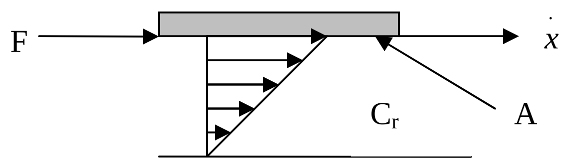
Chapter 3 Fluid Properties

The objective of this Chapter is to introduce you to some of the most important fluid properties that affect the performance of hydraulic circuits and to some of the equations that describe their behavior. We will not be going into great detail; if more information is required, we refer you to the many basic fluid mechanics text books that are published.

3.1 Viscosity:

Viscosity is a relative measure of the fluid's resistance to flow. If you have a very thick fluid, it is hard to "push" the fluid through a line or an orifice; its resistance is high and hence its viscosity is high. If you heat the thick fluid, it becomes thinner and easier to push through the lines; its resistance decreases and hence its viscosity drops. Thus, viscosity is a fluid property that we can readily visualize.



Assumption:
Newtonian Fluid where the viscosity is independent of the shear rate. If the fluid does depend on the shear rate, then it is called a non Newtonian fluid. These fluid pose problems because in regions of high shear rates (small passages or orifices, for example), the viscosity can change and not recover.

For a flat plate of bottom surface area A and separated by a film thickness, C_r, the force necessary to shear the fluid at some velocity $\dot{x}$ is given by :

$$F = \mu A \frac{\dot{x}}{C_r}$$

The constant of proportionality μ is called the **absolute viscosity** (or the dynamic viscosity).

Kinematic viscosity ν is the absolute viscosity divided by the fluid mass density.

$\nu = \mu / \rho$ where ρ is the fluid mass density

$$\nu = (dyne\,\sec/cm^2)/(g/cm^3) = poise/(g/cm^3) = stokes$$

$$\nu = (lb\,\sec/in^2)/((lb\,\sec^2/in)/in^3) = newts$$

Relative viscosity: units SUS (Staybolt Universal Seconds). It is the time (in seconds) for a standard quantity of a fluid (60cc) at a given head (pressure) to pass through a standard orifice (.176 cm dia. and 1.225 cm long). It is not linearly related to absolute or kinetic viscosity. Must use conversion charts which are readily available in fluid texts (ASTM Standards).

3.1.1 Units:

Absolute Viscosity

Metric	**English**
Poise (p) = 100 cp = 1dyn sec/cm^2 = 10^{-5} N sec/cm^2 = 10^{-1} N sec/m^2 = 10^{-1} Kg/m sec 1cp (centipoise) = 10^{-2} poise = 10^{-3} N sec/m^2. Centipoise is more commonly used.	***Reyn*** = 1 lb sec/in^2 1 microreyn = 10^{-6} reyn = 10^{-6} lb sec/in^2. Microreyn is more commonly used

Conversion factor

1.45 * 10 -7 reyn/cp = 1.45 *10^{-1} microreyn/cp

Kinematic viscosity

Metric	**English**
stoke = cm^2/sec = 10^{-4} m^2/sec cs (centistokes) = 10^{-2} cm^2/sec = 10^{-6} m^2/sec Centistokes is more commonly used	1 Newts = in^2/sec

Conversion factor

1.55 *10^{-3} (in^2/sec)/cs
= 1.55 *10-3 Newts/cs

SSU conversion factor

$$\nu\,(centistokes) = .226\,SSU - \frac{195}{SSU} \quad \text{for} \quad 32 < SSU < 100$$

$$\nu\,(centistokes) = .22\,SSU - \frac{135}{SSU} \quad \text{for} \quad SSU > 100$$

3.1.2 Behavior of viscosity**:**

- It is a function of both temperature and pressure, temperature being the major effect.

Temperature

$\mu = \mu_o \, e^{-s(T-T_o)}$ where μ_o is the viscosity at T_o, and s a constant which depends on the fluid.

Viscosity can be improved by the addition of additives. A measure of the dependency of an oil is given by its viscosity index VI. The lower the VI, the greater the variation of temperature with temperature.

$\mu = \mu_o \, 10^{cP}$ where c is typically $1*10^{-8}$/Pa ($7* 10^{-5}$/psi)

3.1.3 Consequences of high and low viscosity

- High viscosity: excessive noise and sluggish operation, poor transmission of power, excessive heat generation, Cavitation may occur, High pressure losses, lower mechanical efficiency.
- Low viscosity: oil is thin and excessive leakage will occur (increased temperature) lower volumetric efficiency; Increased wear because the oil film thickness will decrease. Complete break down can occur resulting in spot welds between moving surfaces.

Note: Under Laminar flow conditions, viscous effects dominate. However, under Turbulent flow conditions, viscous effects do not and hence are not temperature sensitive. This will have a significant effect when it comes to valve design.

Problem:

An oil has a viscosity of 200 SSU at 45°C and a specific gravity of 0.9. What is the viscosity in cs and cp?

Solution:

From $\nu\,(centistokes) = .22\ SSU - \frac{135}{SSU}$, we get

$$\nu\,(centistokes) = .22 * 200 - \frac{135}{200} = 43.3cs$$

But $\nu = \mu / \rho$. **Do a unit analaysis.**

$$\nu \equiv (dyne \sec/ cm^2)/(g / cm^3) \equiv poise /(g / cm^3) \equiv stokes$$

Therefore, $poise \equiv stokes * (g / cm^3)$ or

$$cp \equiv cs * (g / cm^3)$$

So let us put in some numbers. The density of water is 1 g/cm^3. Since the specific gravity of oil is 0.9, then the density is 0.9 g/cm^3.

Thus μ = 43.4 cs * .9 g/cm^3 = 39 cp

The objective of this problem was to get you familiar with using various units involving viscosity.

3.2 Fluid Density:

Weight Density is defined as the weight per unit volume = $\frac{wt}{vol}$. This is sometimes called the **Specific Weight**

Mass density is defined as the mass per unit volume = $\frac{mass}{vol}$. Mass density is the most common form used in the metric system.

Specific gravity = $\frac{density\ of\ the\ fluid}{density\ of\ water}$

Typical values for hydraulic fluids:

Metric: **.9 g/cm^3 = 900 kg/m^3**

English: **$8*10^{-5}\ lb_f\ sec^2/in^4$**

Units

Metric	**English**
$\rho \equiv \dfrac{kg}{m^3}$ How boringly simple!!!!!	Mass $\equiv$ slugs ($lb_f\ sec^2/ft$) Weight $\equiv$ lb_f Weight = mass (in slugs) * g (ft/sec^2) g = 32.174 ft/sec^2 = 386 in/sec^2 Weight density = Specific weight = weight / ft^3 $\equiv \dfrac{lb_f}{ft^3}$ Mass density = mass/ft^3 $\equiv \dfrac{slugs}{ft^3}$ $\equiv \dfrac{lb_f \sec^2 /\ ft}{ft^3}$ $\equiv \dfrac{lb_f \sec^2}{ft^4}$ (most common form) Ugly, ugly, ugly!!!!!

Example:

(a)What is the density of water in kg/m^3? In slugs/ft^3?

Water has a density of 1 g/cm^3 = 10^{-3} kg /$(10^{-2})^3$m^3 = 10^3 kg/m^3

Water has a weight density (specific weight) of 62.4 lb_f/ft^3 . We need mass density in this case. So we know that

Weight (lb_f) = mass (slugs) * g (ft/sec^2)
Thus, mass (slugs) = weight / g
In this case, the weight is 62.4 lb_f
Therefore the mass (slugs) = 62.4 (lb_f)/32.174 ft/sec^2)
= 1.939 lb_f sec^2/ft
And thus, the density of water is
= 1.939 slugs/ft^3

(b) What is the specific weight of water in SI units?

The density of water is 1000 kg/m^3 . The specific weight is the same as the weight density which is the weight per unit volume.

In 1m^3 of water, the weight is 1000kg*9.8 m/sec^2.

Thus the specific weight is $9.8*10^3$kg m/sec^2/m^3 = 9.8 kN/m^3 where 1N $\equiv$ kg m/sec^2

The objective of the example was to get to the various forms of density and to become familiar with various forms of units.

A useful relationship is the equation of state for a gas:

$$P = \rho R T$$

where ρ is the density kg/m^3 (lb_f sec^2/in^4), R the Universal gas constant m^2/sec^2 ^{o}R (in^2/sec^2 ^{o}R) and T, the absolute temperature ^{o}R.

Also density is a function of both pressure and temperature but it is a very small dependency. In hydraulics, unless we expect very large temperature swings, we can assume density constant.

3.3 Fluid Bulk Modulus

Fluid Bulk modulus is one of the most important properties of a fluid. It is blamed for everything that goes wrong so we should be very aware of what it is.!!!!

Bulk modulus is related to fluid compressibility. In fact it is the inverse of compressibility. We normally want a fluid to be very stiff or have a high bulk modulus value (low compressibility). Usually this is true with bulk modulus values being in the range of 10 – 15 GPa ($1.5 * 10^5$ - $2.10 *10^5$ psi) However, if we have even a very small volume of air in the fluid, this can reduce the bulk modulus by an order of 10 or more which means you do not have a stiff system anymore Think of air in your brakes and now you know the problem!!! Think of air in airplane hydraulics and be even more aware (if you walk away).

B has units of psi or N/m^2 (Pa) [(MPa or GPa)].

B appears to have units of pressure but it is not pressure. Thus bulk modulus gives us an idea of how the volume will change if we increase the pressure and vice versa. If you have a stiff system (large bulk modulus), a very small change in volume will result in a very large change in pressure. If you want the aircraft hydraulics to respond quickly (ie pressure increases rapidly) to the addition of a small amount of fluid, then you want exactly this properly.

3.3.1 Isothermal Bulk Modulus

Mathematically, we define **isothermal – secant (temperature constant) bulk modulus** as:

$B = -V_0 \frac{\Delta P}{\Delta V} \Big|_{t=cont}$; Note the minus sign. The gradient term $\frac{\Delta P}{\Delta V}$ is negative.

$B = -V_o \frac{\partial P}{\partial V} \Big|_{t=const.}$ is sometimes called the tangent bulk modulus and is numerically larger than the isothermal secant bulk modulus. *The isothermal (secant or tangent) bulk modulus is usually obtained under conditions of* ***slow compression*** *to allow heat transfer to occur across the volume boundary*.

3.3.2 Adiabatic Bulk Modulus

Another from of bulk modulus is the **adiabatic bulk modulus B_a** (no heat transfer occurs across the volume boundaries, thus the fluid temperature is not constant). It is related to the isothermal bulk modulus by the relationship

$B_a = \frac{C_p}{C_v} B$ where $\frac{C_p}{C_v}$ is the ratio of the specific heats.

At lower temperatures, (in the order of 40oC) $\frac{C_p}{C_v} \approx 1.04$, but as the temperature increases, $\frac{C_p}{C_v}$ also increases and can be significant.

Adiabatic bulk modulus is usually measured under conditions of **rapid compression**.

3.3.3 Sonic Bulk Modulus

The **sonic bulk modulus** is related to the speed of sound, c, and the density ρ of the fluid by the relationship

$$B_a = \rho c^2$$

In the metric system, ρ has units of kg/m^3 and c has units of m/sec. That is

$$B_a \equiv \frac{kg}{m^3}\frac{m^2}{\sec^2} \equiv \frac{kg}{m \sec^2} \equiv \frac{kg\ m^2}{m\ m^2 \sec^2} \equiv \frac{N}{m^2}$$

In the English system ρ has units *of* $\frac{lb_f \sec^2}{in^4}$ and c has units of $\frac{in}{\sec}$ in this case.

$$B_a \equiv \frac{lb_f \sec^2}{in^4}\frac{in^2}{\sec^2} \equiv \frac{lb_f}{in^2}$$

3.3.4 Equivalent Bulk Modulus

A problem with assigning a realistic value for bulk modulus is that even small amounts of air in the oil can reduce the bulk modulus substantially. In addition, the compressibility of the lines can also affect the value. To account for this, the following equation can be used to determine the "effective bulk modulus" of the fluid which accounts for the container and the presence of entrained air.

$$\frac{1}{B_e} = \frac{1}{B_c} + \frac{1}{B_l} + \frac{V_g}{V_t}\left(\frac{1}{B_g}\right)$$

where B_e is the effective bulk modulus, B_c is the bulk modulus of the container, B_l the bulk modulus of the liquid, B_g the bulk modulus of the gas, V_t, the total volume of the liquid and gas and V_g, the volume of the gas.

Special note:

Entrained air (or free air) are bubbles (or a collection of bubbles) that are large enough to be suspended in the fluid. They have a significant effect on the bulk modulus.

Dissolved air are bubbles that are actually in solution (the bubbles can be considered as part of the molecular structure of the fluid). Dissolved air has little effect on the bulk modulus; however, if the pressure reduces suddenly (as could occur as fluid accelerates across an orifice), then dissolved air can become entrained air. If the entrained air bubbles are not too large and if the fluid is not air saturated, an increase in the pressure can force entrained air into solution which then can reduce the dependency of bulk modulus on the air. Don't count on this though in any circuit design!!!

3.3.5 Bulk Modulus of a gas**.**

Since the presence of air has a significant effect on the bulk modulus of a fluid, it is useful to have an expression for the bulk modulus of a gas

For **isothermal** compression, PV = constant.

$$B_{gi} = P$$

For **adiabatic** compression $PV^{\gamma} = \text{constant}$

where γ is the ration of specific heats $\dfrac{C_p}{C_v}$

$$B_{ga} = \gamma\ P$$

3.3.6 Bulk Modulus of a container (or a line)

$$\frac{1}{B_c} = \frac{2}{E}\frac{\left[(1+\gamma)\ D_o^{\ 2} + (1-\gamma)\ D^2\right]}{2T(D_o + D)}$$

where E modulus of elasticity, γ is Poisson's ration (note the same symbol is also used for the ratio of specific heats), D is the inner diameter and D_o is the outer diameter.

Now for thin walled cylinders where λ = ¼ for metals,

$$B_c \cong \frac{(D_o - D)}{2D}\ E$$

And for thick walled metal pipes where $D_o >> D$

$$B_c \cong \frac{E}{2(1+\gamma)}$$

For non metal hoses, B_c is typically in the range of .7 – 3.5 GPa (10,000 – 50000 psi). Specific values can be obtained from hose manufacturers.

Problem:

The bulk modulus of a fluid is 2.1GPs (≅ 300,000 psi). If the pressure of the fluid is 6.9 MPA (≅ 1000 psi), compare how the effective bulk modulus of the fluid changes if there is 10% and .1% by volume of entrained in the fluid. Assume very stiff pipes and isothermal conditions.

We know that the effective bulk modulus is given by

$$\frac{1}{B_e} = \frac{1}{B_c} + \frac{1}{B_l} + \frac{V_g}{V_t}(\frac{1}{B_g})$$

Because we have assumed very stiff pipes, $\frac{1}{B_c} \to 0$. We also know that $\frac{V_g}{V_t}$ =0.1 (10%) and .001 (.1%). We must estimate B_g. For isothermal conditions, $B_{gi} = P$ = 6.9 $M\,Pa$

Thus at 10% by volume	At even 0.1% by volume,
$\frac{1}{B_e} = 0 + \frac{1}{2.1*10^9} + .1(\frac{1}{6.9*10^6})$	$\frac{1}{B_e} = 0 + \frac{1}{2.1*10^9} + .001(\frac{1}{6.9*10^6})$
$= 4.76*10^{-10} + .1*.145*10^{-6}$	$= 4.76*10^{-10} + .001*.145*10^{-6}$
$= 1.45*10^{-8}$	$= 4.76*10^{-10} + 1.45*10^{-10}$
or $B_e = 6.9*10^8\ Pa = .069GPa$ compared to the original 2.1GPa. This is essentially only 100 times the bulk modulus of gas!!!!!	$= 6.21*10^{-10}$ or B_e = 1.61 GPa (again compared to 2.1 GPa)

It is pretty apparent that even small amounts of entrained air by volume reduce the bulk modulus significantly

3.3 Other fluid properties.

3.3.1 <u>Pour point</u>

The temperature at which a fluid will not flow.
It should not be used as a minimum temperature for operation. Actual minimum temperature should be considerably higher.
The pour point can be reduced with the use of additives.

3.3.2 <u>Neutralization Number</u>

- Degree of acidity or alkalinity of a hydraulic fluid
- A low number is most desirable (0 – 0.1)
- As the number increases, the acidity increases. Thus the oil tends to deteriorate in the presence of air (oxidation). Seals can be attacked.

3.3.3 Fire resistance

A very important consideration for safety. Hydraulic fluid can be dangerous in the presence of flames. Be careful.

Flash point

- lowest temperature at which vapors rising to the surface form the oil surface will ignite when exposed to an open flame.

Fire point

- the oil temperature at which exiting vapors will ignite and become self sustaining for a period of 5 seconds. This is usually about 26^{o}C (50^{o}F) higher than the flash point.

Autogenious ignition temperature

- the temperature at which droplets of oil will ignite when impinging on a hot surface in the presence of air.

3.3.4 Lubrication

Hydraulic surfaces require that surfaces slide over each other (relative motion) and have a low coefficient of friction.. To prevent wear, the fluid must have excellent lubrication properties.
Lubrication is a “boundary layer” consideration.
Oils should “stick”, “attach” or “bond” to surfaces (called oiliness).
Consider the lubricating properties as providing a hydraulic bearing between two surfaces.
Poor lubricity will result in increased wear and thus over time, increase clearances (increased leakage).

3.3.5 Thermal stability

The ability of a fluid to resist chemical reactions or decomposition at higher temperatures. If thermal stability is poor, filters can easily clog.

3.3.6 Oxidative stability

Ability of a fluid to resist a chemical reaction with oxygen
Oxidation can be a problem at higher temperatures, and in places where mixture rates with air or oxygen are high. If oxidation is severe, the fluid can become acidic and a sludge can easily form.

3.3.7 Hydrolytic Stability

Ability of a fluid to resist reaction with water. This can be a consideration in water–in–oil emulsions. This can be alleviated somewhat with the addition of rust inhibitors.

3.3.8 <u>Foaming</u>

Ability of a liquid to combine with gases (air , for example) and form emulsions. This can reduce lubricity and the bulk modulus of the fluid. Excessive foaming can readily be observed in the reservoir.

3.3.9 <u>Toxicity</u>

The ability of a fluid to produce toxic vapors. This can be a problem with synthetic fluids at elevated temperatures.

3.3.10 <u>Volatility</u>

This is a measure of the ability of a fluid top produce vapour. We want a very low vapour pressure in a fluid; that is we want to have vapors form only if the pressure is very low.

3.3.11 <u>Cavitation</u>

This is not a fluid property but it is a consequence of fluid properties.

- Cavitation refers to the formation and then collapse of a vapour cavity in a fluid. This can occur when the pressure falls below the vapour pressure of the fluid. The vapour cavities by themselves are not the main problem. When the cavities are exposed to high pressures, the cavities are compressed very rapidly and as a result, the internal pressure in the cavity becomes extremely large. At some point, the cavity "collapses". This means that the individual molecules in the cavity are "shot" into the surrounding fluid at a molecular level at very high velocities. The resulting pressure spikes and high velocity vapour molecules can cause a lot of damage if they are close to any surfaces. If the collapse occurs in the center of the fluid, the only consequence if noise. However, in most cases, the collapse occurs near surfaces so both noise and surface damage can occur. (This is very much an oversimplification of the process but the collapse is a very complex phenomenon).
- The places where cavitation causes most damage are at any venture sections, orifice and at pump inlets. The damage occurs at the venturi and pump outlets because this is where the cavity collapses.

3.5 Types of hydraulic Fluids

3.5.1 <u>Petroleum based fluids (mineral oil)</u>

- These fluids are most common in hydraulic circuits and are relatively inexpensive. They have been around for a long time, have excellent properties and can operate at a wide range of fluid temperatures and pressures. The have one disadvantage in that they are not fire resistant.

3.5.2 <u>Synthetic fluids</u>

- Can be very expensive
- Can have excellent fluid properties including fire resistance

- Can be used at a wide range of temperatures
- But can be hard to handle
- Typical fluids included
    - Phosphate esters, (excellent lubricity but thermal stability decreases at high temperatures),
    - Silcate esters (excellent thermal stability but poor hydrolytic stability),
    - Silicone base fluids: good (high) VI characteristics, high thermal stability, low bulk modulus, which make them ideal for dampers, fluid springs etc .However, they have poor lubrication (silicone is not a good lubricant)

3.5.3 Water-based Fluids

These have been designed for fire resistance. Because they have water in then, they have low vapour pressures, have low viscosity (approaching that of water) and show generally poor lubrication properties.

- Water in oil (95% water- 5% oil) oil surrounded by water
    - Water and oil can separate at times
    - Lower viscosity because of water
    - Poor lubricity

- Invert emulsions (40% oil 60% water) water surrounded by oil
    - Tend to be non-Newtonian in nature
    - Tends to assume the properties of oil (good lubricity)

- Water glycols
    - Excellent viscosity characteristics because if the glycols
    - Medium pressure operation
    - Can attack paints
    - Must watch compatibility with seals (especially cork)