

Hydraulic Fundamentals

Hydraulics is the branch of engineering sciences concerned with the transmission of energy, using incompressible fluids. Hydraulic systems conventionally involve the generation of pressures and development and control of huge forces, through an enclosed incompressible fluid media.

Hydraulics – Definition

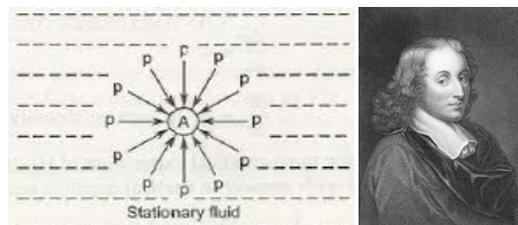
Hydraulics may be defined as the science of transmitting force and/or motion through the medium of pressurized fluid to power/control machines. Study of hydraulics is all about knowing how to produce a definite pressure by using force and the reverse process of how to develop and control load by using the pressure.

Advent of Oil Hydraulics

Initially, water was used as the medium of energy transfer in industrial hydraulic systems. It has the main advantage of fire-resistance. However, it has low lubricity and narrow range of working temperatures. Petroleum-based oils, developed in the late nineteenth century, were found to be highly incompressible and capable of operating at high pressures. As the advantages of petroleum oils were so overwhelming, system designers started using them for industrial hydraulic systems. That marked the beginning of 'Industrial Hydraulics'/'Oil Hydraulics'.

Pascal's Law

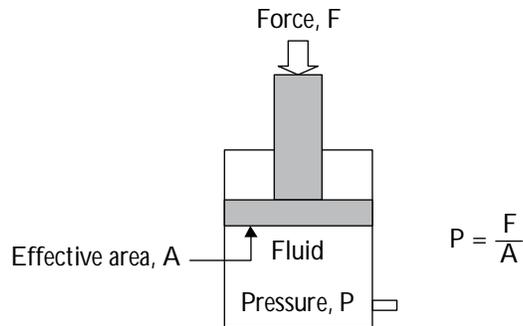
'Pressure at any one point in a static fluid is the same in every direction' and 'Pressure exerted on a confined fluid is transmitted equally in all directions, acting with equal force on equal areas'.



The applications could use fluid as a means to multiply the power. Pascal's law is central to the development of a number of devices, such as hydraulic brakes, hydraulic presses, and hydraulic jacks.

Pressure

Pressure is the result of the resistance offered to compression when the application of force squeezes an incompressible fluid medium. The term 'pressure' is the force acting per unit area.



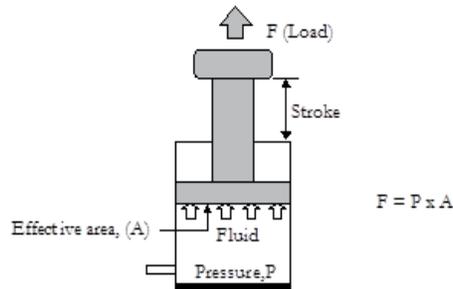
Pressure - Units

1 Pascal = 1 N/m²

1 bar = 100000 Pa (10⁵ Pa / 0.1 MPa)

1 bar = 14.5 psi

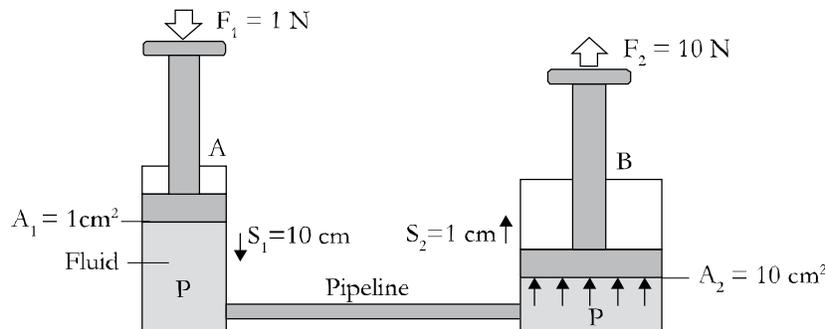
Hydraulic Force



When the pressure (P) is applied to the area (A) of the piston, it develops a force (F). -> $F = P \times A$

Force Multiplication

A hydraulic system can be designed with a positive and rigid transmission medium for force multiplication.



$$F_2 = F_1 \times \left(\frac{A_2}{A_1}\right) = F_1 \times \text{Mechanical advantage}$$

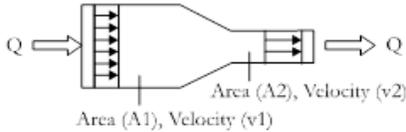
Flow Rate

Volumetric flow rate is a measure of the volume of the liquid passing a cross-section per unit of time. It is usually measured in lpm or in gpm or in other units. It decides the speed of hydraulic actuators.

Velocity of Flow

Velocity of fluid flow is the average speed at which its particles move past a given cross section.

Flow Rate Vs Velocity of Flow



$$\text{Flow rate (Q,m}^3\text{/s)} = \text{Area (A,m}^2\text{)} \times \text{Velocity (v,m/s)}$$

For a constant flow rate (Q), the velocity (v) of the fluid passing through the narrow section increases.

Laminar Flow

Fluid flow is said to be laminar if the viscosity forces dominate. The flow tends to be laminar with low fluid velocities or high fluid viscosities. All the particles of the fluid move parallel to each other, and a particle in a given layer remains in that layer. Heat loss from friction is minimal in laminar flow. If the speed increases beyond a given point, turbulent flow develops.

Turbulent Flow

Fluid flow is said to be turbulent when the inertia forces dominate. The flow tends to be turbulent with high fluid velocities or low fluid viscosities. When the flow velocity goes beyond a critical value, particles in the fluid collide and develop cross currents. The result of the turbulent flow is a significant increase in friction, flow resistance, pressure drop, and energy loss, as compared to the case of laminar flow. An important objective of the hydraulic system is to avoid turbulent flow and keep friction to a minimum.

Reynolds Number (R_e)

Osborn Reynolds (1842–1912) conducted a series of pioneering works for determining the governing condition regarding the transition of fluid flow from the laminar state to the turbulent state.

$$R_e = \frac{v D \rho}{\mu} = \frac{v D}{\nu}$$

v = Fluid velocity (m/s), D = Internal diameter of the pipe (m), ρ = Fluid density (kg/m^3), μ = Absolute viscosity (Pa·s or $\text{N}\cdot\text{s/m}^2$), ν = Kinematic viscosity (m^2/s)

The number 2000 is the decisive value of the Reynolds number for marking a borderline between the laminar flow and the turbulent flow. Experiments have demonstrated that for Reynolds number below 2000, the flow is found to be laminar, and above 4000, the flow is found to be turbulent. The Reynolds number regime between 2000 and 4000 can be considered as the critical zone.

Viscosity

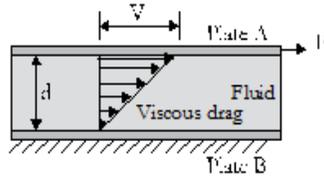
It is a measure of the internal resistance to flow. Low viscosity fluids, such as water and alcohol, flow quickly. High viscosity fluids, such as molasses and cold honey, pour slowly. Two viewpoints of viscosity are well recognized:

- (1) Absolute viscosity
- (2) Kinematic viscosity

The property that represents the resistive movement of different layers of the fluid when subjected to a force is called its absolute viscosity (or dynamic viscosity). The property that describes the difficulty with which fluids move under the force of gravity is called as the kinematic viscosity.

Absolute Viscosity

A thin plate A of surface area 'a' is located at a distance 'd' from a stationary reference plate B. The plate A is subjected to a force 'F_d' and moves with the velocity 'v'. For small values of v and d, the velocity gradient of the particles of the fluid layers tends to be a straight line with a slope (v/d). The force F_d is proportional to area a and velocity v and inversely proportional to the distance d.



$$F_d \propto a \cdot v/d$$

$$F_d = \mu \cdot (av/d)$$

$$(F_d/a) = \mu \cdot (v/d)$$

$$\text{Absolute viscosity, } \mu = \frac{(F_d/a)}{(v/d)} = \frac{\text{Shear stress}}{\text{Shear rate}}$$

Units of Absolute Viscosity

- 1 poise = 1 dyne.s/cm²
- 1 poise = 0.1 Pa.s
- 1 cP = 0.01 Poise
- 1 Pa.s = 1 N.s/m²
- 1 Pa.s = 10 poise
- 1 Pa.s = 1000 cP

Kinematic viscosity (ν or nu)

Kinematic viscosity is the measure of a fluid's resistance to flow under gravity. Kinematic viscosity at a given temp is given by the absolute viscosity (μ) divided by the fluid density (ρ).

$$\text{Kinematic viscosity, } \nu = \frac{\mu}{\rho}$$

Units of Kinematic Viscosity

- 1 stoke = 1 cm²/s
- 1 cSt = 0.01 stoke
- 1 cSt = 1 mm²/s

In addition to the basic units of measuring kinematic viscosity, other units, such as Saybolt Universal Seconds, etc., are used for expressing the kinematic viscosities of fluids.

Saybolt Universal Seconds (SUS)

It is the time measured in seconds required for 60 ml of fluid to flow through the calibrated orifice of a Saybolt Universal viscometer at a specified temperature.

Viscometers

There are primarily two types of viscometers:

1. Glass capillary viscometers
2. Rotational viscometers

Kinematic viscosity is usually measured using glass capillary tube viscometers. The absolute viscosity is typically measured using Rotary viscometers.

Viscosity Classification Systems

The first standard for viscosity classification was developed by the Society of Automotive Engineers (SAE) in 1911. In 1975, the International Standards Organization (ISO), in unison with American Society for Testing and Materials (ASTM) etc., settled upon an approach to establish a viscosity measurement method. It is known as the International Standards Organization Viscosity Grade, ISO VG for short, as per the ISO standard 3448:1992. ISO VG classification consists of a series of 20 different viscosity grades. Some of the Viscosity Grades are as follows: 2, 3, 5, 7, 10, 15, 22, 32, 46, 68, 100, 150, 220, 320, 460, 680, 1000, 1500.

Viscosity: Effect of Variation in Temperature

The viscosity of fluids can change appreciably with a change in their temperature. Fluids have higher viscosity when they are cold and lower viscosity when they are hot. The change in viscosity with temperature is measured with an arbitrary measure called Viscosity Index (VI). Fluid having a low VI exhibits a large change in viscosity with temperature change. High VI fluid has relatively stable viscosity, which does not change appreciably with temperature change.

Compressibility and Bulk Modulus

Hydraulic fluids exhibit some degree of compressibility as a result of increase in pressure. The compressibility is the degree to which the fluid undergoes a reduction in volume under increased pressure. Compressibility is the reciprocal of bulk modulus.

$$B = - \Delta P / (\Delta V / V)$$

B is the bulk modulus, in bar [psi], ΔP is the differential pressure, in bar [psi], ΔV the differential volume change, in m^3 [in^3], V the original volume of the fluid, in m^3 [in^3]

The bulk modulus of a newly purchased hydraulic fluid is typically about 17000 bar, [250000 psi]

Advantages of Hydraulic Systems

- **High power density:** Hydraulic systems transmit energy at high power-to-weight ratios. That is; high forces (torques) can be developed in hydraulic systems with comparatively compact actuators without the need for gearboxes.
- **Simple force multiplication:** In a hydraulic system, a large force can be controlled easily with a small force.
- **Oily fluid medium:** As a lubricant, the fluid reduces the friction in the components of a hydraulic system, which helps in prolonging the life of the system components.
- **Heat dissipation:** The movement of the fluid through a hydraulic system helps to draw heat away from 'hot spots' in the system.

- **Accurate control:** The direction of motion, speed, and force/torque of hydraulic actuators can easily and accurately be controlled by using components, such as discrete valves, proportional valves, and servo valves.
- **Overload protection:** Pressure relief valves protect hydraulic systems against overloading.
- **Electronic Interface:** Hydraulic systems can be readily interfaced with microprocessor-based controllers. A hydraulic actuator can be configured with electronic sensors to provide digital or analog feedback for sensing its position, direction, and speed.

Disadvantages of Hydraulic Systems

- **Energy level:** Hydraulic systems are high-pressure, high-power systems that require a careful design with all safety precautions.
- **Contamination Control:** Hydraulic systems need effective control of contamination as they are sensitive to the effects of dirt, moisture, and corrosion.
- **Wear:** The components used in hydraulic systems tend to wear, as they are subjected to high forces or torques.
- **Temperature Dependence:** The working of hydraulic systems in extreme temperature conditions deteriorates their performance.
- **Leakage:** A hydraulic system tends to leak because of the defects in its seals. The leakage pollutes the environment besides making the surroundings a mess.
- **Noise:** The excessive noise generated by hydraulic systems can have a disturbing effect on the workforce.
- **Fire Hazard:** There is a risk of fire in a hydraulic system with the mineral-based fluid medium if the leakage of the fluid occurs in the vicinity of a hot environment.
- **Line Burst:** The bursting of hydraulic lines under high pressures can cause injuries to personnel due to high-speed oil jets.
- **Maintenance:** Precision parts of hydraulic systems require good maintenance, as they are exposed to extreme climates and dirty atmospheres. The fluid media used in these systems also require good filtration to maintain their quality.
- **Waste disposal:** The disposal of used hydraulic fluids is problematic and costly.

Reference: JOJI PARAMBATH, **Industrial Hydraulic Systems – Theory and Practice**, Universal Publishers, Boca Raton, USA, 2016. Please visit: <http://www.universal-publishers.com/book.php?method=ISBN&book=1627340580>

Note: A comprehensive account of the topic is given in the textbook on 'Industrial Hydraulic Systems-Theory and Practice' by Joji Parambath.