Chapter 1. Fluid Power Properties

I.1. Introduction

The properties of the fluid are important to operate the fluid power system. The fluid can be used as compressible and incompressible. Compressible fluids such as air and gas are used in the pneumatics circuit operation. Whereas, incompressible fluids such as water and petroleum are used in the operation of a hydraulic circuit. This chapter will discuss mass, density, specific weight and gravity, viscosity, pascal law, continuity equation, Bernoulli's equation.

I.2. Mass and Weight

Mass is the fundamental property of an object and simply how much matter stuff an object consists and it is denoted by *m*. The common units of mass are kg, slugs. The mass of the object is the same anywhere in the universe. The mass is how something is to a given force. From Newton's second law, the mass is expressed as [1],

$$m = \frac{F}{a}$$

where,

- F is the force in units of Newton (N),
- a is the acceleration in units of m/s^2,
- m is the mass in units of kg.

All objects either solids or fluids are pulled toward the center of the earth by a force of attraction that is called the weight of the object. In other words, weight is the amount of force that an object's mass generates due to gravity. The weight, W, of a fluid, is defined as the mass multiplied by the gravitational acceleration, g.

Mathematically, it can be expressed as,

$$F = W = mg$$

where,

- F is the force in units of lb,
- W is the weight in units of lb,
- m is the mass of the object in units of slugs,
- g is the proportionality constant called the acceleration of gravity, which equals 33.2 ft/s^2 and 9.81 m/s^2 at sea level.

Example **1.1** The mass of an object is found to be 30 kg. Calculate its weight.

Solution
The value of the weight is calculated as,

$$W = \text{mg} = 30\ (\text{kg}) \times 9.81\ (\text{m/s}^2) = 294.3\,\text{kg-m/s}^2 = 294.3\,\text{N}$$

Example **1.2** The weight of an object is found to be 500 lb. Determine its mass.

Solution
The value of the mass of an object is determined as,

$$m = \frac{W}{g} = \frac{500}{32.2} = 15.58\,\text{lb-ft/s}^2 = 15.58\,\text{slugs}$$

Practice Problem ***1.1***
The mass of an object is found to be 150 kg. Find its weight.

Practice Problem ***1.2***
The weight of an object is found to be 1500 lb. Calculate its mass.

1.3. Density

Any object has an identical density regardless of its shape, size and mass. Let us consider that an object has *n* molecules per atom as shown in Fig. 1.1. Then the density can be expressed as,

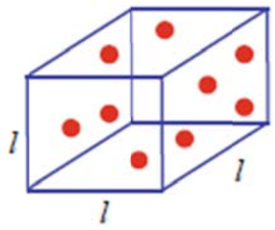

Fig. 1.1 An object with a cubic shape

Therefore, the heaviness of an object refers to density. In other words, the mass per unit volume of a fluid is known as density. The density is denoted by the Greek letter ρ. Its units are kg/m^3, slugs/in.^{3}, slugs/ft^3. A typical density for a hydraulic fluid (oil) is 3.74 slugs/ft^3 or 897 kg/m^3.

A certain object is said to be denser than another if that object has more atoms in a given volume. Again, the mass can be expressed as,

$$m = \rho\, V$$

For example, oil and boat, both float in the water because it is less dense than water. The density of some parameters is shown in Table 1.1.

Table 1.1 Density for a few parameters

Parameter	Density (kg/m^3)
Water	1000
Dry sand	1600
Steel	7849
Mercury	13,600
Cement	1440

1.4. SpecificWeight

The specific weight in a fluid power system is usually related to the volume and its weight. To explain the volume, consider a cubic container that contains the fluid (water) as shown in Fig. 1.2. The length, base and height of the container are the same and it is conserved as *l* = 1 ft.

In fluid mechanics, the specific weight represents the force exerted by gravity on a unit volume of the fluid. The weight per unit volume is known as specific weight. It is denoted by a Greek letter γ and its units are N/m3, lb/ft3, etc. Mathematically, the specific weight is expressed as [2],

$$\gamma = \frac{W}{V}$$

where,

- *W* is the weight in the units of N, lb,
- *V* is the volume in the unit of m^3, ft^3.
- γ is the specific weight in the units N/m^3, lb/ft^3.

The specific weight. on the other hand, is not absolute, since it depends on the value of gravitational acceleration (*g*), which varies with location, primarily latitude and elevation above mean sea level. The specific weight at 20 °C wth g = 9.81 m/s^2 is shown in Table 1.2.

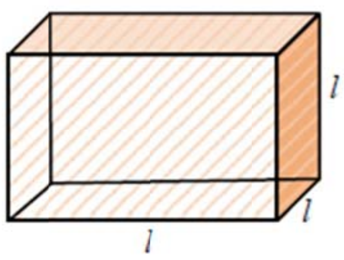

Fig. 1.2 A cubic shape container

Table 3.2 Specific weight at 20 °C with g = 9.81 m/s^3

Parameter	γ (kN/m^3)
Water	9.79
Seawater	10.03
Gasoline	6.6
Glycerin	13.3
Kerosene	7.9
Motor oil	8.5

Example 1.4 The diameter and the height of a cylinder container are 0.4 m and 3.5 m, respectively. The container is filled with a 15 kg liquid. Calculate the specific weight.

Solution
The value of the volume is calculated as,

$$V = Ah = \pi \frac{d^2}{4} h = \pi \frac{0.4^2}{4} \times 1.5 = 0.188\ \mathrm{m}^3$$

The value of the specific weight is calculated as,

$$\gamma = \frac{W}{V} = \frac{15}{0.188} = 79.79\ \mathrm{N/m}^3$$

Practice Problem *1.4*
A cylinder container has a diameter of 0.2 m and a height of 2 m. If it is filled with a liquid having a specific weight of 1500 N/m^3, how many kg of this liquid must be added to fill the container?

1.5. Specific Gravity

The specific gravity is very important in an automobile battery where sulphuric acid (**H_2SO_4**) is mixed with water to get an electrolyte solution. Therefore, the specific gravity is always with water as a reference. Specific gravity is defined as the ratio of the specific weight of an object to the specific weight of the water and it has no unit.

The expression of specific weight is modified as,

$$\gamma = \frac{W}{V} = \frac{m\,g}{V}$$

Substituting yields,

$$\gamma = \rho\, g$$

Mathematically, the specific gravity is expressed as,

$$S = \frac{\gamma_{object}}{\gamma_{\text{water}}}$$

Substituting yields,

$$S = \frac{g\rho_{\text{object}}}{g\rho_{\text{water}}} = \frac{\rho_{\text{object}}}{\rho_{\text{water}}}$$

Therefore, the specific gravity for oil and air can be written as,

$$S_{\text{Oil}} = \frac{\rho_{\text{Oil}}}{\rho_{\text{water}}}$$

$$S_{\text{air}} = \frac{\rho_{\text{air}}}{\rho_{\text{water}}}$$

If the specific gravity of a liquid is greater than 1 ($S > 1$), it is thicker than water, it sinks in water. If the specific gravity of a liquid is less than 1 ($S < 1$), it is thinner than water, it floats on water.

Example 1.5 One litre (1/1000 m^3) of SAE30 oil weighs 0.75 N. Calculate its specific weight, density and specific gravity.

Solution
The value of the specific weight is calculated as,

$$\gamma = \frac{W}{V} = \frac{0.75}{1/1000} = 750 \text{ N/m}^3$$

The value of the density is calculated as,

$$\rho_{oil} = \frac{\gamma}{g} = \frac{750}{9.81} = 76.45 \text{ kg/m}^3$$

The value of the specific gravity is determined as,

$$S_{oil} = \frac{\rho_{oil}}{\rho_{water}} = \frac{76.45}{1000} = 0.076$$

Practice Problem 1.5
The density of gold is 19300 kg/m^3 and the density of water is 1000 kg/m^3. Calculate the specific gravity.

1.6. Pressure

The pressure and the force are the two important parameters that are normally used in the actuators and pumps operation. The pressure is defined as the force per unit area. In otherwords, pressure is the amount of force acting over a unit area. Mathematically, it can be expressed as,

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

The liquid direction inside a cubic container is shown in Fig. 1.3. The pressure developed at the bottom of a container of any liquid is known as hydrostatic pressure and it is expressed as,

$$p = \rho\, g\, h$$

Substituting yields,

$$p = \frac{mg}{V}\, h$$

Again, substituting yields,

$$p = \frac{W}{V}\, h$$

Substituting yields,

$$p = \gamma\, h$$

From the last equation, it is seen that the value of the pressure is can be calculated if the specific weight and the height are known.

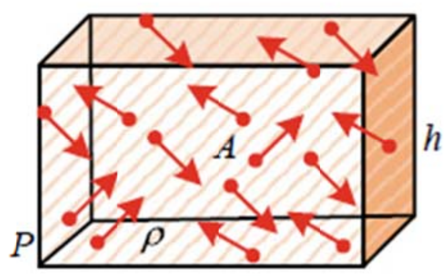

Fig. 1.3 Cubic container for any liquid

1.7. Bottom Pressure of Liquid Column

The pressure will come from water and act on all sides of any object when floating into water. Therefore, when floating a boat into the water, the boat is subjected to pressure coming from all sides of the water. Consider a container with a liquid. The area and the volume of the liquid are *A* and *V*, respectively. The pressure head developed at the bottom due to the column of liquid. Let *h* be the height of the liquid column and *W* be the weight of the liquid as shown in Fig. 1.4.

The liquid has a specific weight and volume. From the basic definition of pressure, the following relation can be expressed as,

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

Substituting *F* = *W* and *V* = *Ah* yields,

$$p = \frac{W}{V} \cdot \frac{A\,h}{A}$$

Substituting yields,

$$p = \gamma\, h$$

Example . *1.6* A tank is filled with oil whose specific weight is 5000 N/m^3. If the depth of the tank is 2 m, find the pressure at the bottom of the tank.

Solution
The value of the pressure at the bottom of the tank is calculated as,

$$P = \gamma h = 5000 \times 2 = 10{,}000\,\mathrm{N/m^2}\ (10\,\mathrm{kPa})$$

Practice Problem *1.6*
The pressure at the bottom of an oil-filled tank is 15 kPa and the specific weight is 2500 N/m^3. Determine the depth of the tank.

1.8 Viscosity

The fluid is used to transmit the power in a fluid power system. The fluid is also used to lubricant both the hydraulic and pneumatic systems. The word ‘Viscosity’ is derived from the Latin word ‘**VISCOUM**’ meaning ‘MISTLETOE’ and ‘VISCOUS GLUE’ made from mistletoe berries. Viscosity is an important fluid property when analyzing liquid behavior and fluid motion near solid boundaries. Viscosity is known as the internal friction of a moving fluid.

Viscosity is a quantitative measure of a fluid’s resistance to flow. In an electrical circuit, resistance is the analogy of viscosity in fluid power. High resistance reduces the flow of electric current and low resistance increases the flow of current in a circuit. Similarly, when the viscosity is low, the fluid can flow easily, and it is thin in appearance. Whereas, when the viscosity is high, the fluid flow is reduced, and it is thick in appearance. High viscosity increases the power losses due to frictional losses and sluggish operation. It also increases pressure drop through the vales and lines.

Viscosity is classified as dynamic or absolute viscosity and kinematic viscosity.

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1.8.1 Dynamic Viscosity

The dynamic or absolute viscosity of a fluid is a measure of internal resistance it offers to relative shearing motion. In other words, the ratio of shearing stress in oil and the slope of the velocity profile is known as dynamic or absolute viscosity. It is represented by a Greek letter μ and its unit is N-s/m^2 or lb-s/ft^2. Mathematically, it can be expressed as,

$$\mu = \frac{\text{Shear stress in oil}}{\text{Slope of velocity profile}} = \frac{\tau}{\frac{v}{y}}$$

Consider that the top plate is moving at a velocity v as it push by a force *F* and the bottom plate is stationary as shown in Fig. 1.5.

The shearing stress is defined as the force per unit area. Now, substituting $\tau = F/A$ yields,

$$\mu = \frac{\frac{F}{A}}{\frac{v}{y}}$$

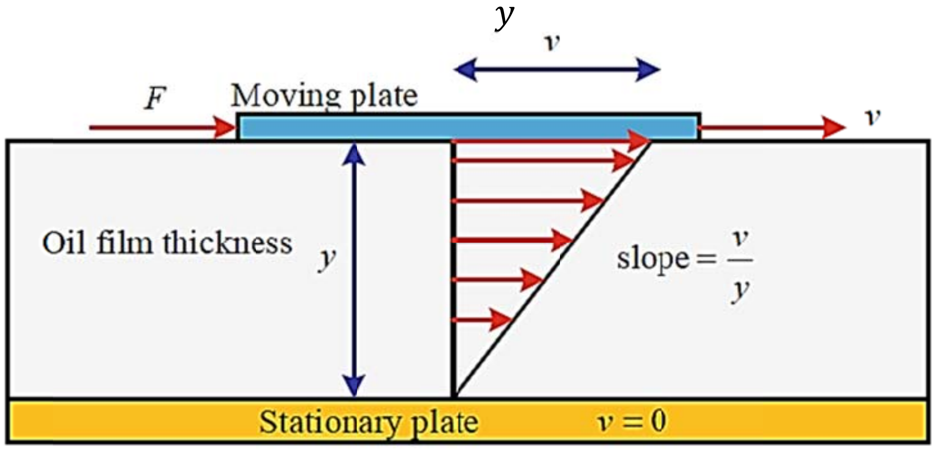

Fig. 1.5 Two plates with oil film thickness

$$\mu = \frac{F\,.\,y}{A\,.\,v}$$

In CGS (centimeter, gram, second) system, the most common unit for the dynamic viscosity is centipoise (cP), which is equivalent to 0.01 Poise (P) in honor of French physicist, Jean Leonard Marie Poiseuille (1797–1869).

1.8.2 Kinematic Viscosity

The kinematic viscosity is used to identify the relationship between the viscous force and the internal force in a fluid. The ratio of absolute viscosity to the density of the fluid is known as kinematic viscosity and it is denoted by a Greek letter υ (nu). In a hydraulic system, kinematic viscosity is used for calculations rather than an absolute viscosity. The SI unit of kinematic viscosity is m^2/s. In the CGS system, the kinematic viscosity is often measured in cm^2/s, after Irish mathematician and inventor of viscosity Sir George Gabriel Stokes (1819–1903). The unit of viscosity cm^2/s is called the Stoke (S), and many scientists used centistoke (cS), which is equivalent to 0.01 Stoke (S). Mathematically, the kinematic viscosity is expressed as,

$$v\ (nu) = \frac{\mu}{\rho}$$

Again, the kinematic viscosity in cS is the ratio of absolute viscosity in cP to the specific gravity and it is expressed as,

$$v\ (nu) = \frac{\mu(\mathrm{cP})}{\rho}$$

Example 1.7 The absolute and kinematic viscosities of fluid are given as 0.85 Ns/m^2 and 5 m^2/s. Calculate the density of a fluid.

Solution

The value of the density of the fluid is calculated as,

$$\rho = \frac{\mu}{\nu} = \frac{0.85}{5} = 0.17\ \mathrm{kg/m^3}$$

Example 1.8 A 3.5 N force moves a piston inside a cylinder at a velocity of 1.5 m/s. The diameters of the cylinder and piston are 9.5 cm and 9.4 cm, respectively. An oil film separates the piston from the cylinder and the length of the piston is 4 cm. Calculate the absolute viscosity of the oil.

Solution

The value of the area of the piston is calculated as,

$$A = \pi DL = \pi \times 9.4 \times 4 = 590.61\ \mathrm{cm^2} = \frac{590.61}{100 \times 100} = 0.059\ \mathrm{m^2}$$

The value of the oil film thickness is calculated as,

$$y = \frac{D - d}{2} = \frac{9.5 - 9.4}{2} = 0.25\,\text{cm} = \frac{0.25}{100} = 2.5 \times 10^{-3}\,\text{m}$$

The value of the dynamic viscosity is calculated as,

$$\mu = \frac{F \times y}{A \times v} = \frac{3.5 \times 2.5 \times 10^{-3}}{0.059 \times 1.5} = 0.098\,\text{Ns/m}^2$$

Practice Problem *1.7*
The absolute viscosity and density of fluid are given as 0.95 Ns/m^2 and 3.5 kg/m^3. Calculate the kinematic viscosities of a fluid.

Practice Problem *1.8*
A 5 N force moves a piston inside a cylinder at a velocity of 3.5 m/s. The diameters of the cylinder and piston are 8 cm and 7.9 cm, respectively. An oil film separates the piston from the cylinder and the length of the piston is 5.2 cm. Calculate the absolute viscosity of the oil.

1.9. Viscosity Index

The viscosity of hydraulic oil is inversely related to the temperature. The viscosity of hydraulic oils decreases with an increase in temperature as shown in Fig. 1.6. Therefore, the variation of viscosity with respect to temperature is different for different types of oil.

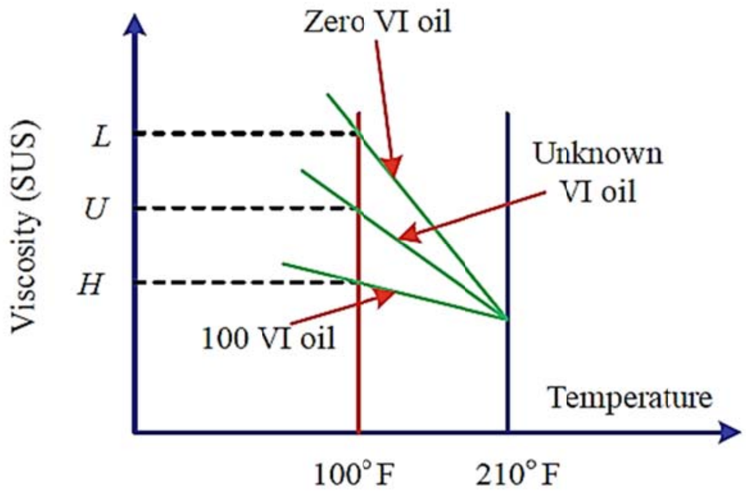

Fig. 1.6 Variation of viscosity with temperature

In general, the viscosity index (VI) is a relative measure of the change in the viscosity of oil with respect to a change in temperature. The *VI* of any hydraulic oil can be expressed as,

$$VI = \frac{L - U}{L - H}\,.100$$

where,

- L is the viscosity in SUS (Saybolt Universal Second) of 0-VI oil at 100 °F,
- U is the viscosity in SUS of unknown-VI oil at 100 °F,
- H is the viscosity in SUS of 100-VI oil at 100 °F.

Example 1.9 The viscosity index of a sample oil of 65. It is tested with a 0 VI oil and a 100 VI oil whose viscosity values at 100 °F are 356 and 121 SUS, respectively. Find the viscosity of the sample oil at 100 °F in units of SUS.

Solution
The value of the U is calculated as,

$$65 = \frac{356 - U}{356 - 121} \times 100$$

$$152.75 = 356 - U$$

$$U = 203.25\,\text{SUS}$$

Practice Problem 1.9
Find the viscosity index of sample oil is tested with a 0 VI oil and a 100 VI oil whose viscosity values at 42 °F are 425 and 139 SUS, respectively. The viscosity of the sample oil at 42 °F is 215 SUS.

1.10. Young's Modulus

Consider a container full of water and place a sphere inside the container as shown in Fig. 1.7. The fluid will exert a force in all directions on the sphere and the volume of the sphere will change (will decrease) as can be seen in Fig. 1.8. Let the initial volume of the sphere is $V0$ and the final volume is Vf . The change in volume is expressed as,

$$-\Delta V = V_f - V_0$$

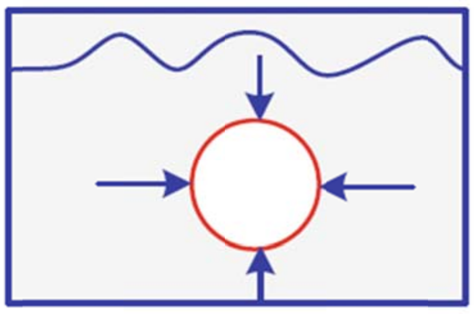

Fig. 1.7 A container with a sphere

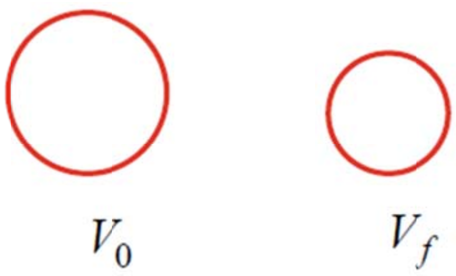

Fig. 1.8 Different sphere volumes

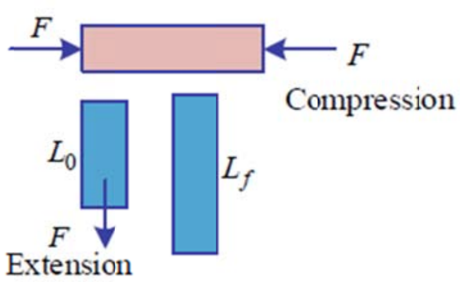

Fig. 1.9 Compression and extension of an object

As the volume decrease, the change in volume is negative. A force is applied horizontally to an object that is compressed as shown in Fig. 1.9. A force is also applied to an object and it is extended. The elongation per unit length is called the strain and it is denoted by ε. The strain is expressed as,

$$\epsilon = \frac{\Delta L}{L}$$

Normal stress σ is expressed as,

$$\sigma = \frac{P}{A}$$

The ratio of the unit stress to the unit strain is the modulus of elasticity of the material in tension, or, as it is often called, Young's modulus, *E* is expressed as,

$$E = \frac{\sigma}{\varepsilon}$$

Substituting yields,

$$E = \frac{\frac{P}{A}}{\frac{\Delta L}{L}}$$

$$E = \frac{P}{A} \cdot \frac{L}{\Delta L}$$

From the last equation, it is seen that Young Modulus can be calculated if other parameters are known.

1.11. Reynold Number

In 1883, British engineer Professor Osborne Reynolds conducted an experiment to demonstrate the existence of three types of flow i.e. Laminar flow, transition flow and Turbulent flow. The type of flow in which the fluid molecules move along well defined paths or all streamlines and all the streamlines are straight lines and parallel to the boundaries of the tube is known as laminar flow as shown in Fig. 1.10. Laminar flow depends on the high viscosity of the fluid, low velocity of the fluid and less area of the tube or pipe. The flow through a uniform cross-section of a pipe is an example of laminar flow in Fig. 1.10a.

The type of flow that the fluid molecules are way and parallel among themselves but are not parallel to the boundaries of the tube is known as transition flow as shown in Fig. 1.10b. The type of flow that the fluid molecules move in a zigzag way that led to the mixing of the dye is known as turbulent flow in Fig. 1.10c. In this type of flow, the fluid particles cross each other. The flow in a river during the flood and through a pipe of different cross-sections are examples of turbulent flow.

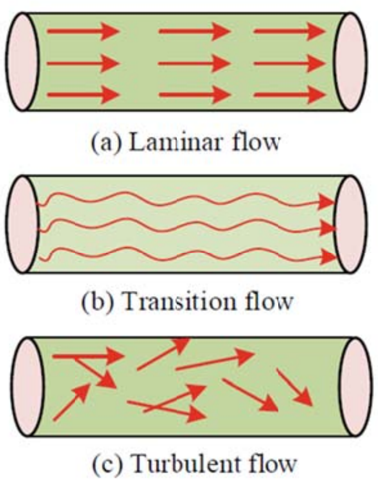

Fig. 1.10 Different types of flow

He developed a relationship to find the fluid friction in a hydraulic which is known as **Reynold'**s number. Reynold's conducted an experiment related to fluid friction as shown in Fig. 1.11. At a low velocity, the dye will move in parallel to the tube boundaries and it also does not get any sort of dispersed as shown in Fig. 1.11a. This condition of the flow describes the laminar flow of the fluid. The velocity is slightly higher than the first case the dye will move in the way fashions as shown in Fig. 1.11b. This situation is expressed as the transition flow.

Whereas the velocity is higher than the second case, the dye will no longer move in the straight lines but will be diffused. This condition of the flow is usually described by the turbulent flow.

The ratio of inertia force to viscous force is called the Reynolds number (*Re*) and mathematically, it is expressed as,

$$R_e = \frac{\text{Inertia force}}{\text{Viscous force}} = \frac{F_i}{F_v}$$

The resistance of an object (body) to a change in its state of motion is known as inertia force and it is expressed as,

$$F_i = m \,.\, a$$

Substituting yields,

$$F_i = \rho\, V\, a$$

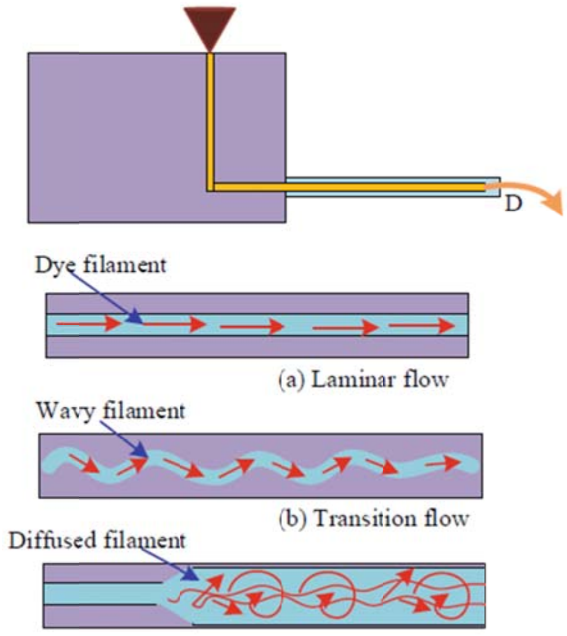

Fig. 1.11 Different types of flow filament

Substituting the volume $V = A\, l$ yields,

$$F_i = \rho\, A\, l\, a$$

Again, substituting $l\, a$ = m. m/s^2 = (m/s)^2 = v^2 yields,

$$F_v = \rho\, A\, v^2$$

The resistance of a liquid to change of form is known as viscous force and it is expressed as,

$$F_v = \frac{\mu\, v\, A}{y}$$

The distance *y* is changed by the pipe diameter as,

$$F_v = \frac{\mu\, v\, A}{D}$$

Substituting yields,

$$R_e = \frac{F_i}{F_v} = \frac{\rho\, A\, v^2}{\frac{\mu\, v\, A}{D}}$$

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

And it can be rearranged as,

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

Substituting yields,

$$R_e = \frac{v\, D}{\vartheta(nu)}$$

1.12. Pascal Law

French mathematician, physicist **Blaise Pascal** (1623–1662) experimented that when a force is applied to a confined liquid, the change in pressure is transmitted equally to all parts of the fluid as shown in Fig. 1.12. According to his name, it is known as Pascal law. This law stated that "a change in pressure applied to any part of the enclosed fluid is transmitted without reduction to every point of the fluid and the walls of the container". In an enclosed fluid, the molecules of the fluid are free to move about. Therefore, the molecules of the fluid transmit pressure to all parts of the fluid and the walls of the container. The pressure is defined as the force per unit area and mathematically, it is expressed as,

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

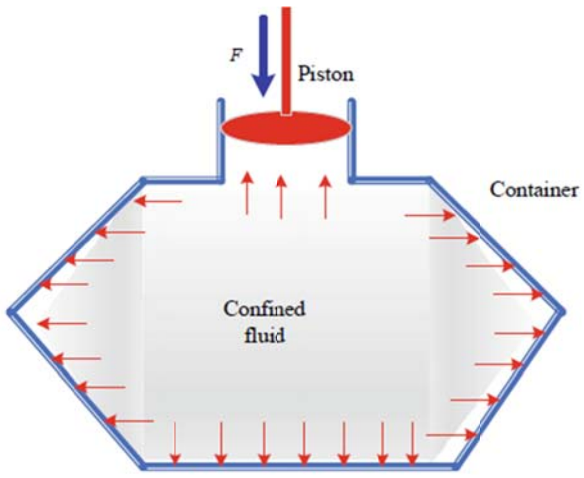

Fig. 1.12 A container with liquid

The last equation can be more visualized using Fig. 1.13. From Fig. 1.13, the expressions of force and area can also be written for specific calculation purposes.

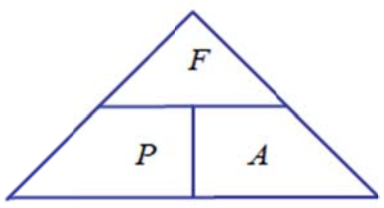

Fig. 1.13 A pressure triangle