CHAPTER 2

BASIC LAWS AND PRINCIPLES

FLUID PROPERTIES

Force

A force is a push or a pull, or more generally anything that can change an object's speed or direction of motion. The International System of Units (SI) unit used to measure force is the Newton (symbol N).

$$F = ma$$

where F stands for force in Newton, m stands for mass in Kg and a represents acceleration expressed as meters divided by seconds squared m/s^2.

Pressure

Pressure is the ratio of force to the area over which the force acts.

Mathematically, it can be expressed as:

$$p = \frac{F}{A}$$

where p is pressure, F is force, and A represents area. Pressure is usually expressed in Newton per square meter, given the name Pascal, and traditionally, it was expressed in pounds force per square inch (PSI).

Atmospheric Pressure

Atmospheric pressure is defined as the pressure due to the weight of the atmosphere (air and water vapor) on the earth's surface. Atmospheric pressure is determined by a mercury column barometer, that is why it is sometimes called as barometric pressure. The average atmospheric pressure at sea level has been defined as 1.01325 bars, or 14.696 pounds per square inch absolute (PSIA).

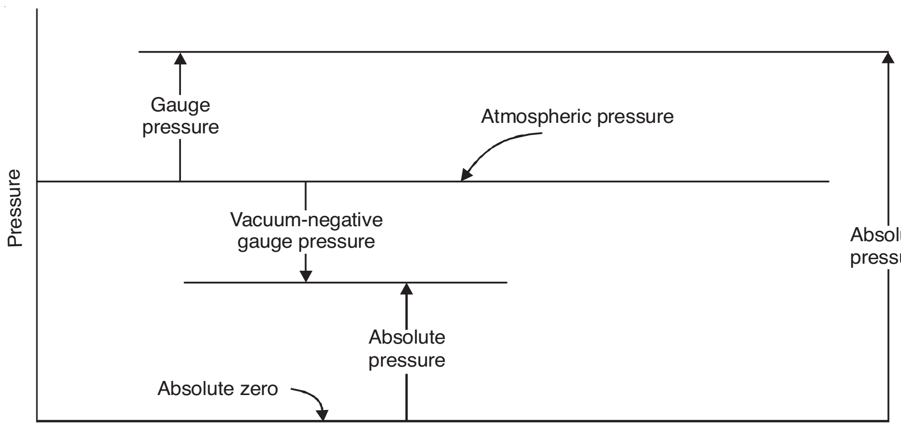


FIGURE 2.1 Pressure Relationship.

Absolute Pressure

Absolute pressure can be given as gauge pressure plus barometric or atmospheric pressure. Absolute pressure is referenced against absolute zero pressure, or a complete vacuum. The units of absolute pressure are followed by suffix "a," such as psia. If we hold an absolute pressure instrument in the open air, the reading should be well above zero, in the range of 14.7 to 12 psia.

Gauge and Vacuum Pressure

Gauge pressure is referenced against the atmospheric pressure at the measurement point. The units of gauge pressure are followed by a "g," such as psig. A gauge pressure instrument should always read zero when exposed to atmospheric pressure. Similarly, when the pressure falls below atmospheric, it is called vacuum pressure, sometimes it is also called negative gauge pressure.

Based upon the above discussions, the following equations can be derived:

$$P_{abs} = P_{atm} + P_{gauge}$$

$$P_{abs} = P_{atm} - P_{vacuum}$$

Where P_{abs} = Absolute pressure

P_{atm} = Atmospheric pressure

P_{gauge} = Gauge pressure

P_{vacuum} = Vacuum pressure (– ve gauge pressure).

Conversion of various units of pressure in Pascal

Unit	*Symbol*	*No. of pascals*
Bar	bar	1×10^5 Pa
Millibar	mbar	100 Pa
Hectopascal	hPa	100 Pa
conventional mm of Hg	mmHg	133.322 Pa
conventional inch of Hg	in Hg	3,386.39… Pa
Torr	torr	101325/760 ≈ 133.322 Pa
pound-force per square inch	lbf/in^2	6,894.76 ≈ 6895 Pa

Pascal's Law

Blaise Pascal formulated this basic law in the mid-17th century. His law states that pressure in a confined fluid is transmitted undiminished in every direction and acts with equal force on equal areas and at right angles to container walls. Hydraulic brakes, lifts, presses, syringe pistons, etc. work on the principle of Pascal's law.

According to Pascal's law, inside the pipes of a confined system pressure is uniform at all points. Mathematically,

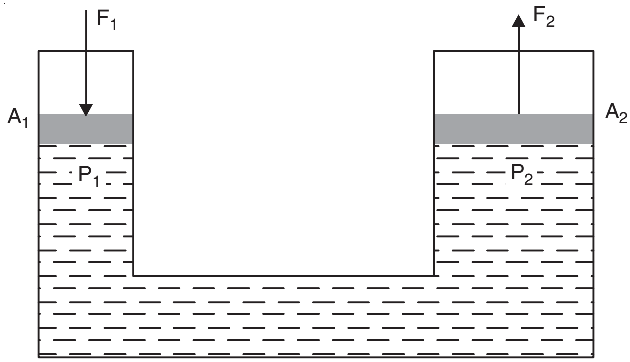


FIGURE 2.2 Pascal's Law Illustrated.

$$\frac{F_1}{A_1} = P_1 = P_2 = \frac{F_2}{A_2}$$

$$F_2 = \frac{A_2}{A_1} \cdot F_1$$

From the above expression, $P_1 = P_2$, therefore F_2 is greater than F_1 because A_2 is greater than A_1. This means that, in order to obtain a greater output force, it is enough to have suitably sized surfaces available.

Flow and Flow Rate

The volume of a substance passing a point per unit time is called flow and the volume of water, a pump or a compressor can move during a given amount of time is called, "flow rate."

Volumetric Flow Rate

It is the volume of the fluid flowing through a cross section per unit time. Air related flows are usually expressed in cubic feet per minute (CFM) and for liquid-based fluids, they are expressed as liters or gallons per minute (LPM or GPM) or cubic meters per second, etc.

$$\text{Volumetric Flow Rate} = \text{Area} \times \text{Velocity}$$

Mass Flow Rate

Volumetric flow rate times density, i.e., pounds per hour or kilograms per minute.

$$\text{Mass Flow Rate} = \text{Area} \times \text{Velocity} \times \text{Density}$$

Conversion of various flow rate units into m^3/s

Unit	*Symbol*	*No. of m^3/s*
Liters/second	l/s	10^{-3} m^3/s
Gallons/second	gps	0.003788 m^3/s
cubic feet/min	cfm	4.719×10^{-4} m^3/s

Bernoulli's Equation

It states that, for a non-viscous, incompressible fluid in steady flow, the sum of pressure, potential, and kinetic energies per unit volume is constant at any point. Mathematically, it can be expressed as:

$$\frac{\rho \cdot v_1^2}{2} + p_1 = \frac{\rho \cdot v_2^2}{2} + p_2 = \text{Constant}$$

Where

$$g = \text{gravity}$$
$$v = \text{flow speed}$$
$$h = \text{height}$$
$$p = \text{pressure}$$
$$\rho = \text{density}$$

Bernoulli's principle states that in fluid flow, an increase in velocity occurs simultaneously with a decrease in pressure. It is named for the Dutch/Swiss mathematician/scientist Daniel Bernoulli; this phenomenon can be seen in airplane lift, a carburetor, the flow of air around the ball, etc.

Venturi Effect

A fluid passing through smoothly varying constrictions is subject to changes in velocity and pressure, as described by Bernoulli's principle. In case of fluid or airflow through a tube or pipe with a constriction in it, the fluid must speed up in the restriction, reducing its pressure, and producing a partial vacuum.

As shown in the Fig. 2.3 fluid density = (ρ), area = (A), and velocity = (V). Let the properties of fluid at entrance and exit be (ρ_1,A_1,V_1) and at constriction be (ρ_2, A_2 ,V_2). There is a drop in pressure at the constriction as shown by the height of the column and it is due to conservation of energy. The fluid experiences a gain in kinetic energy and a drop in pressure as it enters the constriction; this effect is called *Venturi effect, it is named after the Italian physicist Giovanni Battista Venturi*.

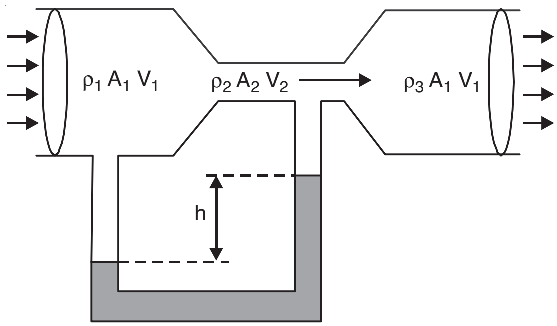
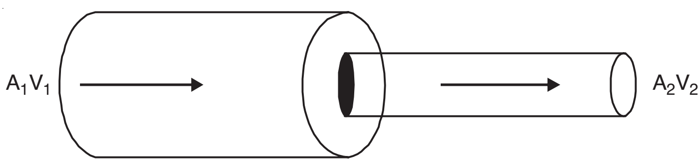


FIGURE 2.3 Venturi's Law Illustrated.

Continuity Equation

It is simply a mathematical expression of the principle of conservation of mass. Mass is neither created nor destroyed. For a steady flow, it states that:

$$\text{Mass flow rate in} = \text{mass flow rate out}$$
$$\rho_1\ A_1\ V_1 = \rho_2\ A_2\ V_2\ (\rho_1 = \rho_2)$$
$$A_1\ V_1 = A_2\ V_2$$



The "continuity equation" is a direct consequence of the rather trivial fact that what goes into the pipe must come out. This has the important consequence that as the area of the hole decreases, the velocity of the fluid must increase, in order to keep the flow rate constant.

Specific Weight, Density, and Specific Gravity

(a) *Specific Weight or Weight Density*

The weight per unit volume of a substance. Usually it is expressed in N/m^3 or lbs/ft^3. Mathematically,

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

Where

$$\rho = \text{density}(\text{N/m}^3)$$
$$w = \text{weight}(\text{N})$$
$$V = \text{volume}(\text{m}^3)$$

(b) Density

Density is defined as the ratio of the mass of an object to its volume; usually it is expressed in kg/m^3 or g/cm^3. Mathematically,

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

Where

$$\rho = \text{density}(\text{kg/m}^3)$$
$$m = \text{weight}(\text{kg})$$
$$V = \text{volume}(\text{m}^3)$$

(c) Specific Gravity

The ratio of the density (or specific weight) of a substance to the density (or specific weight) of a standard fluid is called *Specific gravity* or *Relative density*. The usual standard of comparison for solids and liquids is water at 4°C at atmospheric pressure. Gases are commonly compared to dry air, under standard conditions (0°C and atmospheric pressure).

Specific gravity is not expressed in *units*, as it is purely a ratio. Mathematically,

$$SG = \frac{m_0}{V \times \rho_{H_2O}}$$

Where

$$SG = \text{specific gravity}$$
$$m_0 = \text{mass weight of oil to be compared(kg)}$$
$$V = \text{volume of oil}(\text{m}^3)$$
$$\rho_{H_2O} = \text{density of water}(1000\ \text{kg/m}^3)$$

Compressibility and Bulk Modulus

Compressibility is the measure of change in volume of substance when pressure is exerted on it. Liquids are incompressible fluids. For each atmosphere increase in pressure, the volume of water would decrease 46.4 parts per million. The hydraulic brake systems used in most cars operate on the principle that there is essentially no change in the volume of the brake fluid when pressure is applied to this liquid.

On the other hand, the volume of the gases can be readily changed by exerting an external pressure on the gas. An internal combustion engine provides a good example of the ease with which gases can be compressed.

The compressibility is the reciprocal of the bulk modulus. Compressibility is denoted by "k" and is expressed mathematically as:

$$k = \frac{1}{b}$$

Where B is called the bulks modulus of elasticity and is defined as the ratio of change in pressure to volumetric strain (change in volume/original volume) over a fluid element. It is expressed as follows:

$$\mathrm{B} = -\frac{dP}{\mathrm{V}_{\mathrm{change}}/\mathrm{V}_{\mathrm{initial}}}$$

Where

$$\mathrm{B} = \text{Bulks modulus}$$

$$\mathrm{V}_{\mathrm{initial}} = \text{Original volume before application of force.}$$

$$\mathrm{V}_{\mathrm{change}} = \text{Net change in volume after the application of force.}$$

$-$Ve sign indicates that volume decreasesas pressure increases.

Viscosity and Viscosity Index

Viscosity is the measure of the internal friction of a fluid or its resistance to flow. A hydraulic fluid that is too viscous usually causes high-pressure drop, sluggish operation, low-mechanical efficiency, and high-power consumption. Low-viscosity fluids permit efficient low-drag operation, but tend to increase wear, reduce volumetric efficiency, and promote leakage.

Viscosity index is an arbitrary scale, which indicates how the viscosity of a fluid varies with changes in temperature. The higher the viscosity index, the lower the viscosity changes with respect to temperature and vice versa. Ideally, the fluid should have the same viscosity at very low temperatures as well as at high temperatures. In reality, this cannot be achieved. This change is common to all fluids. Heating tend to make fluids thinner and cooling makes them thicker.

Gas Laws

(a) Boyle's Law

English scientist Robert Boyle investigated the relationship between the volume of a dry ideal gas and its pressure. It states that at constant temperature, the pressure is inversely proportional to the volume of a definite amount of gas. Mathematically,

$$P_1V_1 = P_2V_2$$

therefore $PV = C$

Where
P_1 = Initial Pressure
V_1 = Initial Volume
P_2 = Final Pressure
V_2 = Final Volume.

(b) Charle's Law

French scientist Jacques Charles experimented with gas under constant pressure and his observations have been formalized into Charle's law.

The volume of a gas at constant pressure is directly proportional to the absolute temperature. Mathematically, it can be expressed as:

$$V_1 / T_1 = V_2 / T_2$$

therefore $V / T = C$

Where
V_1 = Initial Volume
T_1 = Initial Temperature
T_1 = Final Volume
T_2 = Final Temperature.

(c) Gay-Lussac's Law

French scientist Joseph Gay-Lussac investigated the relationship between the pressure of a gas and its temperature. It states that the pressure of a gas at constant volume is directly proportional to the absolute temperature. The mathematical statement is as follows:

$$P_1 / T_1 = P_2 / T_2$$

therefore $\quad P / T = C$

Where $\quad P_1 = \text{Initial Pressure}$

$T_1 = \text{Initial Temperature}$

$P_2 = \text{Final Pressure}$

$T_2 = \text{Final Temperature.}$

(d) Combined Gas Laws

Any two of the three gas laws of Boyle, Charles, or Gay-Lussac can be combined, hence the name, combined gas law. In short, this combined gas law is used when it is difficult to keep either the temperature or pressure constant:

$$P_1 V_1 T_2 = P_2 V_2 T_1$$

This relationship can be used to predict pressure, volume, and temperature relationships where any five of the six variables are known.

Moisture in the Air

(a) Humidity

Humidity is the concentration of water vapor in the air. The concentration can be expressed as *specific humidity*, *absolute humidity*, or *relative humidity*. A device used to measure humidity is called a *hygrometer*.

(i) *Specific humidity*. Is defined as mass of water vapor present per kg of dry air. It is expressed in g/kg of dry air. Humidity is measured by means of a hygrometer.

(ii) *Absolute humidity.* Is expressed as the mass of water vapor contained in a given volume of air. The hotter the air is, the more water it can contain. It may be measured in grams of vapor/cubic meter of air. Absolute humidity finds greatest application in ventilation and air-conditioning problems.

(iii) *Relative humidity.* Is defined as the ratio (usually expressed as a percentage) of the mass of water in a given volume of moist air divided by the maximum mass of water that can be held by that same volume of air (saturated air) at a given temperature. We can compare how much water vapor is present in the air to how much water vapor would be in the air if the air were saturated. A reading

of 100 percent relative humidity means that the air is totally saturated with water vapor and cannot hold any more.

Example: If 20 grams of water vapor were present in each m^3 of dry air, and the air would be saturated with 30 grams of water vapor per m^3 of dry air, the relative humidity would be 20/30 = 66.66%.

Practically, "relative humidity" is the amount of moisture in the air at a certain temperature. It is called "relative" because it is being compared to the maximum amount of moisture that could be in the air at the same temperature.

(b) Dew Point Temperature and Holding Capacity of Air

Air present at certain temperatures could consume a certain quantity of water in it, likewise when this temperature is attained, air becomes completely saturated. If the air is further cooled then water will start condensing out of it. Dew point is the temperature at which water vapor begins to condense out of the air. Dew points can be defined and specified for ambient air or for compressed air. Dew point normally occurs when a mass of air has a relative humidity of 100%. This temperature can be recorded by a thermometer.

(c) Atmospheric Dew Point

Atmospheric dew point is the value of the temperature at which moisture present in the air begins to condense at atmospheric pressure, *i.e.*, at 1.01325 bar. Atmospheric dew point is not at all important for pneumatics, as pressure is always more than atmospheric pressure in a pneumatic line.

(d) Pressure Dew Point

Pressure dew point is the value of the temperature at which moisture present in the air begins to condense at pressures more than the atmospheric pressure. As pressures encountered in pneumatics are generally more than atmospheric so it is of great importance. Obviously, at higher pressures, the water present in air condenses at higher temperatures in comparison to atmospheric pressure, so dew point should be kept very low so as to ensure the least amount of moisture in the pneumatic line (as moisture is the biggest enemy in pneumatics).

Energy, Work, and Power

Energy is the ability to do work and is expressed in foot pound (ft lb) or Newton meter (Nm). The three forms of energy are potential, kinetic, and heat. Work measures accomplishments; it requires motion to make a force do work. Power is the rate of doing work or the rate of energy transfer.

Potential Energy

Potential energy is energy due to position. An object has potential energy in proportion to its vertical distance above the earth's surface. For example, water held back by a dam represents potential energy because until it is released, the water does not work. In hydraulics, potential energy is a static factor. When force is applied to a confined liquid, potential energy is present because of the static pressure of the liquid. Potential energy of a moving liquid can be reduced by the heat energy released. Potential energy can also be reduced in a moving liquid when it transforms into kinetic energy. A moving liquid can, therefore, perform work as a result of its static pressure and its momentum.

Kinetic Energy

Kinetic energy is the energy a body possesses because of its motion. The greater the speed, the greater the kinetic energy. When water is released from a dam, it rushes out at a high velocity jet, representing energy of motion—kinetic energy. The amount of kinetic energy in a moving liquid is directly proportional to the square of its velocity. Pressure caused by kinetic energy may be called *velocity pressure*.

Heat Energy and Friction

Heat energy is the energy a body possesses because of its heat. Kinetic energy and heat energy are dynamic factors. Pascal's Law dealt with static pressure and did not include the friction factor. Friction is the resistance to relative motion between two bodies. When liquid flows in a hydraulic circuit, friction produces heat. This causes some of the kinetic energy to be lost in the form of heat energy. Although friction cannot be eliminated entirely, it can be controlled to some extent. The three main causes of excessive friction in hydraulic systems are:

(i) Extremely long lines.

(ii) Numerous bends and fittings or improper bends.

(iii) Excessive velocity from using undersized lines.

EXERCISES

1. What are the differences between a liquid and a gas?
2. What do you mean by pressure dew point? Does it have any importance in pneumatics?
3. State the importance of gas laws.
4. Define the terms specific weight, density, and specific gravity.
5. What is the effect of temperature on viscosity of fluids?
6. State continuity equation.
7. Differentiate between the terms viscosity and viscosity index.
8. What is the difference between pressure and force?
9. Explain venturi effect. Give the name of important pneumatic equipment, which uses this principle.
10. State Bernoulli's equation.
11. What is meant by the term bulk modulus?
12. State and prove Pascal's law.
13. What is the relationship between atmospheric, absolute, and vacuum pressure?
14. Differentiate between absolute and relative humidity.