Chapter 1

Fluid Properties

1.1. Introduction

What is hydraulics?

Hydraulics is derived from a Greek Word " Hydraulikos" which means water. It is the study of water and some engineering fluids, which a hydraulic/civil engineer is called upon to store, convey or pump. Engineering fluid includes wastewater in waste disposal and oils in hydraulic control gear.

The basic aim of hydraulics is to understand and control the occurrence, movement and use of water for the benefit of society whether it is in lakes, rivers, pipes, drains, percolating through soils or pounding the coastline as destructive waves. Therefore, the fundamentals in hydraulic engineering systems involve the application of engineering principles and methods to the planning, control, transportation, conservation, and utilization of water.

Why do we study hydraulics?

All organized societies need adequate water supplies, drainage to dispose of waste or excess water, as well as protection from uncontrolled water. Thus an obvious necessity for a study of hydraulics exists.

Applications of hydraulics include

- Design of a wide range of hydraulic structures (dams, canals, weirs etc.) and machinery (pumps, turbines and fluid couplings)
- Design of a complex network of pumping and pipelines for transporting liquids.
- Power generation
- Flood protection
- Surface and ground water studies
- Flow metering like orifice meter
- Pressure measurement

1.2. Fluids and their properties

Matter can be distinguished by the physical form of its existence (**phases**) as solid, liquid and gases, for example water appears in liquid, solid (Snow and ice), or gaseous (moisture or water vapor) form depending on the extent of hydrogen bonding. Liquid and gaseous phases are usually combined and given a common name of fluid.
Exercise: Distinguish solid, liquid and gas.

Definitions

Fluids: *Fluids are substances, which deform continuously under the application of a shear force, no matter how small the force might be. They are characterized by their ability to flow.*
(Shear force = force component tangent to a surface. This force divided by the area = average shear stress).

Properties: *intensive, extensive, physical and chemical.*

Every fluid has certain characteristics by which its physical condition may be described. We call such characteristics properties of the fluid. These properties can be divided in to two broad categories: Extensive properties, which depend on the size of a sample of matter; and intensive properties, which are independent of the sample size. Of the two intensive properties are the more useful because a fluid will exhibit the same intensive property regardless of how much of it we examine. Examples of extensive property are mass and volume as the amount of a substance increases; its mass and volume also increase. Intensive properties include density, pressure and temperature.

In speaking of the properties of fluids, we also distinguish between physical and chemical properties. A physical property can be specified with out reference to any other fluid. Density, mass volume, colour etc are all examples of physical properties. A chemical property on the other hand states some interaction between chemical substances.

The way fluid (water) behaves under various conditions encountered in practice depends primarily on its fundamental and physical properties, which are briefed as follows.

1.2.1. Physical Properties

An understanding of fluid behavior and application of its basic laws through experimentation advances the subject of hydraulics. Fluid properties play principal roles both in open channel and pipe flow.

The principal physical properties of fluids are described as follows.

1. Density

There are three forms of density

a. Mass density or density, denoted by ρ (Greek, rho)
It is defined as the mass per unit volume.

$$\text{or density} = \frac{Mass\ of\ fluid\,(m)}{Volume\ occupied\,(v)}\ ,\ \rho = \frac{m}{v}$$

- ☞ SI unit $Kg/\ m^3$
- ☞ Dimensionally ML^{-3}
- ☞ For an incompressible fluid, 'ρ' is constant
- ☞ For water, ρ is 1000 $kg/\ m^3$ at 4^0 c and standard pressure (760 –mm Hg) (There is a slight decrease in density with increasing temperature, but for normal practical purposes the value is constant)
- ☞ Generally, the density of liquids is only slightly dependent on either temperature or pressure and the variation can be ignored but for gases, it significantly varies with both temperature and pressure.

b. Specific weight / unit weight / unit gravity force /, designated by γ (Gk, gamma)
It is defined as the weight per unit volume.

$$\gamma = \frac{W}{V} = \frac{mg}{v} = \rho g$$

W = weight = mass x gravitational acceleration (g)

$$\gamma = \rho g$$

- ☞ SI unit N/m^3 (usually $KN/\ m^3$)
- ☞ Dimensionally $(ML^{-2}\ T^{-2})$
- ☞ At 4^0c 'γ' for water is 9.806 / 9.81 KN/m^3/
- ☞ It changes with location on the earth's surface depending upon g.

c. Specific gravity (S) or relative density (rl. dn.)

It is defined as the ratio of mass of a body to mass of an equal volume of a substance taken as a standard (for liquids water at 4^0 c)

$$\text{Re}lative\ density = \frac{mass\ of\ \ fluid}{mass\ of\ \ equal\ \ volume of\ \ water}$$

$$= \frac{density\ of\ \ fluid}{density\ of\ \ water}$$

- ☞ It is a pure no (dimensionless parameter)

Typical values of specific gravities:

- ☞ Relative density of water is 1.00 (S water = 1.00, standard for measuring relative density of other liquids).
- ☞ S mercury = 13.6, commonly used secondary fluid in manometers for pressure measurement.
- ☞ Oils usually have a relative density less than one and they float on water.
- ☞ If relative density of a given oil is 0.8 its density is 0.8 (1000 kg / m^3) = 800 kg/ m^3

Note:

It is clear that density, specific weight, and specific gravity are all interrelated and from knowledge of any one of the three the others can be calculated.

2. Specific Volume (Vs)

It is the volume occupied by a unit mass of fluid or simply the reciprocal of density.

$$Vs = \frac{v}{m} = \frac{1}{\rho}$$

- ☞ Commonly applied to gases

Example 1

A mass of liquid weights 600N when exposed to standard earth's gravity g = 9.81m/sec^2

a. What is its mass?

b. What will be its weight in a planet with acceleration due to gravity is 4m/sec^2.

c. What will be its density if the volume of the liquid is equal to 0.06116m^3?

Solution

Let w = weight of liquid

m = mass of liquid

a) W = mg

$$m = \frac{W}{g} = \frac{600N}{9.81m/\sec^2} = 61.16kg \qquad (ans)$$

b) If g = 4m/sec^2

Therefore weight = mg

= 61.16*4

= 244.6N

c) $$\rho = \frac{m}{V} = \frac{61.16kg}{0.06116}$$

$$= 1000kg/m^3$$

Example 2

10 liters of a liquid of specific gravity 1.3 is mixed with 8 liters of a liquid of specific gravity 0.8. If the bulk of the liquid shrinks by 1% on mixing, calculate the specific gravity, mass density, the volume and weight of the mixture.

Solution

Let V_1 = 10 liters = 0.01m^3, Sp. gr 1 = 1.3

V_2 = 8 liters = 0.008m3, Sp. gr 2 = 0.8

Total volume = $V_1 + V_2$

= 0.01 + 0.008

= 0.018m^3 (ans)

After shrink by 1%, volume of mixture = 0.018 * 0.99

= 0.01782m^3

$$Sp.gr = \frac{\rho_{liquid}}{\rho_{water}}$$

ρ_{liquid} 1 = Sp. gr 1 * ρ_{water}

= 1.3 * 1000kg/m^3

= 1300kg/m^3

Therefore mass $m_1 = \rho_{liquid\ 1}$ * Vol. 1

= 1300*0.0

= 13kg

ρ_{liquid} 2 = Sp. gr 2 * ρ_{water}

= 0.8 * 1000

= 800kg/m^3

mass $m_2 = \rho_{liquid\ 2}$ * Vol. 2

= 800 * 0.008

m_2 = 6.4 kg

Total mass = $m_1 + m_2$ = 13 + 6.4 = 19.4 kg

- Density of mixture = $\frac{Total\ mass}{Total\ volume} = \frac{19.4kg}{0.01782m^3} = 1088.7kg/m^3$ (ans)
- Specific gravity = $\frac{1088.7kg/m^3}{1000kg/m^3} = 1.0887$ (ans)
- Weight of mixture = mass * g

  = 19.4 * 9.81

  = 190.314N (ans)

3. Bulk modulus of elasticity or Compressibility, K (kappa)

For most practical purposes liquids may be regarded as incompressible. However, there are certain cases, such as water hammer, where the compressibility should be taken into account. If water were not compressible, then closing a valve on a pipeline could be a dangerous task. Imagine trying to stop suddenly a solid column of water several kilometers long. The force involved would be immense. Fortunately water is compressible and compresses like a spring to absorb the energy of the impact as the valve is closed. Water hammer pressures are quite large. Therefore, engineers must design piping systems to keep the pressure within acceptable limits. This is done by

- Installing an accumulator near the valve and/or operating the valve in such a way that rapid closure is prevented. Accumulators may be in the form of air chambers for relatively small systems, or surge tanks.
- Installing pressure-relief valves at critical points in the pipe system.

Analysis of water hammer is beyond the scope of this course.

If the pressure of a volume of fluid is increased by dp, it will cause a volume decrease dv, then the bulk modulus of elasticity is defined as

Bulk modulus (K) = (stress=change in pressure) / (volumetric strain)

$$K = -\frac{dp}{dv/v} \qquad v = \text{original fluid volume}$$

The negative sign indicates a decrease in volume with the increase in pressure.
$\rho = m/v$

Mass of a certain volume is constant, differentiating ρ.

$$d\rho = d\left(\frac{m}{v}\right) = md\left(\frac{1}{v}\right) = -m\frac{dv}{v^2} = -\frac{m}{v}\frac{dv}{v} = -\rho\frac{dv}{v}$$

$$\Rightarrow \frac{d\rho}{\rho} = -\frac{dv}{v}$$

Substituting: $k = \dfrac{dp}{d\rho/\rho}$

- ☞ The concept of the bulk modulus is mainly applied to liquids, since for gases the compressibility is so great that the value of K is not a constant
- ☞ For water, k is approximately 2150 N/ mm^2 at normal temperatures and pressures.
- ☞ For steel k = 215000 N/ mm2 (i.e. water is 100 times more compressible than steel)

4. Absolute / (Dynamic) Viscosity (μ = mu)

The resistance to flow because of internal friction is called viscous resistance and the property, which enables the fluid to offer resistance to relative motion between adjacent layers, is called the viscosity of liquid. It is a measure of resistance to tangential or shear stress and arises from the interaction and cohesion of fluid molecules.

The liquid molecules are closely spaced, with strong cohesive forces between molecules, and the resistance to relative motion between adjacent layers of fluid is related to these intermolecular forces. As the temperature increases, the cohesive forces are reduced with a corresponding reduction in resistance to motion, since viscosity is an index of this resistance, it follows that the viscosity is reduced by an increase in temperature.

A gas, on the other hand, has very small cohesive forces. Most of its resistance to shear stress is the result of molecular interaction. As the temperature of the gas increases, the random molecular activity increases hence viscosity increases with temperature.
The effect of temperature on viscosity is approximated by

for gases

$$\mu = \frac{CT3/2}{T+S}$$

C and S empirical constant

(Sutherland equation)

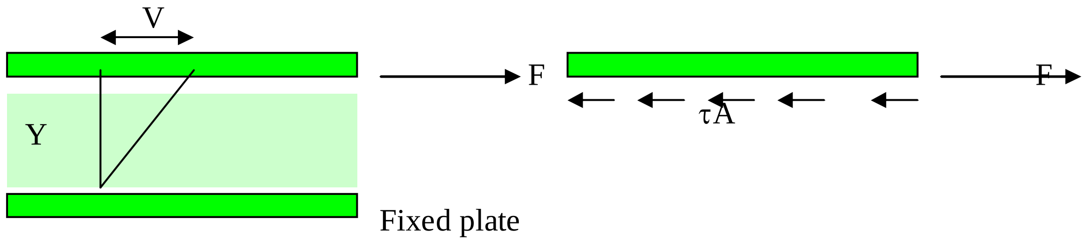
for liquids

$$\mu = D \quad e^{B/T}$$

D and B constant, T=absolute temperature

(Andrade's equation)

Consider a fluid confined between two plates which are situated a very short distance y-apart. The lower plate is stationary whilst the upper plate is moving at a velocity v. Hence; the fluid in immediate contact with the moving plate has a velocity v and with the stationary plate has zero velocity. (The experimental observation that the fluid "sticks" to the solid boundary is very important one in fluid mechanics and is usually referred to as the no slip condition. All fluids satisfy this condition.)



F is the force required to move the surface at constant velocity.

Fig. Viscous deformation

If distance y and velocity V are not great, the velocity variation (gradient) will be a straight line. Experiments show that, F is directly proportional to A and V and inversely proportional to thickness Y.

- Similarity of triangles

$$F \; \alpha \; \frac{AV}{Y} = A \frac{dv}{dy} \qquad \frac{v}{y} = \frac{dv}{dy}$$

- A = area of upper plate

$$\text{or} \quad \frac{F}{A} \; \alpha \; \frac{dv}{dy} \qquad \frac{F}{A} = \tau \text{ (tau) = shear stress}$$

$$\tau \; \alpha \; \frac{dv}{dy}$$

If a proportionality constant μ, called absolute (dynamic) viscosity, is introduced.

$$\tau = \mu \frac{dv}{dy} \quad or \quad \mu = \frac{\tau}{\frac{dv}{dy}}$$

This expression was first postulated by Newton and is known as Newton's equation of viscosity.

- ☞ Heavy oils have greater viscosity than water and water is more viscous than air.
- ☞ All real fluids posses' viscosity, though to varying degrees.
- ☞ There can be no shear stress in a fluid, which is at rest
- ☞ The SI unit of μ is N.s /m^2or Pa.s (kg/ m.s),
- ☞ Or in cgs system $\frac{gm}{cm.s}$ termed as poise
- ☞ One poise = 0.1 kg m^{-1} s^{-1} = 0.1 Pa.s
- ☞ Dimensionally = (ML^{-1} T^{-1}) (FL^{-2} T)

In many problems concerning fluid motion the viscosity appears in the form of μ/p and it is convenient to employ a single term ν (nu), known as kinematic viscosity, and so called because the units mm^2/s (L^2T^{-1}) is independent of force.

Kinematic viscosity = $\frac{absolute viscosity(\mu)}{mass\ \ density\ (\rho)}$ $i.e\ \upsilon = \frac{\mu}{\rho}$

- ☞ SI unit of ν is m^2/s in cgs system cm^2/s called stoke.
- ☞ For water, ν = 1.14 mm^2/s at $15^0{}_c$
- ☞ For heavy air ν may be as high as $900mm^2/_s$.
- ☞ Viscosities (absolute of dynamic) of liquids decrease with increasing temperature but are not affected appreciably by pressure changes.

Determination of viscosity

The following methods may be employed to determine the viscosity of liquid

I. Capillary Tube (Reading exercise)
II. Sphere Resistance (attend the experimental demonstration)
III. Rotating cylinder (see example no 7)

Viscometer

It is an instrument to measure viscosity. It measures some quantity which is a function of viscosity. The quantity measured is usually the time taken to pass a certain volume of liquid through an orifice fitted in the bottom of viscometer. The temperature of liquid while it is being passed through the orifice should be maintained constant.

Example

If the velocity distribution over a plate is given by $u = \frac{2}{3}y - y^2$ in which u is the velocity in m/sec at a distance y meters above the plate, determine shear stress in N/m^2 at y=0 and y=0.15m. Take μ = 8.63poise

Solution

$$u = \frac{2}{3}y - y^2$$

$$\frac{du}{dy} = \frac{2}{3} - 2y$$

$$\therefore \left(\frac{du}{dy}\right)_{y=0} = \frac{2}{3}$$

Hence $\tau_y = \mu\left(\frac{du}{dy}\right)_{y=0} = 0.863 * \frac{2}{3} = 0.575 N/m^2$ (ans)

$$\left(\frac{du}{dy}\right)_{y=0.15} = \frac{2}{3} - 2 * 0.15 = 0.367$$

hence $\tau_y = \mu\left(\frac{du}{dy}\right)_{y=0.15} = 0.367 * 0.863 = 0.315 N/m^2$ (ans)

Newtonian and Non - Newtonian fluids

Fluids are classified as Newtonian or non - Newtonian.

A fluid, which obeys Newton's law of viscosity, is known as a Newtonian fluid and they will have a certain constant viscosity. For these fluids the plotting of shear stress against velocity gradient is a straight line passing through the origin. The slope of the line gives viscosity.
Ex Newtonian fluid = water, air, gasoline and light oils. (Under normal condition)

In a non- Newtonian fluid there is a non -linear relation between the magnitude of applied shear stress and the rate of angular deformation.
Ex: non - Newtonian fluid: human blood, butter, printers ink etc….

- ☞ Gases and most common liquids tend to be Newtonian.
- ☞ Newtonian and Non - Newtonian fluids are real fluid.

Ideal fluid

For purposes of analysis, the assumption is frequently made that a fluid is non -viscous (frictionless) and incompressible (inelastic). Such an imaginary fluid is called ideal or perfect fluid.

Ideal fluids with zero viscosity always have zero stress and hence the plotting coincides with the x -axis.

No real fluids fully comply with this concept, but some liquids, including water, are near to an ideal fluid and the assumption is useful and justified.

Ideal solid

No deformation will occur under any loading condition, and the plotting coincides with the y -axis. Real solids have some deformation; with in the proportional limit (Hooke's law) the plotting is straight line, which is almost vertical.

Ideal plastic

Sustain a certain amount of shearing stress with out deformation and there after it would deform in proportion to the shearing stress. If not proportion they are called thyxotropic fluid.

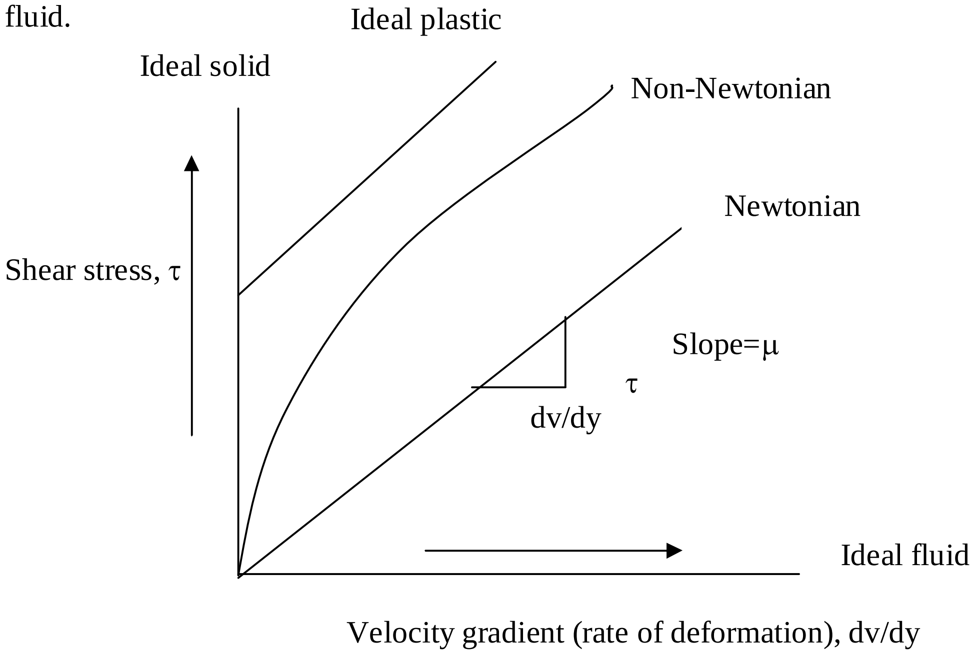


Fig. Plot of τ versus dv/dy

5. Surface tension denoted by σ (Gk. Sigma)

Considering the behavior of molecules at the interior & along the surface of a fluid mass can give us a clear understanding of surface phenomena. Take molecules in the interior of a fluid mass. They are under attractive forces in all directions and the vector sum of these forces is zero. However, at the surface between liquid and air or two immiscible liquids the upward and downward attraction are unbalanced (acted on by a net in ward cohesive force that is perpendicular to the surface) which causes the surface to behave as if it were a 'skin' or elastic membrane stretched over the fluid mass giving rise to the phenomenon of surface tension. Actually such a skin doesn't present, but this conceptual analogy allows as to explain several commonly observed phenomenon. This is demonstrated schematically in the following figure for water with a free surface.

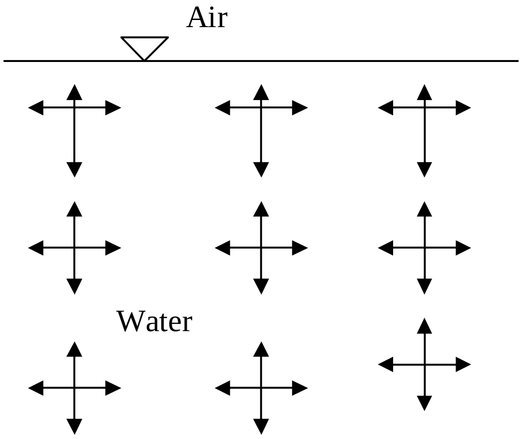


Fig. Surface tension due to molecular attraction.

Generally surface tension is a force, which exists on the surface of a liquid when it is in contact with another fluid or a solid boundary. Its magnitude depends up on nature of the liquid, and the surrounding matter which may be a solid, liquid or a gas, Kinetic energy and hence the temperature of liquid molecules (or the relative magnitude of cohesive and adhesive forces.)

Surface tension effect enables:

- An isolated drop of liquid to take nearly a spherical shape.
- A drop of water to be held in suspension at a tap.
- Birds to drink water from ponds.
- A vessel to be filled slightly above the brim.
- Dust particles and needle to float on the surface of liquids.
- Capillary rise and depression in thin-bored tubes.

Capillarity or meniscus effect

When a tube of small diameter called capillary tube is inserted in to a container of liquid, the level will rise or fall within the tube depending up on the relative magnitudes of the cohesion of the liquid and the adhesion of the liquid to the wall of the containing vessel. Liquids rise in tubes they wet (adhesion > cohesion) and fall in tubes they do not wet (cohesion > adhesion) see the following figure.

The phenomenon of rise and fall of liquid in a capillary tube is known as capillarity. Capillarity is important in capillary tubes, monometer or open pores in the soil. (Tubes ≤ 10 mm diameter).

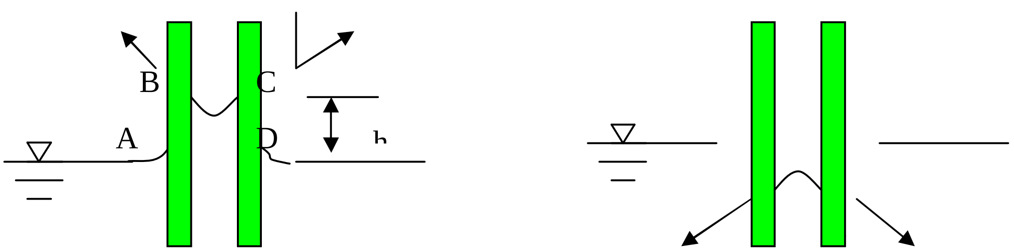


Fig. A) Rise of column of liquid for wetting liquid b) depression of column for non-wetting liquid.

The magnitude of the capillary rise (or depression), h, is determined by the balance of adhesive force between the liquid and solid surface and the weight of the liquid column above (or below) the liquid free surface.

For Fig a   The gravitational force on the column of liquid elevated must be supported by surface tension acting around the periphery of the tube.

$$\therefore \quad \sum Fy = 0$$

Component of forces due to surface tension = weight of volume (ABCD) $\rightarrow$ neglecting pressure forces.

$$\Rightarrow \quad h = \frac{4\sigma\cos\theta}{\rho g d} = \frac{4\sigma\cos\theta}{\gamma d} \qquad h = \frac{4\sigma\cos\theta}{\gamma d}$$

It is to be noted that for $0 \subseteq \theta \subseteq 90^0$ h is positive (concave meniscus and capillary rise) and that for $90 \subseteq \theta \subseteq 180^0$ h is negative (convex meniscus and capillary depression).

- ☞ For pure water and clean glass $\theta = 0^0$
- ☞ 6 for water = 0.0735 N/m

In case of liquid drop or inside a jet, the action of surface tension is to increase the internal pressure

For a liquid droplet

Considering force balance on a hemispherical drop, it is possible to equate the change in pressure (which is trying to blow apart the two hemispheres) and the surface tension σ (which is trying to pull them together).See the following figure

Therefore, $\Delta p\ \pi d^2/4 = \sigma \pi d$

$\Delta p = 4\sigma/d$

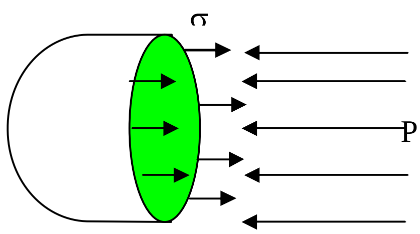


Fig. Pressure in a sphere due to surface tension

6. Vapor pressure

The vapor pressure of a liquid is the (generally small) pressure at which the liquid vaporizes or boils as it changes from the liquid to the gaseous or vapor state. The vapor pressure is strongly dependent on temperature. Water boils at atmospheric pressure when the temperature is 100^0c and at higher elevations the atmospheric pressure is less; hence, water evaporates at temperatures lower than 100^0C. This property usually has no effect on a fluid flow; however, if a flowing liquid experiences a pressure at any point, which lowers the pressure locally to the vapor pressure for that temperature, then this vaporization, will take place. In problems involving siphoning, the result of pressure reduction to the vapor point will be to break the siphon and interrupt the flow. In other cases the flow will continue, altered in form, as the phenomenon of cavitation occurs. Cavitation is the rapid formation and collapse of small vapor bubbles, which are not only disruptive, but are also frequently destructive as well. This subject will be treated more fully in other courses.