becomes

$$SG = \frac{\rho}{\rho_{H_2O \ at \ 4 \ °C}} = \frac{1.265}{1000} = 0.001265$$

Finally, the volume and the mass of air are
$$\forall = 2{\times}3{\times}4 = 24 \ m^3 \quad m = \rho\forall = 1.265{\times}24 = 30.36 \ kg$$

2.3. Vapor Pressure

The temperature and pressure are dependent properties for pure substances during phase-change processes, and there is one-to-one correspondence between temperatures and pressures.

Vapor pressure or **equilibrium vapour pressure** is defined as the pressure exerted by a vapor in thermodynamic equilibrium with its condensed phases (solid or liquid) at a given temperature in a closed system. The equilibrium vapor pressure is an indication of a liquid's evaporation rate. It relates to the tendency of particles to escape from the liquid (or a solid)

At a given pressure, the temperature at which a pure substance changes phase is called the **saturation temperature, *T*sat**. Likewise, at a given temperature, the pressure at which a pure substance changes phase is called the **saturation pressure, *P*sat**.

At an absolute pressure of 1 standard atmosphere (1 atm or 101.325 kPa), for example, the saturation temperature of water is 100°C. Conversely, at a temperature of 100°C, the saturation pressure of water is 1 atm.

The **vapor pressure *Pv*** of a pure substance is defined as *the pressure exerted by its vapor in phase equilibrium with its liquid at a given temperature. Pv* is a property of the pure substance, and turns out to be identical to the saturation pressure *P*sat of the liquid (*Pv* " *P*sat). Saturation (or vapor) pressure of water at various temperatures are given in Table 2.4.

We must be careful not to confuse vapor pressure with *partial pressure*. **Partial pressure** is defined as *the pressure of a gas or vapor in a mixture with other gases*. The rate of evaporation from open water bodies such as lakes is controlled by the difference between the vapor pressure and the partial pressure.

For example, the vapor pressure of water at 20°C is 2.34 kPa. Therefore, a bucket of water at 20°C left in a room with dry air at 1 atm will continue evaporating

until one of two things happens: the water evaporates away (there is not enough water to establish phase equilibrium in the room), or the evaporation stops when the partial pressure of the water vapor in the room rises to 2.34 kPa at which point phase equilibrium is established.

Table 2.4. Saturation (or vapor) pressure of water at various temperatures

Temperature T, °C	Saturation Pressure P_{sat}, kPa
−10	0.260
−5	0.403
0	0.611
5	0.872
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3 (1 atm)
150	475.8
200	1554
250	3973
300	8581

Boiling, which is the formation of vapor bubbles within a fluid mass, is initiated when the absolute pressure in the fluid reaches the vapor pressure.

A *liquid boils when the pressure is reduced to the vapor pressure*. An important reason for our interest in vapor pressure and boiling lies in the common observation that in flowing fluids it is possible to develop very low pressure due to the fluid motion, and if the pressure is lowered to the vapor pressure, boiling will occur. For example, this phenomenon may occur in flow through the irregular, narrowed passages of a valve or pump. When vapor bubbles are formed in a flowing fluid, they are swept along into regions of higher pressure where they suddenly collapse with sufficient intensity to actually cause structural damage. The formation and subsequent collapse of vapor bubbles in a flowing fluid, called *cavitation,* is an important fluid flow phenomenon.