MENG2520 Pneumatics and Hydraulics

Module 2 – Hydraulic Fluids

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Hydraulic Fluids

This is the beginning of the study of Hydraulic Fluid Power

In this Module we will study

-Physical properties of Hydraulic Fluids

-Energy and Power in a Hydraulic System

-Pascal, Bernoulli and Torricelli Equations

2.1 Physical Properties of Fluids

The <u>single most important</u> material in a hydraulic system is the working fluid itself.

https://www.powertransmissionworld.com/hydraulic-fluids-risks-of-fire-and-toxicity/

A hydraulic fluid has the following 4 primary functions:

1. Transmit power
2. Lubricate moving parts
3. Seal clearances between mating parts
4. Dissipate heat

Hydraulic fluid characteristics have a crucial effect on equipment performance and life.

It is important to use a clean, high-quality fluid in order to achieve efficient hydraulic system operation.

Most modern hydraulic fluids are complex compounds which include special additives to provide desired characteristics

2.1 Physical Properties of Fluids

Desirable properties of a hydraulic fluid, not all of which may be optimized for a given application

1. Good lubricity
2. Ideal viscosity
3. Chemical stability
4. Compatibility with system materials
5. High degree of incompressibility
6. Fire resistance
7. Good heat-transfer capability
8. Low density
9. Foam resistance
10. Nontoxicity
11. Low volatility

2.3 Mass, Weight and Density

Mass is the amount of matter in an object, measured in slugs

Weight is the Force created by the earth's gravity on that mass, measure in lbs

Force = Weight = Mass x Gravity

$F = W = m \times g$

$F(lbs) = W(lbs) = m(slugs) \times g(\frac{ft}{s^2})$, at sea level gravity g=32.2 ft/s^2 (9.8 m/s^2)

Density is the mass per unit volume, measure in slugs/ft^3

$$\rho = \frac{m\ (slugs)}{V\ (ft^3)}$$

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2.3 Specific Weight, and Specific Gravity

Specific Weight is the weight per unit volume

$$\gamma = \frac{W\ (lb)}{V\ (ft^3)}$$

Specific Weight is related to density through $\rho = \frac{\gamma}{g}$

Specific Gravity is the ratio of a Specific Weight to water

$$SG = \frac{\gamma}{\gamma_{water}} \text{ where } \gamma_{water} = 62.4\ lb/ft^3$$

This can be expressed as a ratio of density using the relationship $\rho = \frac{\gamma}{g}$

$$SG = \frac{\rho}{\rho_{water}}$$

A typical hydraulic oil has a specific weight of 55 to 58 lb/ft^3 thus a SG < 1

2.4 Force and Pressure

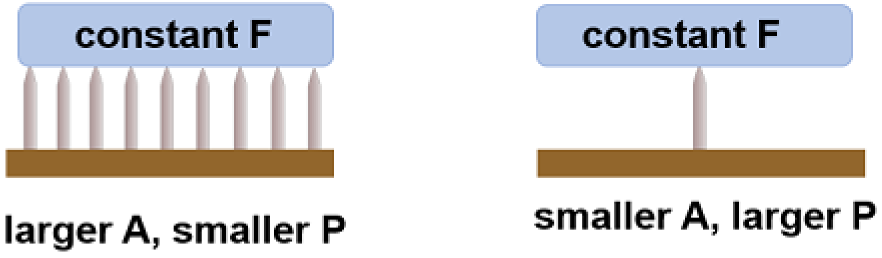
Force and Pressure are interrelated

Pressure is defined as force per unit area.

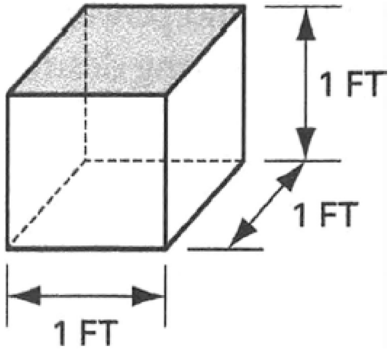
$$pressure\left(\frac{lbs}{in^2}\right) = \frac{Force(lbs)}{Area(in^2)}$$

$$p(psi) = \frac{F}{A}$$

$\left(\frac{lbs}{in^2}\right)$ is “pounds per square inch” = psi



2.4 Force and Pressure



Example: What is the pressure on the bottom surface of this square vat if filled with water?

Solution: use $p(psi) = \frac{F}{A}$

1. Find force $F = m \times g = W$

   F=force (lb)

   m=mass (slug)

   g=gravity (ft/s^2)

   W=weight (lb)

   We can use the specific weight $\gamma = \frac{W\ (lb)}{V\ (ft^3)}$ for water $\gamma = 62.4$ lb/ft^3 to find W

$$W = \gamma \times V$$

$$W = 62.4 \frac{lb}{ft^3} \times 1ft^3$$

$$W = F = 62.4\ lb$$

2. Find pressure $p = \frac{F}{A}$

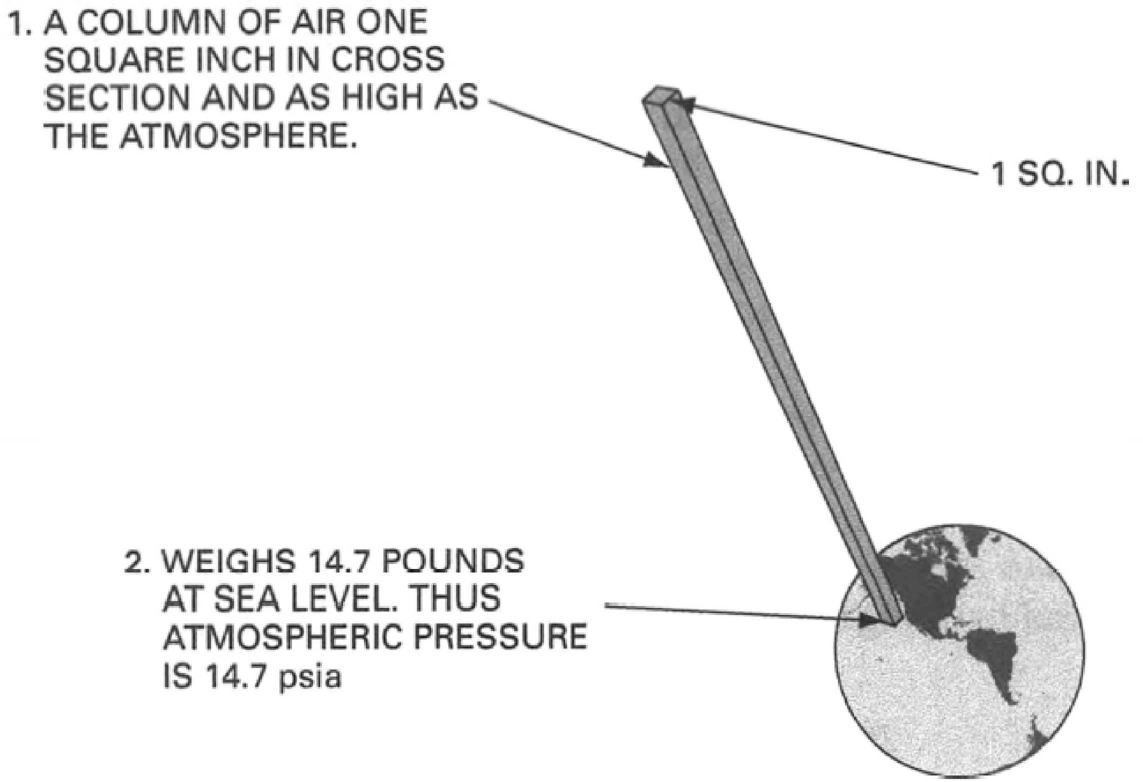
$$p(psi) = \frac{62.4\ lb}{1ft^2 \times 144 \frac{in^2}{ft^2}}$$

$$p(psi) = 0.433 \frac{lb}{in^2} = 0.433 psi$$

Otherwise known as
<u>Pressure head</u>, or just <u>head</u>.

2.4 Atmospheric Pressure

Standard Atmospheric pressure at sea level is 14.7 psi resulting from a pressure head of air reaching the edge of space

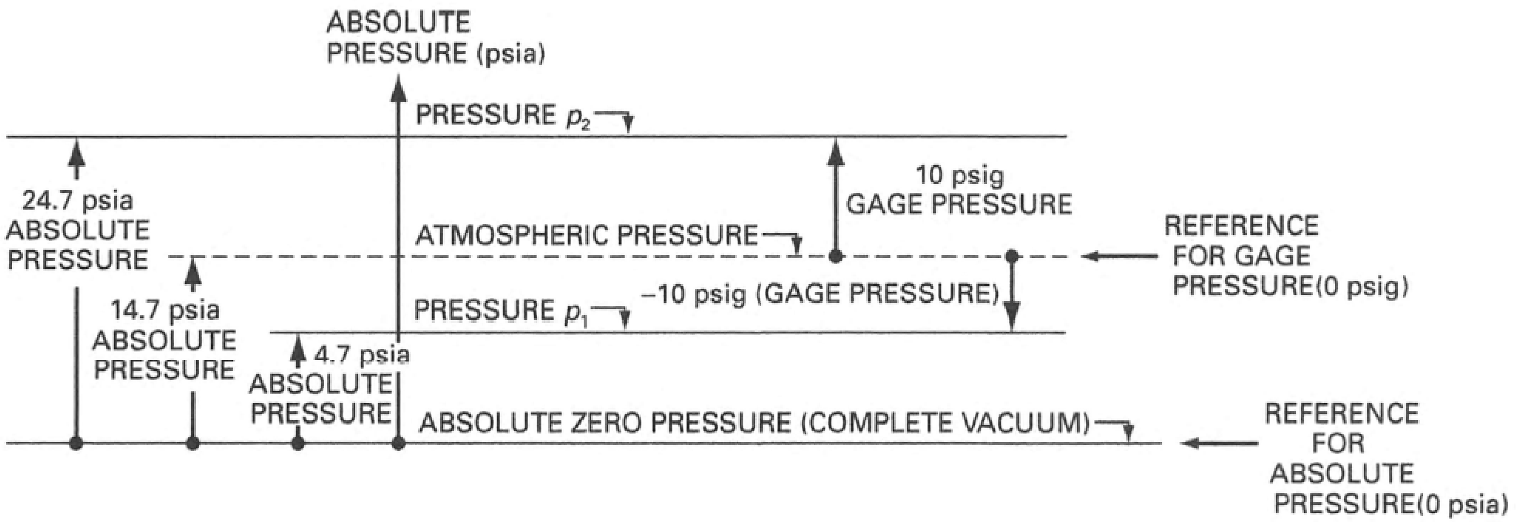


2.4 Gauge and Absolute Pressure

Pressure gauges measure the pressure of a vessel *relative* to atmospheric pressure

Absolute pressure = gauge pressure + atmospheric pressure

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



Note that is most relevant when dealing with pneumatic systems, because p_{atm} of 14.7 psi is negligible when dealing with hydraulic system pressures in hundreds and even thousands of psi

2.6 Bulk Modulus

Bulk Modulus is a measure of the compressibility of a fluid, or the stiffness of the hydraulic system

$$\beta = \frac{-\Delta p}{\frac{\Delta V}{V}}$$

β = bulk modulus (psi)
Δp= change is pressure (psi)
ΔV= change in volume (in^3)
V= original volume (in^3)

The bulk modulus for typical oil is very high, ~250 kpsi, making it a great fluid for high power-to-weight ratio performance and stiffness, whereas air is highly compressible.

2.7 Viscosity

Viscosity is the measure of the fluids resistance to flow
It is one of the most important characteristics of a hydraulic fluid to consider

A low viscous fluid will have a thin appearance and will flow freely
A high viscous fluid will have a thick appearance and flows with difficulty

A low viscous fluid A high viscous fluid

2.7 Viscosity

The ideal viscosity for a given hydraulic system is a compromise.

Too high a viscosity results in

1. High resistance to flow, which causes sluggish operation.
2. Increased power consumption due to frictional losses.
3. Increased pressure drop through valves and lines.
4. High temperatures caused by friction.

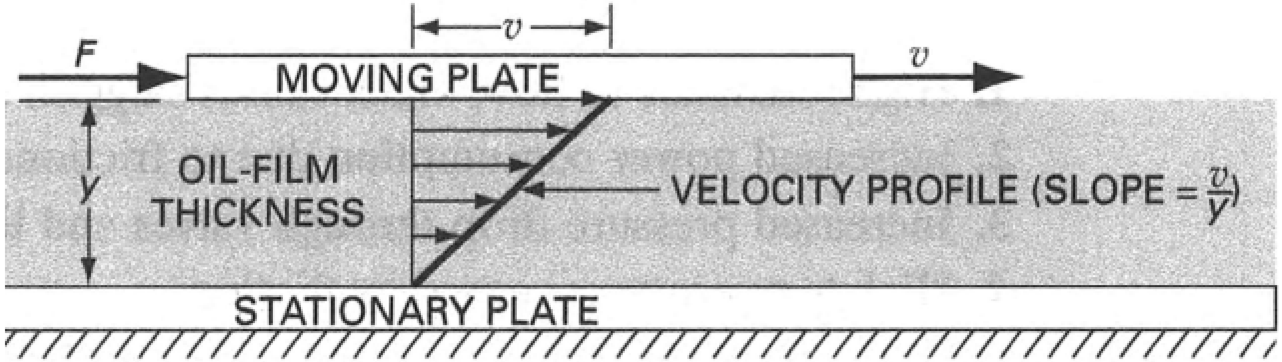
Too low a viscosity results in

1. Increased oil leakage past seals.
2. Excessive wear of moving parts due to lack of sufficient lubrication
   e.g. pump parts, DCV spools, cylinders

2.7 Viscosity

Absolute Viscosity is a measure of the amount of force required to move a plate, at a unit velocity, relative to a parallel stationary plate, separated by a fluid.

$$\mu = \frac{\tau}{v/y} = \frac{F/A}{v/y} = \frac{\text{shear stress in oil}}{\text{slope of velocity profile}}$$



μ = absolute viscosity (lb·s/ft^2)
τ = the shear stress in the fluid in units of force per unit area (lb/ft^2)
v= velocity of the moving plate (ft/s);
γ= oil film thickness (ft);
μ= the absolute viscosity of the oil;
F = force applied to the moving upper plate (lb);
A = area of the moving plate surface in contact with the oil (ft$_2$).

2.7 Viscosity

Absolute Viscosity (Dynamic Viscosity) is measured in metric units centiPoise (*cP*)

$$\mu = \frac{\text{dyn/cm}^2}{(\text{cm/s})/\text{cm}} = \text{dyn} \cdot \text{s/cm}^2$$

dyne is the force that will accelerate a 1-g mass at a rate of 1 cm/s^2 (1 dyn = 10^{-5}N)

1 dyn . s/cm^2 is called a poise, and typically expressed as a centi-poise, or cP

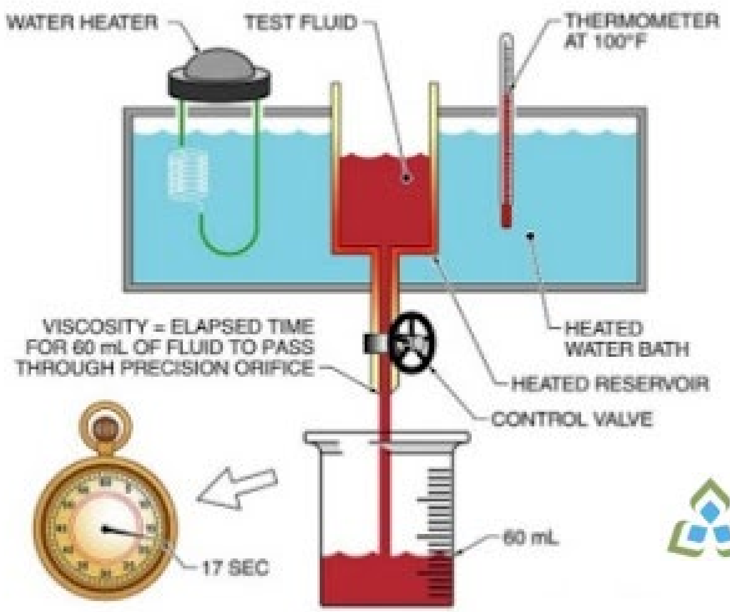
2.7 Viscosity

Kinematic Viscosity is a measure of the absolute viscosity relative to the density, in the metric system units centistoke (cSt)

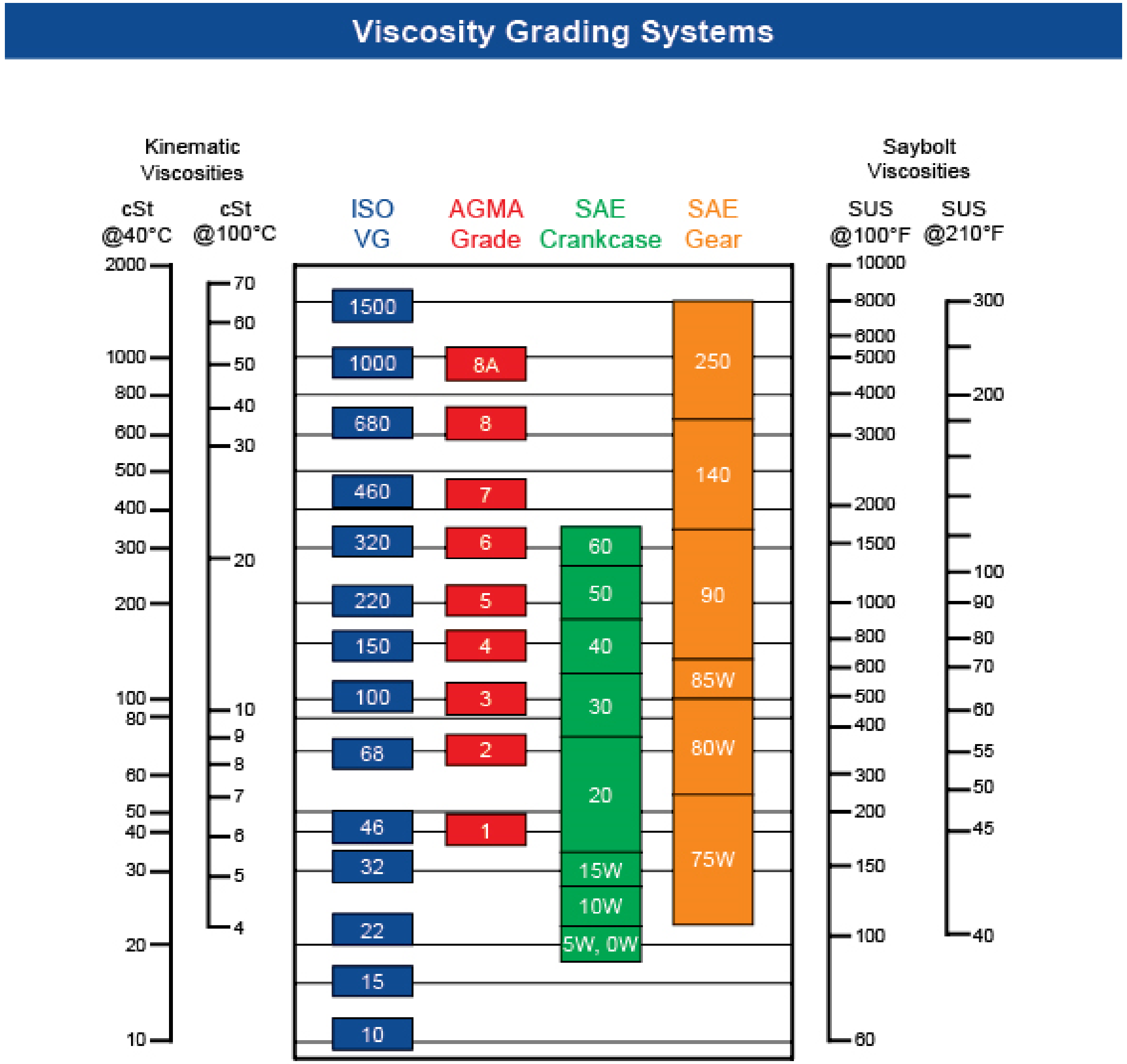
$$\nu = \frac{\mu}{\rho}$$

A viscosity of 1 cm^2/s is called a stoke, S, or expressed as cS (centi-stoke)

Relative Viscosity is a measure of time to flow a given quantity of oil through a standard orifice measured in Saybolt Unit Seconds (SUS)



2.7 Viscosity



ISO VG 15	typically used in power steering and hydraulic brake systems.
ISO VG 22	generally used in air lines for air tools.
ISO VG 32	ideal for use in high-powered machine tools.
ISO VG 46	normally required for industrial plant working under high-pressure.
ISO VG 68	designed for use in systems which require a large load-carrying ability.
ISO VG 100	used in industrial machinery with heavy loads.

https://www.mobilehydraulictips.com/wp-content/uploads/2015/02/Viscosity-Chart.jpg

2.7 Viscosity

Viscosity Index is a relative measure of an oil’s viscosity change with respect to temperature change.

The higher this number, the more stable the oil's viscosity with varying temperature

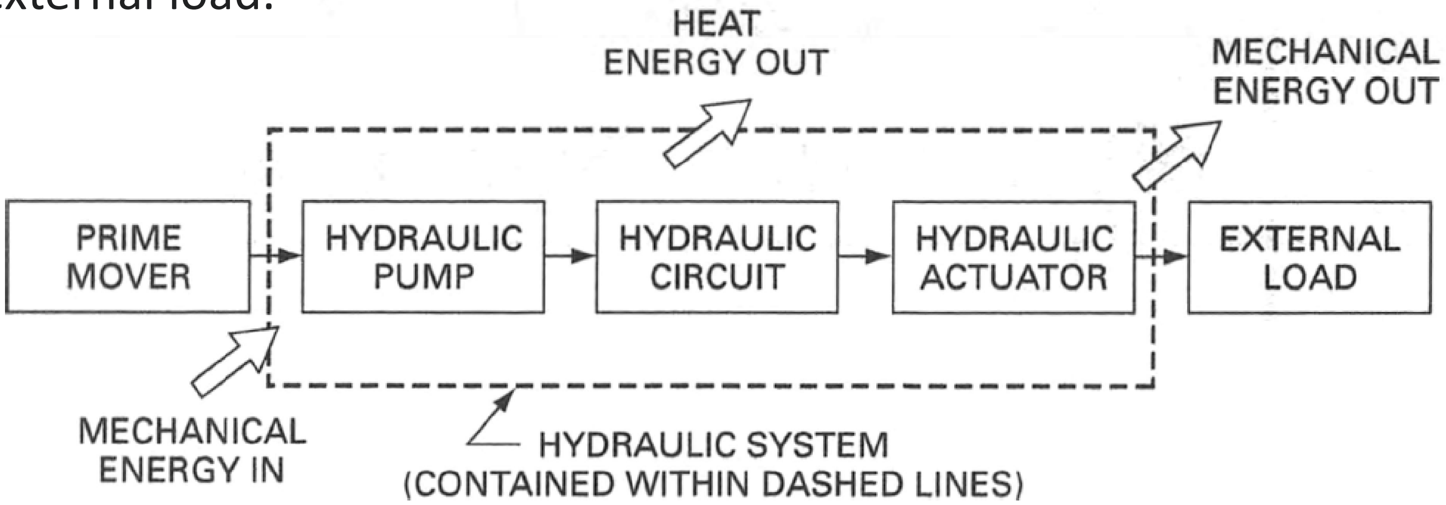
V.I. was originally devised on a scale from 0 to 100, but research and development in this field resulted in some liquids with a V.I much more than 100 due to additives

V.I is an important property to consider in systems with large variations in temperatures, such as outside mobile equipment

https://www.shearpowercorp.com/hydraulic-excavators.html

3.1 Energy and Power in a Hydraulic System

A hydraulic system works by converting and transferring an input energy source from the prime mover to an external load.



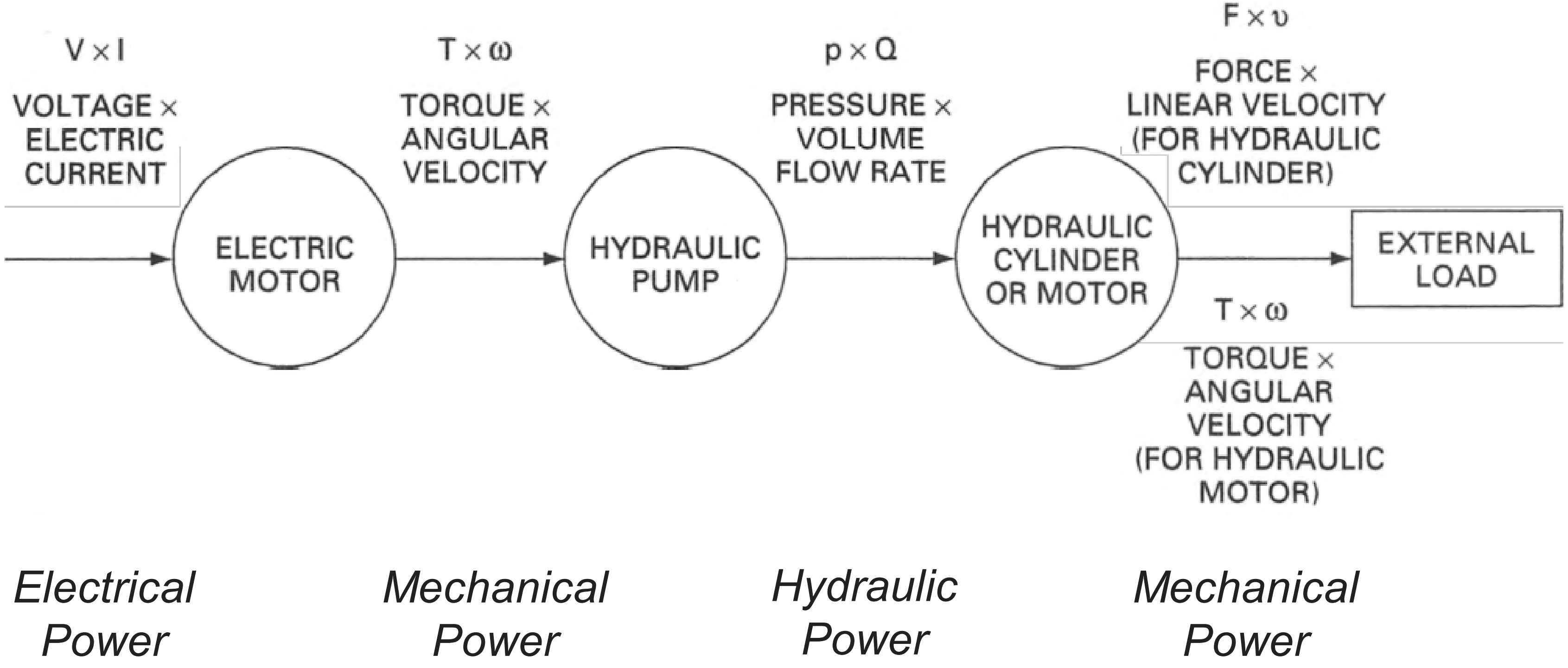
The system will have frictional losses (heat) of moving fluids and other parts

Input ME – Lost HE = Output ME

ME = mechanical energy

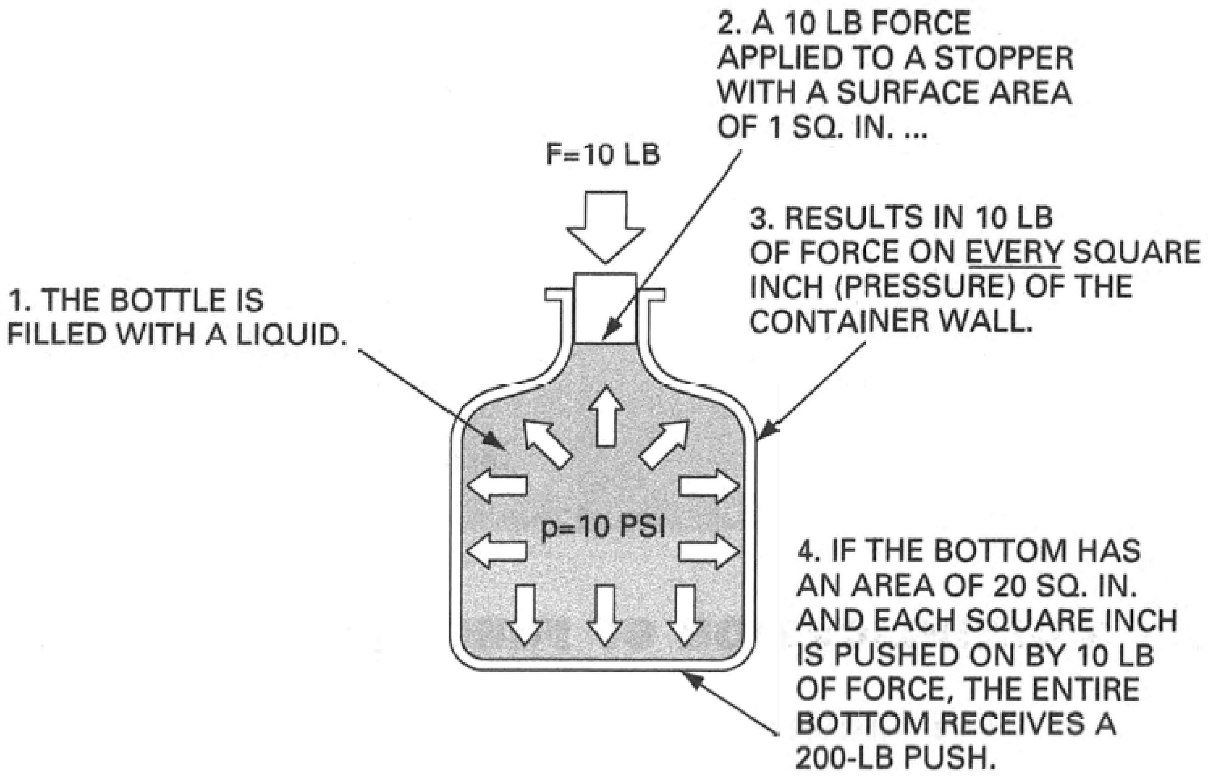
HE = hydraulic energy

3.1 Energy and Power in a Hydraulic System



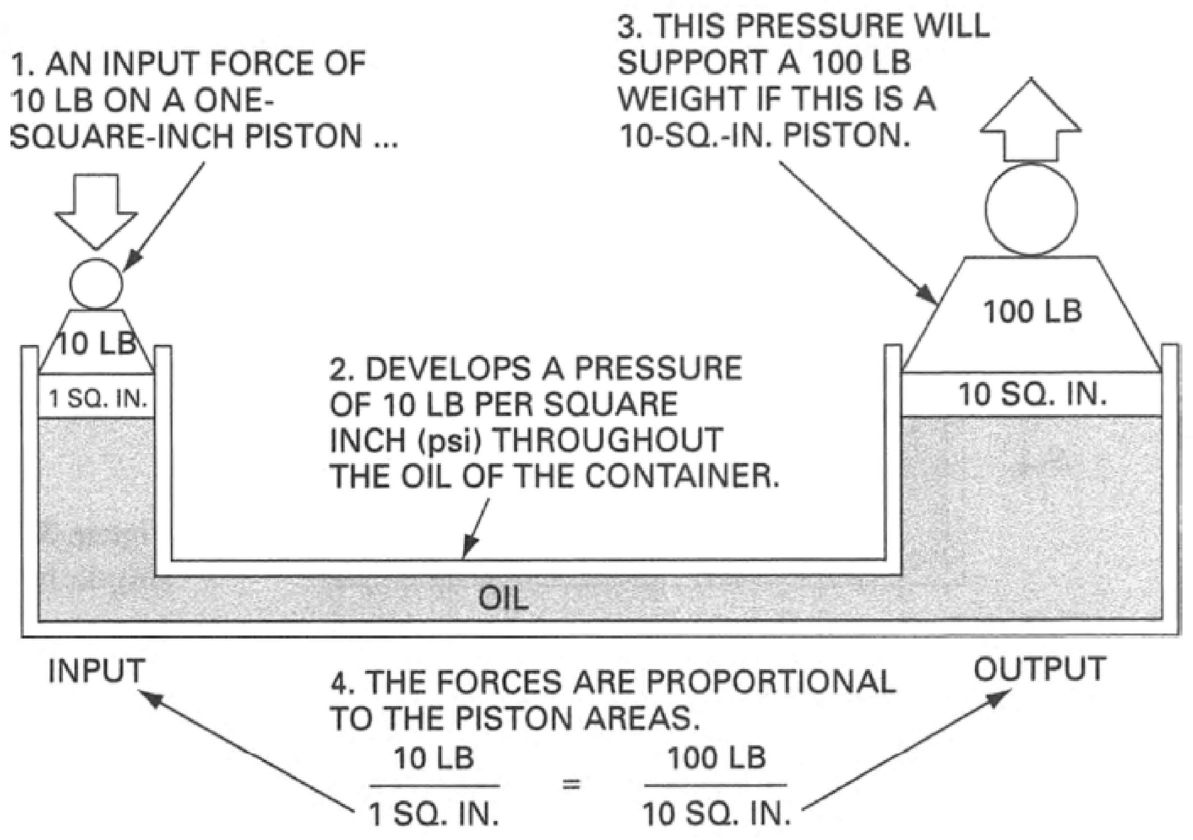
3.3 Pascal's Law

Pascal's Law: *Pressure applied to a confined fluid is transmitted undiminished in all directions throughout the fluid and acts perpendicular to the surfaces in contact with the fluid.*



3.3 Pascal's Law

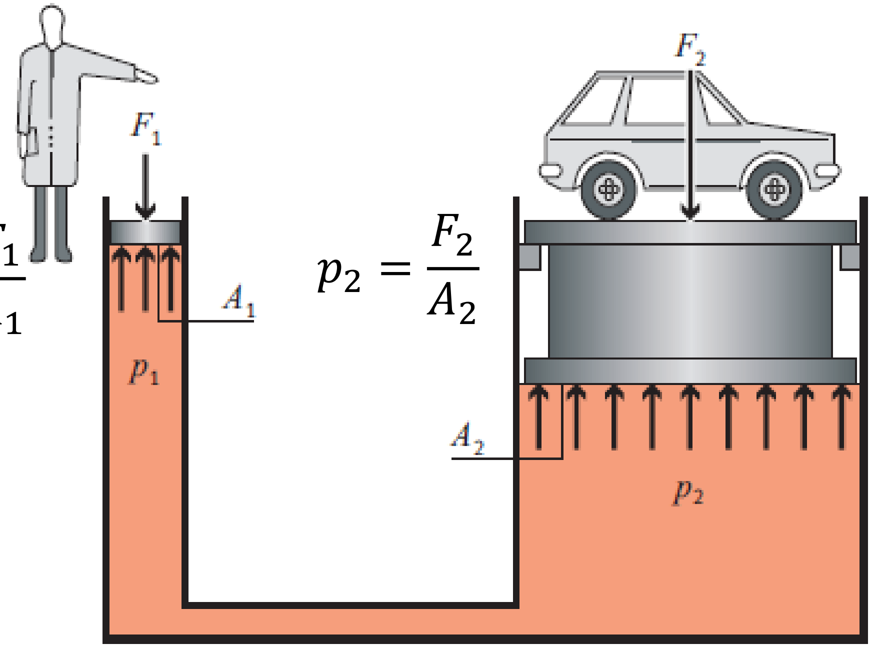
Pascal's Law applied to a simple hydraulic jack



3.3 Pascal's Law

A force F_1 exerted on surface one
is transferred through the *fluid* resulting in
a force F_2 exerted on surface two

$$p_1 = \frac{F_1}{A_1}$$



$$p_2 = \frac{F_2}{A_2}$$

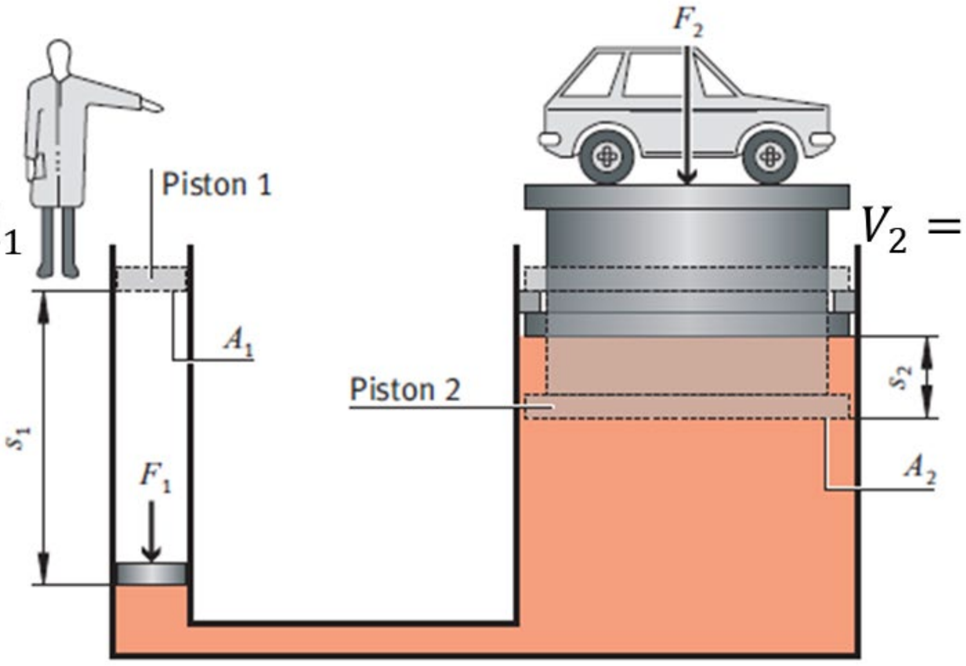
Pressure everywhere in a closed vessel is the same
so p_1=p_2 and therefore

Since A_2>A_1 then F_2>F_1 which means the system results in force multiplier

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

3.3 Pascal's Law

$V_1 = s_1 \times A_1$



$V_2 = s_2 \times A_2$

The volume V displaced is the same so $V_1 = V_2$ and therefore

Since $A_2 > A_1$ then $s_2 < s_1$ which means the system's <u>output displacement is less than the input</u>

$$s_2 = \frac{s_1 \times A_1}{A_2}$$

Work in = work out
Work = force x distance

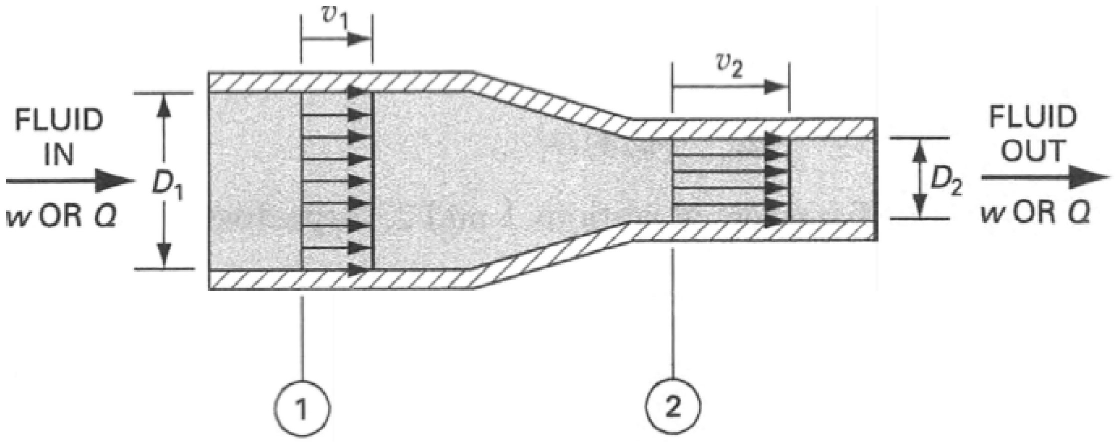
$$F_1 \times S_1 = F_2 \times S_2$$

But in reality, there are looses

3.7 Continuity Equation

The continuity equation states that for steady flow in a pipeline, the flow rate (amount of fluid passing a given station per unit time) is the same for all locations of the pipe.

$$Q_1 = A_1 v_1 = A_2 v_2 = Q_2$$



Where
Q = volume flow rate in ft^3/s
A = cross sectional area in ft^2
v = velocity in ft/s

Or: $$\frac{v_1}{v_2} = \left(\frac{D_2}{D_1}\right)^2$$

Conversion:
$Q(ft^3/s) = Q(gpm) / 449$

3.8 Hydraulic Power

Hydraulic Horsepower (HHP) is the measure of the power delivered by a hydraulic system to do work, such as move a cylinder connected to a load

HHP is the fluid pressure $\times$ flow rate

$$\text{HHP} = \frac{p(\text{psi}) \times Q(\text{gpm})}{1714} \qquad \text{Recalling that } 1 \text{ hp} = 550 \text{ ft} \cdot \text{lb/s}$$

p is determined by the load the cylinder is required to move

Q is determined by knowing the stroke length and speed required for the cylinder.

With HHP determined for a given system, the hydraulic pump can then be selected to provide this require HHP

3.9 Bernoulli's Equations

Bernoulli's Equation states that the total energy per pound of fluid at station 1 equals the total energy per pound of fluid at station 2

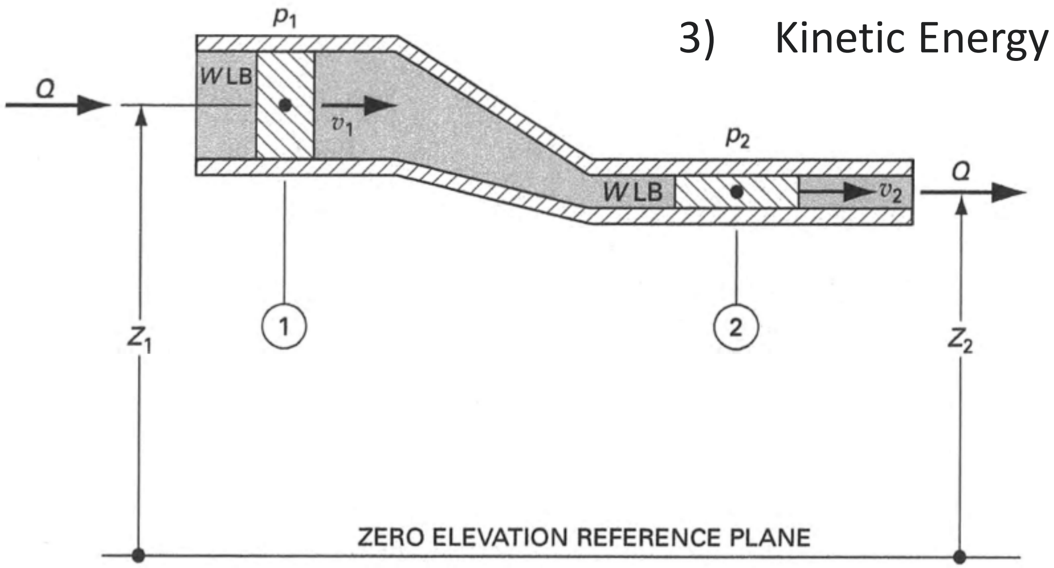
The Total Energy (E_T) of a chunk of fluid is the sum of

1) Potential energy due to elevation EPE
2) Potential energy due to pressure PPE
3) Kinetic Energy

$$EPE = WZ$$

$$PPE = W\frac{p}{\gamma}$$

$$KE = \frac{1}{2}\frac{W}{g}v^2$$



$$WZ_1 + W\frac{p_1}{\gamma} + \frac{Wv_1^2}{2g} = WZ_2 + W\frac{p_2}{\gamma} + \frac{Wv_2^2}{2g}$$

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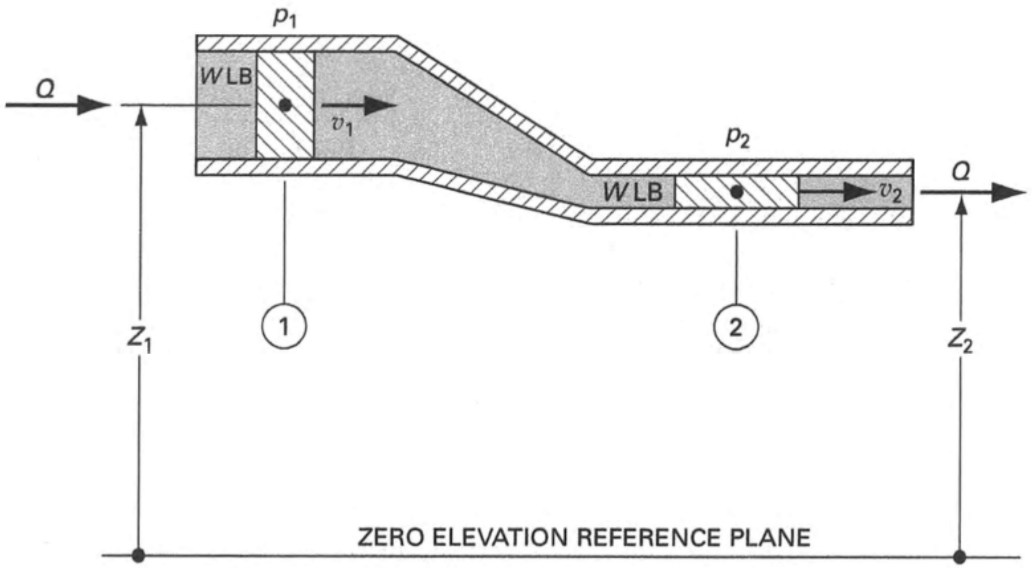
3.9 Bernoulli's Equations

Since the weight of the fluid does not change (assuming no lost fluids) the Bernoulli's Equation simplifies to

$$Z_1 + \frac{p_1}{\gamma} + \frac{v_1^2}{2g} = Z_2 + \frac{p_2}{\gamma} + \frac{v_2^2}{2g}$$

Each term of this equation has a unit of length (ft) and can be referred to as *head*



Z_1 *Elevation head*

$\frac{p_1}{\gamma}$ *Pressure head*

$\frac{v_1^2}{2g}$ *Velocity head*

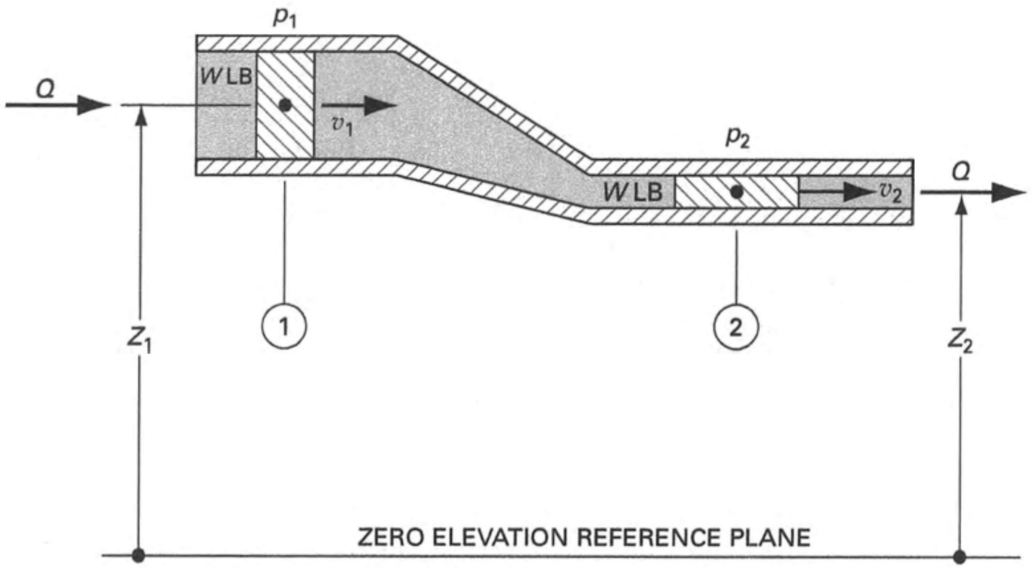
3.9 Bernoulli's Equations

The equation can be further expanded to consider additional gains and losses in the system

H_L represents frictional losses (or head loss)
H_P represents pump head, additional energy added to the system with a pump
H_m represents motor head, energy loss due to a hydraulic motor

This final equation is known as the *Energy Equation* states

The total energy possessed by a 1-lb chunk of fluid at station 1 plus the energy added to it by a pump minus the energy removed from it by a hydraulic motor minus the energy it loses due to friction, equals the total energy possessed by the 1-lb chunk of fluid when it arrives at station 2.



$$Z_1 + \frac{p_1}{\gamma} + \frac{v_1^2}{2g} + H_p - H_m - H_L = Z_2 + \frac{p_2}{\gamma} + \frac{v_2^2}{2g}$$

3.9 Bernoulli's Equations

The equation can be further expanded to consider additional gains and losses in the system

H_L represents frictional losses (or head loss)

Determined based upon a number of factors which may impede the flow of the oil (Reference Ch4)

- -length and size of pipe
- -roughness of type
- -type of flow: laminar or turbulent
- -effect of fittings and valves

H_P represents pump head, additional energy added to the system with a pump

Determined by the HHP equation with a substitution of $p = \gamma H$

$$H_p(\text{ft}) = \frac{3950 \times (\text{HHP})}{Q(\text{gpm}) \times \text{SG}}$$

H_m represents motor head, energy loss due to a hydraulic motor

Determined using the same method as H_p

3.9 Bernoulli's Equations

At Station 1:

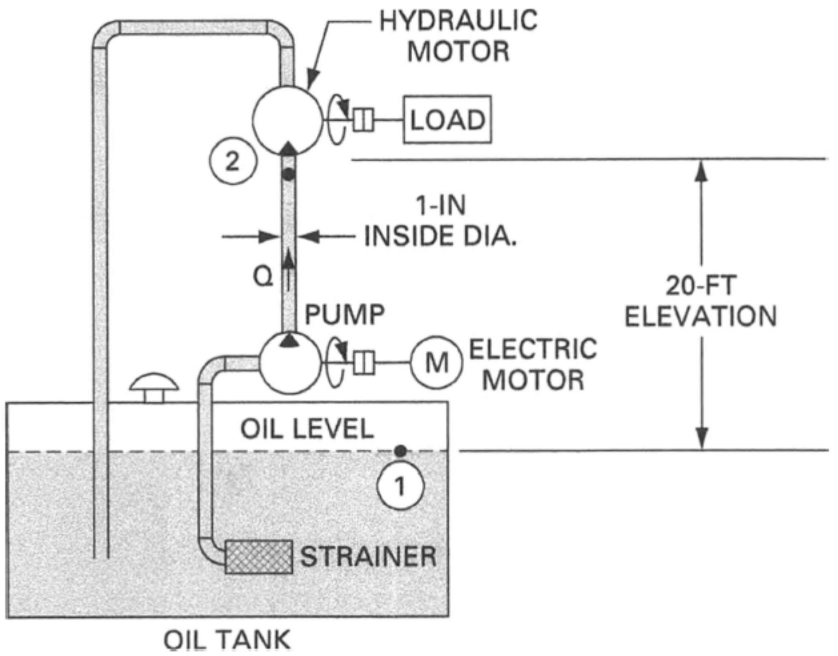
Elevation Head = 0 ft, this is the reference oil height
Pressure Head = 0 ft, the oil is at atmospheric pressure, p_1=0 psi
Velocity Head = 0 ft, the velocity of the bulk oil in the tank is negligibly small, v_1=0 ft/sec

At Station 2:

Elevation Head = the height of Station 2 above Station 1
Pressure Head = the contribution resulting from the pressurized oil
Velocity Head = the contribution from the moving oil

Pump Head = contribution of pump
Motor Head = 0 ft, pump is outside of Station 1-2 range
Friction Head = losses due to piping and fittings

$$Z_1 + \frac{p_1}{\gamma} + \frac{v_1^2}{2g} + H_p - H_m - H_L = Z_2 + \frac{p_2}{\gamma} + \frac{v_2^2}{2g}$$



Chapter Reading

Chapter 2

2.2, 2.5, 2.8, 2.9

Chapter 3

3.2, 3.4, 3.5, 3.6, 3.10, 3.11, 3.12