Fluid Properties and Hydrostatics Bench

Instruction Manual

F9092

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Disclaimer

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General Overview

A fluid is defined as any substance which when acted upon by a sheer force, however small, undergoes a continuous and unlimited deformation. If the rate of deformation is directly proportional to the magnitude of the applied force the substance is termed a Newtonian fluid and the apparatus provided here has been selected to permit the study of all the important properties of such fluids.

With this apparatus students are able to develop their knowledge of a wide range of principles and techniques that will be of lasting value in their studies of fluid mechanics.

The equipment is entirely self-contained, mobile and independent of all laboratory services. It includes a full range of ancillary equipment required for the experiments.

Equipment Diagrams

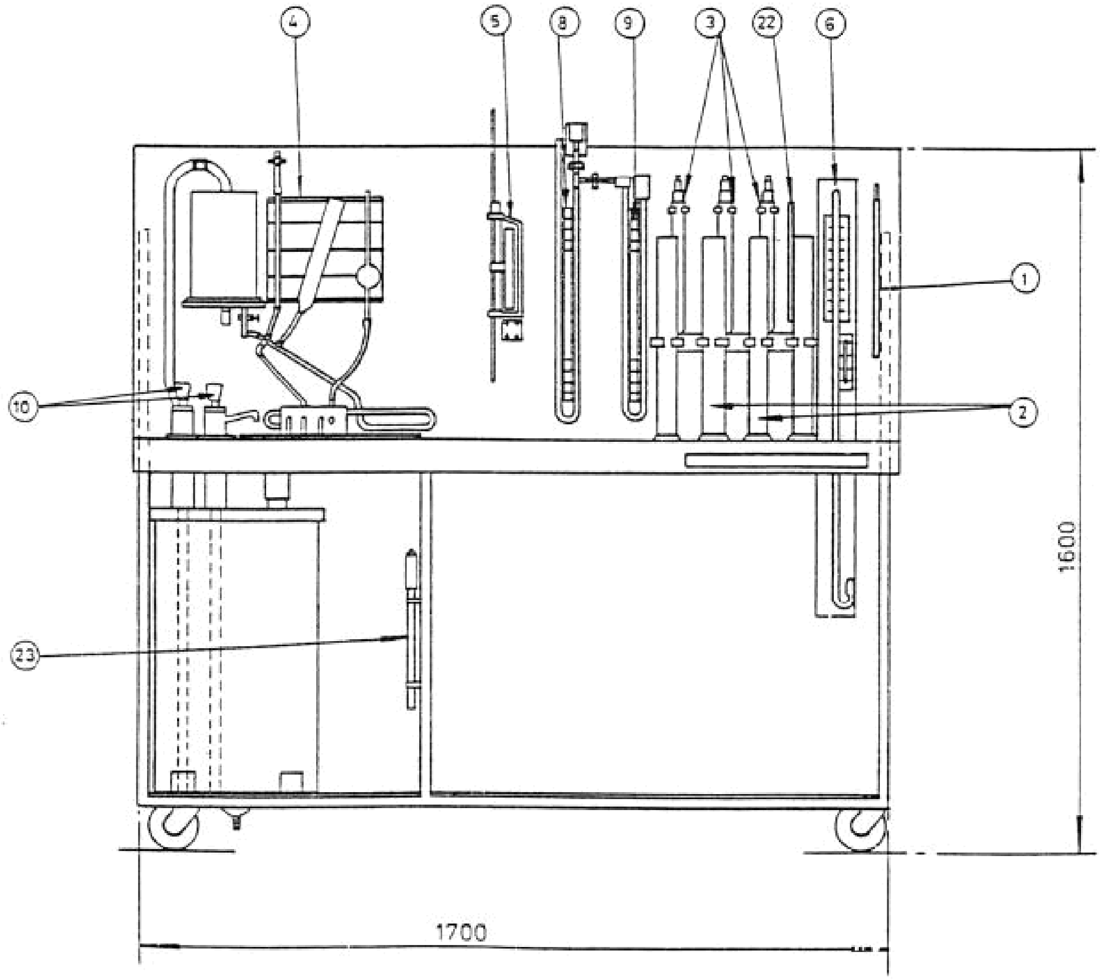


Figure 1: F9092 Fluid Properties and Hydrostatics Bench Equipment diagram

1. Universal hydrometer (Stored on backboard)
2. Hydrometer jars (Free standing & clipped to backboard)
3. Falling sphere viscometers (Clipped to backboard)
4. Free surface tubes (Permanently mounted on backboard)
5. Hook and point gauge (Permanently mounted on backboard)
6. Mercury barometer (Permanently mounted on backboard)
7. Bourdon gauge: part of F1-11 (Free standing)
8. Mercury 'U' tube manometer (Mounted on backboard)
9. Mercury 'U' tube manometer (Mounted on backboard)

10. Hand operated water pumps (Mounted in bench top alongside sink)
11. Dead-weight pressure gauge calibrator and weights: part of F1-11 (Free standing)
12. Hydrostatic pressure apparatus and weights: F1-12 (Free standing)
13. Pascal's apparatus and shaped tubes (Free standing)
14. 600ml beaker (Free standing)
15. Stop clock (Free standing)
16. Parallel plate capillary apparatus (Free standing)
17. Capillary tube apparatus (Free standing)
18. Lever balance (Free standing)
19. Displacement vessel, bucket and cylinder (Free standing)
20. Metacentric height apparatus: F1-14 (Free standing)
21. Measuring cylinder (Free standing)
22. Thermometer (Stored on backboard)
23. Air pump (Clipped to frame)
24. Circular spirit level (Free standing)

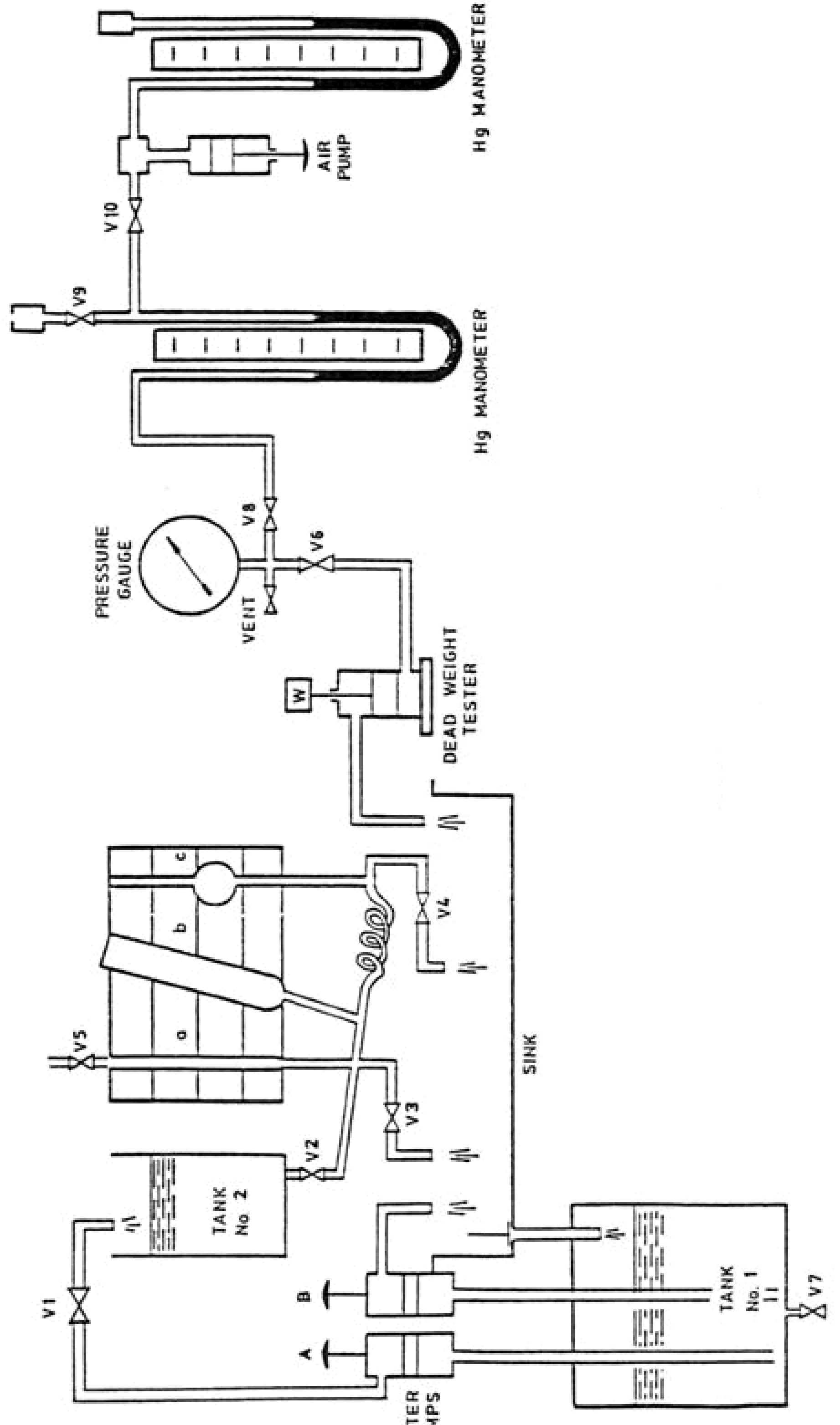


Figure 2: F9092 Schematic diagram

Important Safety Information

Introduction

Before proceeding to install, commission or operate the equipment described in this instruction manual we wish to alert you to potential hazards so that they may be avoided.

Although designed for safe operation, any laboratory equipment may involve processes or procedures which are potentially hazardous. The major potential hazards associated with this particular equipment are listed below.

- Injury through misuse
- Poisoning from toxic materials (eg. mercury)
- Injury from incorrect handling
- Damage to clothing
- Risk of infection through lack of cleanliness

Accidents can be avoided provided that equipment is regularly maintained and staff and students are made aware of potential hazards. A list of general safety rules is included in this manual, to assist staff and students in this regard. The list is not intended to be fully comprehensive but for guidance only.

Please refer to the notes overleaf regarding the Control of Substances Hazardous to Health Regulations.

The Control of Substances Hazardous to Health Regulations (1988)

The COSHH regulations impose a duty on employers to protect employees and others from substances used at work which may be hazardous to health. The regulations require you to make an assessment of all operations which are liable to expose any person to hazardous solids, liquids, dusts, vapours, gases or micro-organisms. You are also required to introduce suitable procedures for handling these substances and keep appropriate records.

Since the equipment supplied by Armfield Limited may involve the use of substances which can be hazardous (for example, cleaning fluids used for maintenance or chemicals used for particular demonstrations) it is essential that the laboratory supervisor or some other person in authority is responsible for implementing the COSHH regulations.

Part of the above regulations are to ensure that the relevant Health and Safety Data Sheets are available for all hazardous substances used in the laboratory. Any person using a hazardous substance must be informed of the following:

- Physical data about the substance
- Any hazard from fire or explosion
- Any hazard to health
- Appropriate First Aid treatment

- Any hazard from reaction with other substances
- How to clean/dispose of spillage
- Appropriate protective measures
- Appropriate storage and handling

Although these regulations may not be applicable in your country, it is strongly recommended that a similar approach is adopted for the protection of the students operating the equipment. Local regulations must also be considered.

Water Borne Hazards

The equipment described in this instruction manual involves the use of water, which under certain conditions can create a health hazard due to infection by harmful micro-organisms.

For example, the microscopic bacterium called Legionella pneumophila will feed on any scale, rust, algae or sludge in water and will breed rapidly if the temperature of water is between 20 and 45°C. Any water containing this bacterium which is sprayed or splashed creating air-borne droplets can produce a form of pneumonia called Legionnaires Disease which is potentially fatal.

Legionella is not the only harmful micro-organism which can infect water, but it serves as a useful example of the need for cleanliness.

Under the COSHH regulations, the following precautions must be observed:

- Any water contained within the product must not be allowed to stagnate, ie. the water must be changed regularly.
- Any rust, sludge, scale or algae on which micro-organisms can feed must be removed regularly, i.e. the equipment must be cleaned regularly.
- Where practicable the water should be maintained at a temperature below 20°C. If this is not practicable then the water should be disinfected if it is safe and appropriate to do so. Note that other hazards may exist in the handling of biocides used to disinfect the water.
- A scheme should be prepared for preventing or controlling the risk incorporating all of the actions listed above.

Further details on preventing infection are contained in the publication “The Control of Legionellosis including Legionnaires Disease” - Health and Safety Series booklet HS (G) 70.

Description

Where necessary, refer to the drawings in the Equipment Diagrams section.

Overview

Figure 1 shows the general layout of the bench and Figure 2 shows the relevant pipework and isolating valves.

The equipment is mounted on a steel-framed bench fitted with castors. Water is stored in a polythene tank situated on the lower shelf of the bench. A positive displacement hand-operated pump, situated on the bench top, is used to transfer water from the storage tank to an elevated open surface tank. This latter tank is connected to a number of glass tubes for free surface studies. Alternatively, the water may be transferred via another positive displacement hand-operated pump directly to a plastic sink which is recessed into the working surface so that bench top experiments may be conducted without spillage. All excess water is returned to the storage tank via the sink drain.

The remainder of the equipment consists of individual pieces of apparatus which are either free standing or fastening to the backboard of the bench.

Installation

Advisory

Before operating the equipment, it must be unpacked, assembled and installed as described in the steps that follow. Safe use of the equipment depends on following the correct installation procedure.

Installing the Equipment

The equipment is supplied with the bench unit as the major sub-assembly and the associated glassware and equipment is packed separately. The individual items should be placed on the bench in accordance with Figure 1. Several items should be secured to the backboard using the wood screws provided.

Commissioning

The bench should be positioned in a convenient location on a level floor and the castors should be locked.

Close valve V7 in the base of the sump.

Fill the sump, tank no. 1, with clean water.

Operate the positive displacement hand pump (B) and check that water is delivered to the sink.

Open the sink drain and allow the water to return to the sump.

Close valves V2, V3 and V4.

Open valve V1.

Operate the positive displacement hand pump (A) and check that water is delivered to tank no. 2.

Open valves V2 and V3 and check that tank no. 2 drains to the sink.

Open the sink drain and allow the water to return to the sump.

Open valve V9.

Close valve V10.

The two mercury manometers should be filled with clean mercury by inserting a syringe through the catch pots at the top of the manometers.

Mercury should be admitted until the level in both limbs is 250mm.

All inter-connecting pipework on the bench should be filled with water and air bubbles expelled prior to experimental use.

To avoid possible problems in shipping and prevent damage to the barometer during transit, the barometer supplied with the F9092 (Fluid Properties and Hydrostatics Bench) is not filled with mercury prior to despatch. Before use it will be necessary to fill the barometer with clean mercury (not supplied by Armfield).

A filling kit consisting of a syringe, fine tube (catheter with luer fitting to fit the syringe) and detailed filling instructions is supplied with the barometer.

Operation

Operating the Equipment

Please see the Laboratory Teaching Exercises for details on operating the equipment.

Equipment Specifications

Environmental Conditions

This equipment has been designed for operation in the following environmental conditions. Operation outside of these conditions may result reduced performance, damage to the equipment or hazard to the operator.

a. Indoor use;

b. Altitude up to 2000m;

c. Temperature 5°C to 40°C;

d. Maximum relative humidity 80% for temperatures up to 31°C, decreasing linearly to 50% relative humidity at 40°C;

e. Mains supply voltage fluctuations up to ±10% of the nominal voltage;

f. Transient over-voltages typically present on the MAINS supply;

   Note: The normal level of transient over-voltages is impulse withstand (over-voltage) category II of IEC 60364-4-443;

g. Pollution degree 2.

   Normally only nonconductive pollution occurs.

   Temporary conductivity caused by condensation is to be expected.

   Typical of an office or laboratory environment.

Routine Maintenance

Responsibility

To preserve the life and efficient operation of the equipment it is important that the equipment is properly maintained. Regular maintenance of the equipment is the responsibility of the end user and must be performed by qualified personnel who understand the operation of the equipment.

General

In addition to regular maintenance the following notes should be observed:

1. Water should be drained from the equipment when it is not in use.
2. The exterior of the equipment should be periodically cleaned. DO NOT use abrasives or solvents.
3. The polythene tank should be periodically cleaned to remove debris and deposits on the walls. DO NOT use abrasives or solvents.
4. The displacement vessel from item (19) must be completely dried after use.

Laboratory Teaching Exercises

Index to Exercises

Properties of Fluids

Density

The density of any fluid is defined as the mass per unit volume and is denoted by ρ

$$\rho = \frac{\text{Mass of fluid}}{\text{volume occupied by the mass}} = \frac{M}{L^3} \qquad .....1.1$$

since any volume is proportional to a linear dimension cubed.

It should be noted that the density of a liquid remains sensibly constant because the volume occupied by a given mass of liquid is almost invariable. But in the case of gas, the density will vary as the volume occupied by a given mass of gas varies. From this it may be deduced that a liquid may be taken as virtually incompressible while, of course, gases are compressible.

Specific gravity or relative density

The specific gravity or relative density of a fluid is defined as the mass of a given volume of a fluid divided by the mass of the same volume of water and is denoted by s

$$s = \frac{\text{Mass of a given fluid}}{\text{mass of an equal volume of water}}$$

If V is the volume of a liquid and of the water, ρ_1 is the density of the liquid and ρ_w is the density of the water

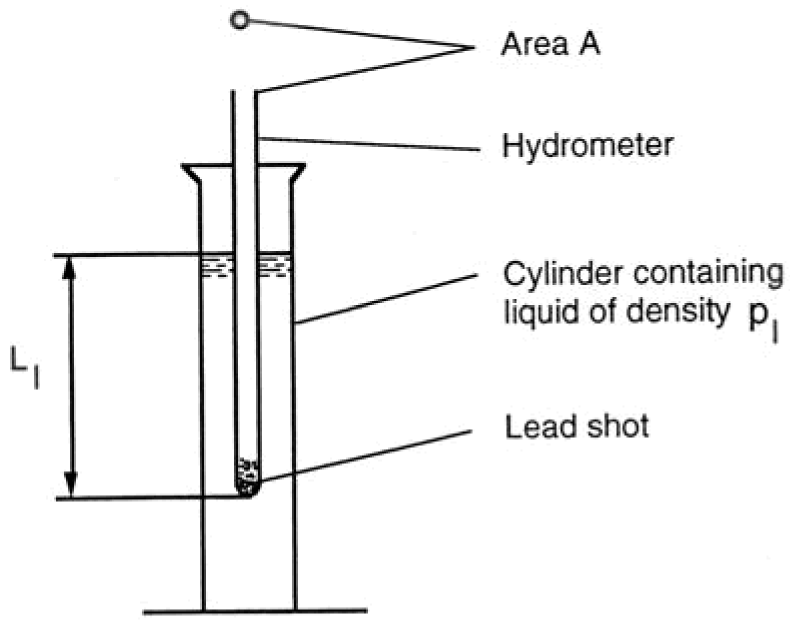
then $$s = \frac{\rho_1 V}{\rho_w V} = \frac{\rho_1}{\rho_w} \qquad .....1.2$$

The Hydrometer

In the Armfield Limited Properties of Fluids, Hydrostatics Education System are two properties dealt with above (Density and Specific gravity or relative density) obtained using the hydrometer situated on the extreme right of the apparatus (see item 1 in the Equipment diagrams).

The principle of the common hydrometer depends upon the fact that when a body floats in a liquid the gravitational force on the mass of the volume of liquid displaced is equal to the gravitational force on the mass of the body. That is, it depends upon Archimedes' principle which will be dealt with in "Stability of Floating Bodies".

A simple hydrometer may be made, therefore, from a piece of glass tube closed at one end and inside of which is placed a paper scale. A small amount of lead shot or sand should be placed in the bottom of the tube as shown below.



First immerse the tube in water and mark on the paper scale the length immersed. Then repeat by immersing the tube in another liquid, and again, mark the length immersed.

If L_W = length immersed in water of density ρ_w

and L_l = length immersed in liquid of density ρ_1

$\rho_1 = s\rho_w$

then the gravitational force on the mass of water displaced = $\rho_w g.A.L_w$ (where A = cross section area of glass tube), the gravitational force on the mass of liquid displaced = $\rho_1 g.A.L_1 = s\rho_w g.A.L_1$. From Archimedes' principle the gravitational force on tube = gravitational force on the mass of water displaced = gravitational force on the mass of liquid displaced.

$\rho_w g.A.L_w = s\rho_w g.A.L_1$

$$s = \frac{L_w}{L_1} = \frac{\text{length immersed in water}}{\text{length immersed in liquid}}$$

If then, the depth of immersion in water is marked on the paper scale as 1.00 and for the liquid by L_w/L_1 using a number of different liquids a scale may be constructed to read specific gravities directly.

Viscosity

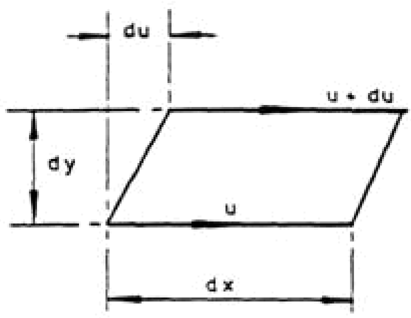
The viscosity of a fluid is that property of the liquid which resists the action of a shear force. Since viscosity depends upon the combined effect of molecular activity and cohesion, the viscosity of gases, in which the effect of cohesion is small, increase as temperature rises. Whereas, with liquids, because the greater cohesion, particularly at low temperature, has a greater effect than the molecular activity, the viscosity decreases as temperature rises.

To obtain a measure of viscosity it is necessary to consider the viscous flow of a fluid and for this two basic assumptions must be made.

1. There can be no slip or motion relative to any solid boundary.

2. The shear stress is directly proportional to the rate of shear perpendicular to the motion.

Consider an element of fluid as shown below:



Let the one face of the element move with a velocity u and then other with a velocity u + du.

Then the rate of shear perpendicular to the motion, or the transverse velocity gradient

$$= \frac{du}{dy}$$

$\therefore$ From assumption 2 the shear stress $\tau \propto \frac{du}{dy}$

$$\tau = \mu \frac{du}{dy} \qquad .....1.3$$

where μ is a coefficient of proportionality termed the coefficient of viscosity.

By arranging for the transverse velocity gradient to be numerically equal to unity, Maxwell defined the coefficient of viscosity as follows:

If two plane surfaces are placed parallel to one another and at unit distance apart, the space between them being completely filled with fluid, and if one of the plane surfaces is moved parallel to its surface at unit velocity relative to the other, then the force per unit area acting on either plane surface, in the form of a resistance to motion is numerically equal to the coefficient of viscosity of the fluid.

From Eqn 1.3

$$\mu = \tau \frac{dy}{du} = \frac{\text{force}}{\text{area}}.\frac{\text{linear dimension}}{\text{velocity}}$$

$$= \frac{\text{mass.acceleration}}{\text{area}}.\frac{\text{linear dimension}}{\text{velocity}}$$

$$= \frac{M}{L^2}.\frac{M}{T^2}.L.\frac{T}{L}$$

$$\mu = \frac{M}{LT} \qquad ......1.4$$

Thus the coefficient of viscosity is expressed as a unit of mass per unit of length and time,

eg. $= \frac{gm}{cm.s}$ or $\frac{kg}{m.s}$

An alternative measure of viscosity is the kinematic viscosity which is denoted by

$$\upsilon = \frac{\mu}{\rho} \qquad ....1.5$$

$$= \frac{M}{LT}\frac{L^3}{M}$$

$$= \frac{L^2}{T} \qquad ......1.6$$

The kinematic viscosity is expressed as a linear dimension squared per unit of time.

eg. $\frac{cm^2}{s}$ or $\frac{m^2}{s}$

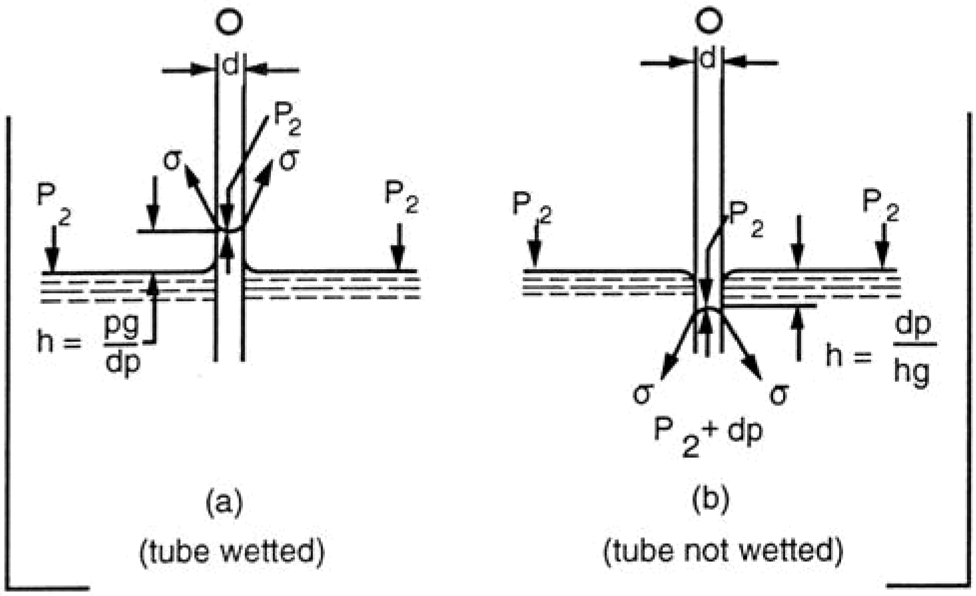
Note: μ expressed in $\frac{gm}{cm.s}$ is termed poise *

and υ expressed in $\frac{cm^2}{s}$ is termed Stoke **

$*\text{One} \quad p = \frac{1}{10}\frac{kg}{m.s} \qquad **\text{One} \quad st = 0.0001\frac{m^2}{s}$

Capillarity

When a tube of small bore is inserted into a container of liquid, the level will either rise or fall within the tube as shown below, depending upon the angle of contact between the liquid surfaces.



For liquids, such as water, which wet the tube, the conditions are as shown at (a) and result in a capillary elevation, while for liquids which do not wet the tube, such as mercury, a capillary depression results as shown at (b).

The gravitational force on the column of liquid elevated must be supported by the surface tension σ, acting round the periphery of the tube.

Resolving vertically $\rho g h \frac{\pi}{4} d^2 = \sigma \pi d \quad \cos \quad \Theta$

$$\therefore h = \frac{4\sigma \cos\Theta}{\rho g d} \qquad ......1.7$$

When the liquid wets the wall of the tube θ is zero

then Eqn 1.7 becomes $h = \dfrac{4\sigma}{\rho g d}$ 1.8

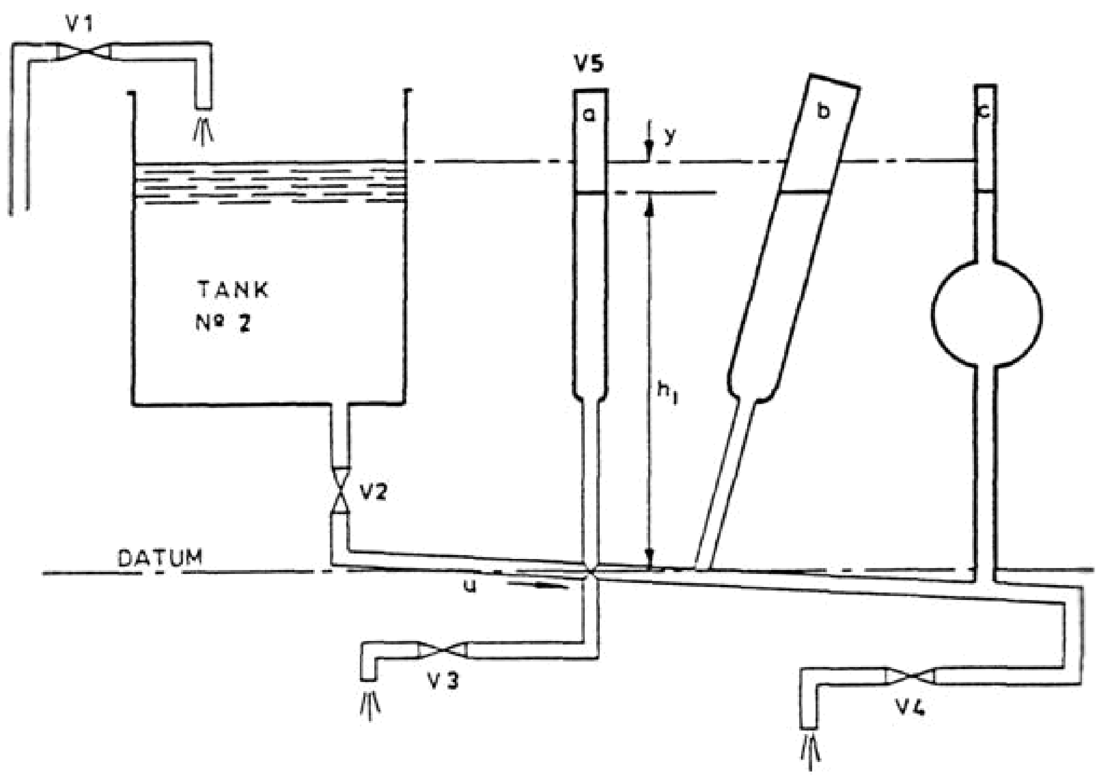
This capillary action can cause serious errors when measuring pressures in terms of a head of liquid such as with a piezometer tube, if the bore of the tube is too small.

Static Pressure

Introduction

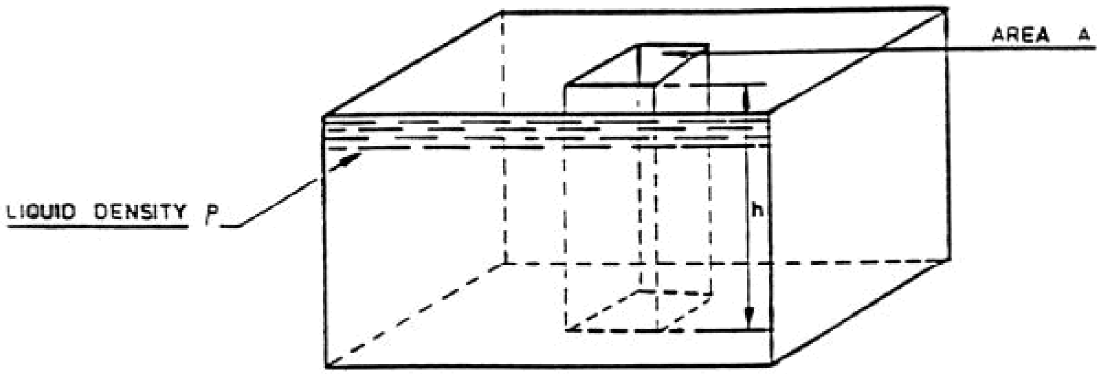
Fluid statics is concerned with fluid at rest. A fluid is said to be at rest when it is completely free from shear stress and hence all forces due to a static pressure must act at right angles to the containing surface.

With a static fluid, the only physical factor concerned is gravity. Accordingly, the free surface of the fluid will always be horizontal and, therefore, the intensity of pressure on any horizontal plane within the body of the fluid will be the same.



Variation in Intensity of Pressure with Depth

In the figure below is shown a tank containing a liquid to a depth h. Consider a vertical prism of liquid in Area A.



Total pressure on the base of Prism P.

= gravitational force on mass of liquid above it

= density x g x volume of liquid.

= ρ g Ah

Intensity of pressure at base of prism $P = \frac{P}{A}$

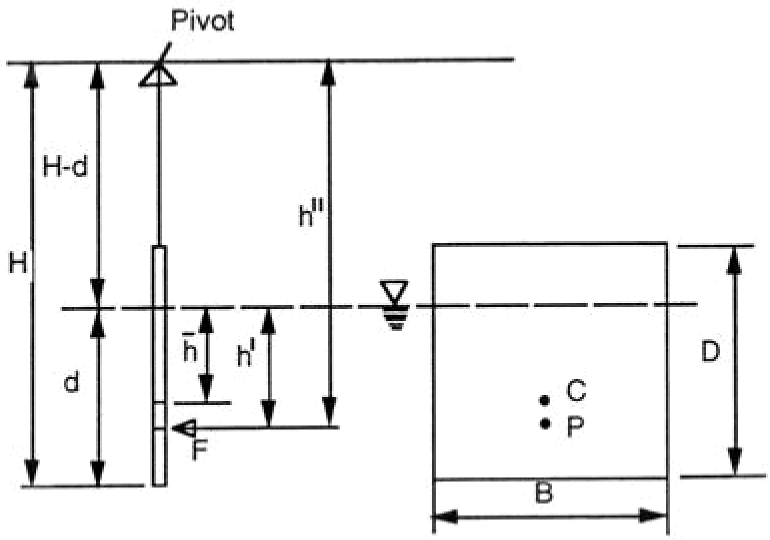
$$= \frac{P}{A} = \frac{\rho g A h}{A} = \rho g h \qquad ......2.2$$

It follows, therefore, from Eqn 2.2 that the intensity of pressure varies only with depth (for a liquid of given density).

Pressure on a Surface Immersed in a Liquid

Whilst the basic theory for the partly submerged and fully submerged plane is the same, it will be clearer to consider the 2 cases separately.

i. Partly submerged vertical plane surface



Partly submerged

a. Thrust on surface:

hydrostatic thrust, F = ρgAh (Newtons)

where A = Bd and d = depth of immersion (see figure above)

and h = depth of the centroid, C, = d/2

hence $F = \rho g \frac{Bd^2}{2}$ 2.4

b. Moment of thrust about pivot:

Moment, M = Fh" (Nm),

where h" = depth of line of action of thrust (centre of pressure, P) below pivot.

c. Equilibrium condition:

A balancing moment is produced by the weight (W) applied to the hanger at the end of the balance arm = WL (Nm).

For static equilibrium the two moments are equal

ie. $Fh'' = WL = mgL$ (m = applied mass) hence $$h'' = \frac{mgL}{F} = \frac{2mL}{\rho B d^2}$$ (metres)

experimental result, obtained by substitution for F from eqn 2.4.

d. Theoretical result for depth of centre of pressure, P, below free-surface

$$h^1 = \frac{I_x}{A\bar{h}}$$ 2.5

where I_x = 2nd moment of area of immersed section about an axis in the free surface

$I_x = I_c + A\bar{h}^2$ (by use of parallel axes theorem)

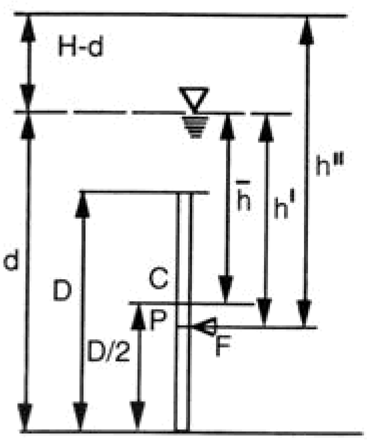
$$I_x = \frac{Bd^3}{12} + Bd\left(\frac{d}{2}\right)^2 = \frac{Bd^3}{3}\left(m^4\right)$$ 2.6

e. Depth of P below pivot point.

h" = h^1 + H - d (m) 2.7

substitution of 2.6 into 2.5 and thence to 2.7 yields h" = H - d/3 (m), as the theoretical result.

ii. Fully submerged vertical plane surface



Fully submerged

a. Thrust on surface:

$F = \rho g A\bar{h} = \rho g B D\left(d - D/2\right)$ (Newtons) (see figure above)

b. Moment of thrust about pivot:

M = Fh" (Nm as before)

c. Equilibrium condition:

Fh” = (WL) = mgL (as before)

hence, $$h'' = \frac{mL}{\rho BD\left(d - D/2\right)}$$ (metres) (experimental result)

d. Theoretical result for depth of centre of pressure (P) below free-surface

$$h^1 = \frac{I_x}{A\bar{h}},$$ (as before)

where I_x = 2nd moment of area of plane surface about an axis in the free surface.

By use of the parallel axis theorem $I_x = I_c + A\bar{h}^2$.

and $$I_x = BD\left[\frac{D^2}{12} + \left(d - \frac{D}{2}\right)^2\right]\left(m^4\right)$$

e. Depth of P below pivot point

h” = h^1 + H - d (m), as before

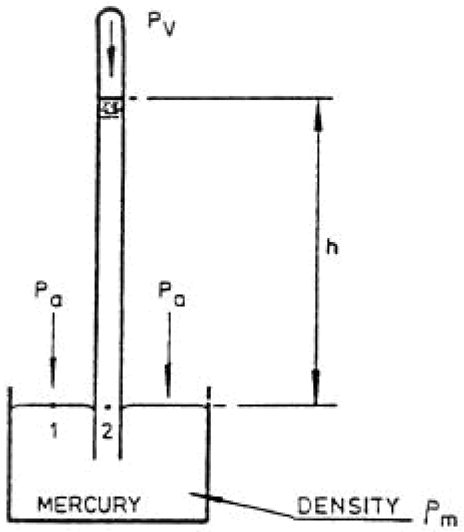
which yields $$h'' = \frac{\frac{D^2}{12} + \left(d - \frac{D}{2}\right)^2}{d - \frac{D}{2}} + H - d(m)$$

Measurement of Pressure

The Barometer

The barometer is one of the most widely used pressure measuring instruments. It is found not only in scientific laboratories but also in many homes. In the home it is used not so much as to record pressure as to indicate the weather conditions to be expected, but scientifically it is the instrument used to record the absolute pressure exerted by the atmosphere.

Torricelli was the first to discover that the pressure exerted by the atmosphere could support a column of liquid and, therefore, that the height of the column is a measure of the pressure of the atmosphere.



As shown in the figure above, if a long, sealed tube is filled with mercury and inverted so that the open end is immersed in a reservoir of mercury, thus excluding air from the tube, a vacuous space will be left at the top. The length of the resulting column of mercury will be approximately 760mm. This arrangement forms the basis of the modern barometer. The relationship between the height of the column of mercury, termed the barometric height, and the pressure of the atmosphere may be determined by equating pressure at the points 1 and 2, as shown in the figure above.

Equating pressures $P_a = \rho_m gh = s_m \rho_w gh$

neglecting the vapour pressure above the mercury where

$$S_m = \text{specific gravity of mercury} = \frac{\rho_m}{\rho_w}$$

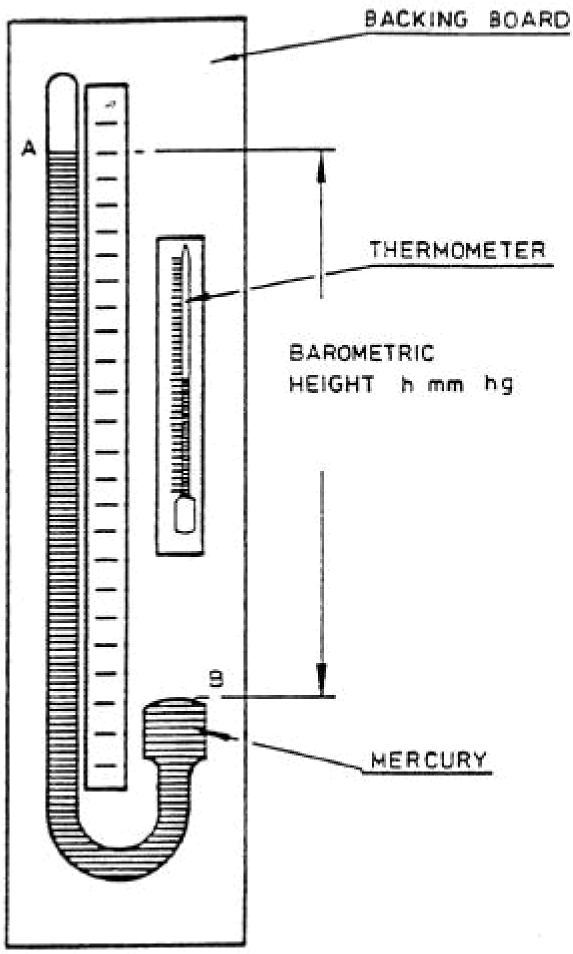
$= 13.6$ (ρ_w = density of water)

$$h = \frac{P_a}{s_m \rho_w g} \qquad ......3.1$$

The standard barometric height, which gives the standard atmospheric pressure, is 760mm of mercury, hence

$$P_a = \frac{760 \quad x \quad 10^3 \quad x \quad 9.81 \quad x \quad 13.6}{10^3 \quad x \quad 9.81} = 1.013 \quad \text{bar}$$

The type of barometer fitted to this Hydrostatics Bench is the siphon barometer as shown below.



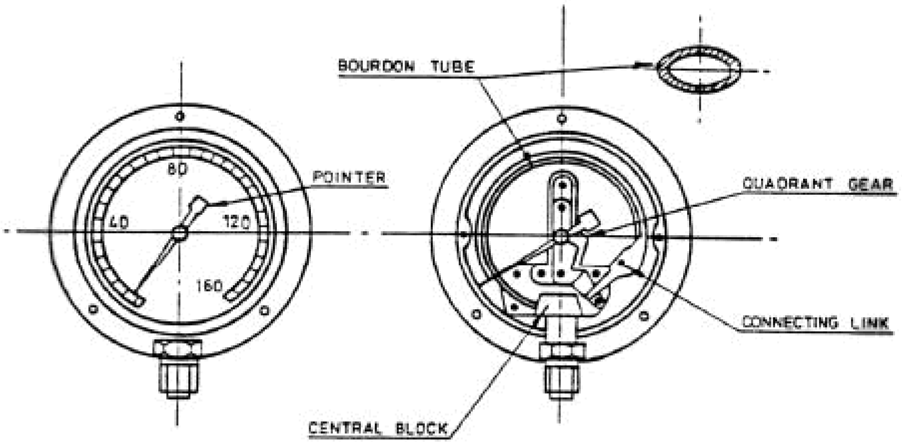
The instrument consists of a U-tube with limbs of unequal length. The shorter limb which has an enlarged end, is open to the atmosphere. The longer limb, which is about 900mm in length, is closed. The tube contains mercury and the space above "A" is a Torricellian vacuum. When the mercury rises at "A" it falls at "B". The pressure of the atmosphere, acting at "B", supports a weight of a column of mercury whose height is the difference of level of the mercury in the two limbs.

Alternative types of barometer are the Fortin barometer and the aneroid barometer, and the student should familiarise himself with both these types.

IMPORTANT: DO NOT REMOVE CAP OF PLUG FROM THE BAROMETER UNTIL THE BAROMETER HAS BEEN SET UP FOR OPERATIONAL USE.

The Bourdon-Type Pressure Gauge

This type of industrial pressure measuring instrument is shown in the figure below and measures the pressure above atmospheric or gauge pressure. The principle on which this type of gauge works is described below.



The pressure is applied to the elliptical sectioned, phosphor bronze tube through the central block. The free, sealed end of the tube straightens by an amount which is directly proportional to the applied pressure. This movement of the free end of the tube is transmitted through the connecting link to the pivoted quadrant gear which meshes with the central pinion carrying the pointer.

Before use this type of gauge should be calibrated against a standard pressure gauge or by using a dead-weight pressure gauge calibrator, a diagrammatic sketch of which is shown in Exercise K - Calibration of a Bourdon-Type Pressure Gauge.

Manometry

The Bourdon-type pressure gauge is generally used to measure large pressures above atmospheric. If the pressure to be recorded is relatively small, some convenient form of manometer should be used. All manometers are basically U-tubes but the exact shape depends upon the magnitude of the pressure to be recorded. Simple U-tubes of the type included in this test rig can, depending on their size, read pressures accurately over a range of about 1.38 bar down to 0.1 bar. The two gauges actually provide cover ranges of approximately 0.6 bar, down to 0.1 bar and 0.05 bar down to 0.01 bar.

For smaller pressure differences, the following alternative forms of the basic U-tube may be used :

a. The inverted U-tube

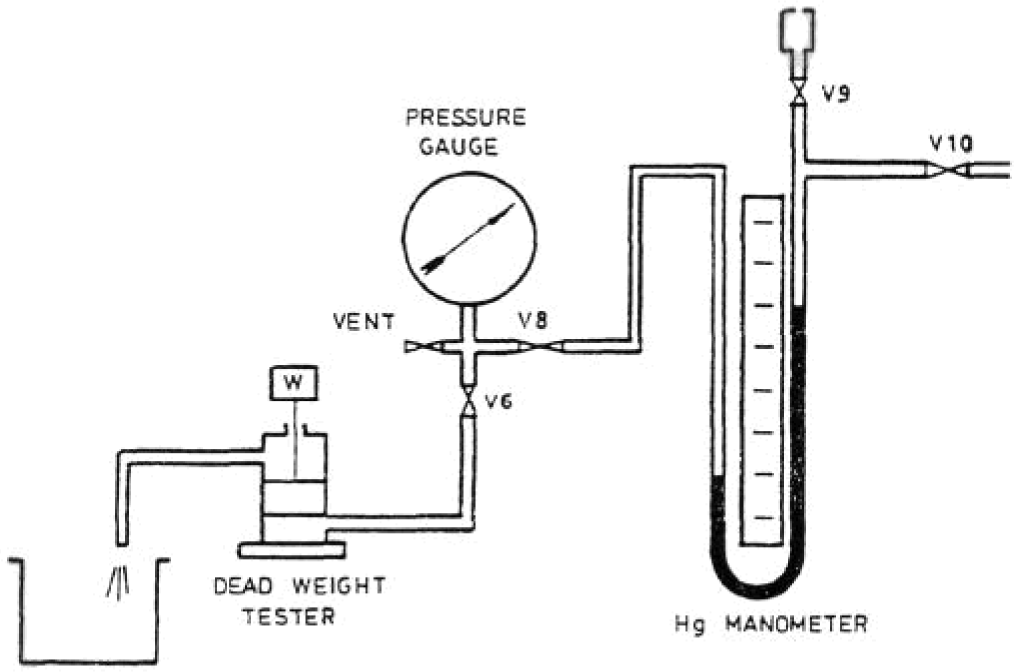
b. U-tube with enlarged ends.

c. Inclined gauge.

d. Micro-manometers.

The student should refer to any good standard text book for further details of these gauges.

The simple U-tube is shown below.



Referring to fig 21:

Equating pressures at the datum OO

$$p + \rho_f gy = p_a + \rho_m gh$$

Gauge pressure = $p - p_a = \rho_m gh - \rho_f gy$ N/m^2 ......3.2

Substituting specific gravities in equation 3.2

$$p - p_a = S_m \rho_w gh - S_f \rho_w gy$$

where ρ_w = density of water

$$\therefore \frac{p - p_a}{\rho_w g} = S_m h - S_f y$$ metres of water 3.3

Where ρ_f is very small compared with ρ_m, as in the case of f being a gas, the term $\rho_f gy$ may be neglected.

hence, in this instance, $p - p_a = \rho_m gh$ N/m^2 ......3.4

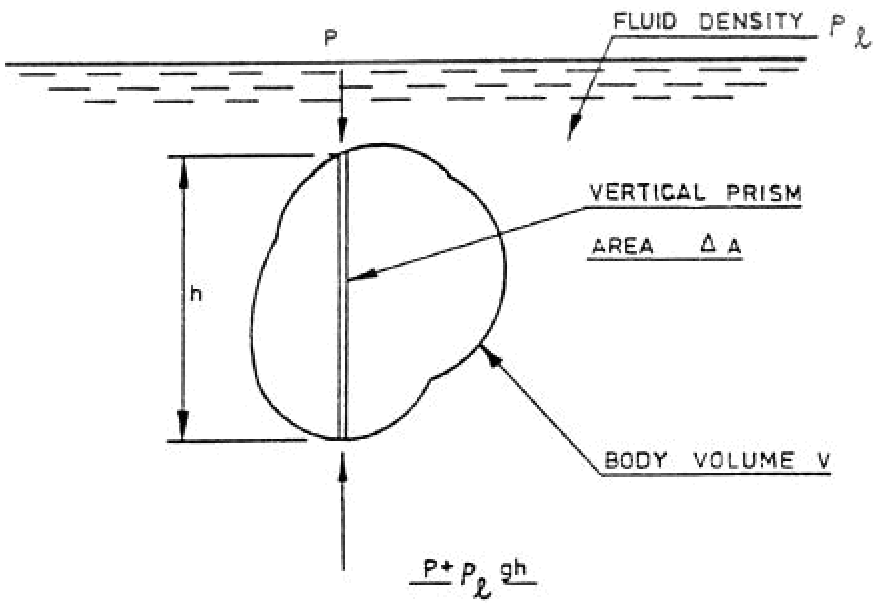
or $$\frac{p - p_a}{\rho_w g} = S_m h$$ metres of water 3.5

Stability of Floating Bodies

Buoyancy

When a body floats freely in a fluid, whether completely or partially immersed, it is acted upon by two forces only: the gravitational force on the mass of the body acting vertically downward through its centre of gravity; the buoyant force or upthrust exerted by the surrounding fluid on the body. This upthrust acts vertically upward through the centre of buoyancy which is at the centre of gravity of the displaced liquid.

A body totally immersed and floating freely in a fluid of density ρ_1 is shown in the figure below.



Consider a vertical prism taken from within the body and having an area)A.

Let the pressure acting on the top of the prism be p and that on the bottom be (p+ $\rho_1$gh)

The net vertically upward force or upthrust acting on the prism

$$\Delta F_B = (p + \rho_1 gh)\Delta A - p\Delta A$$

$$= \rho_1 gh\, \Delta A$$

If the whole body is considered to be made up of a large number of such prisms, then the net total upthrust on the whole body

$$\Delta F_b = \Sigma \Delta F_b = \rho_1 g \Sigma (h\Delta A)$$

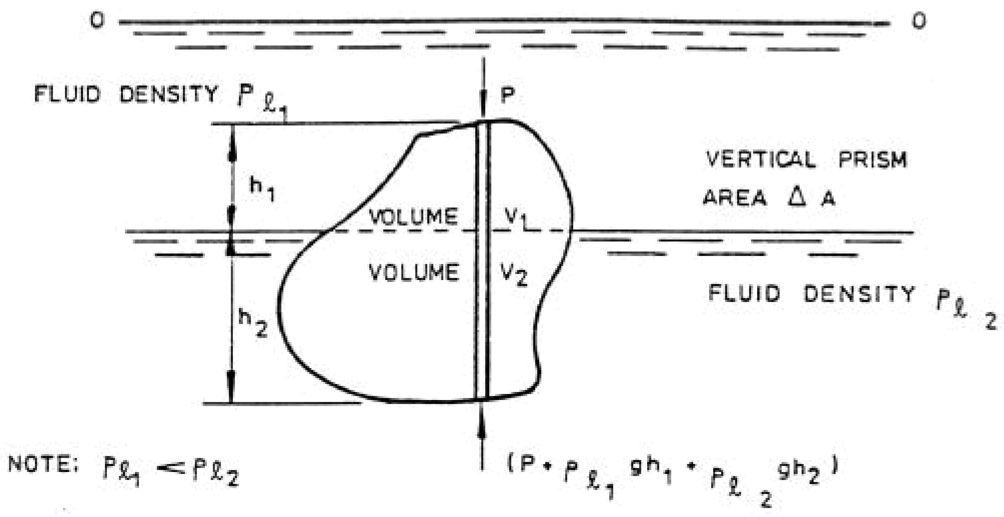
but $\Sigma(h\Delta A)$ - Volume of body = V

$\therefore F_B = \rho_1 g V$ 4.1

= gravitational force on the mass of fluid displaced by the body.

Equation 4.1 expresses algebraically Archimedes' principle, which states that every body experiences an upthrust equal to the gravitational force on the mass of fluid it displaces.

In practice, the body usually floats at the surface of separation of two fluids and the fluids commonly encountered are air and water. In general, let a body float freely in two fluids which do not mix having densities of Δ_{11} and Δ_{12} as shown in figure below.



Considering a vertical prism taken from within the body and having an area)A.

Let the pressure acting on the top of the prism be Δ and that on the bottom be $(\Delta + \Delta_{11} gh_1 + \Delta_{12} gh_2)$

The net vertical upward force or upthrust acting on the prism

$F_B = (p + \Delta_{11} gh_1 + \Delta_{12} gh_2)$)A - p)A

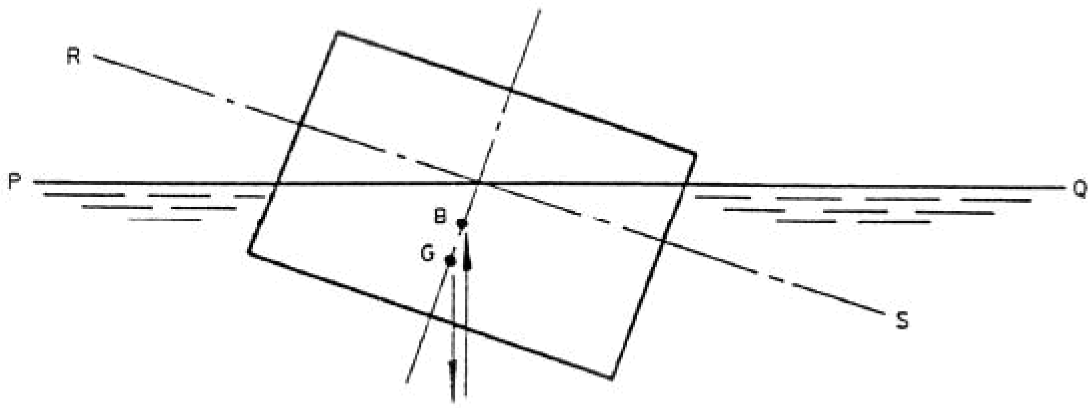
$= (\Delta_{11} gh_1 + \Delta_{12} gh_2)$)A

Equilibrium of Floating Bodies

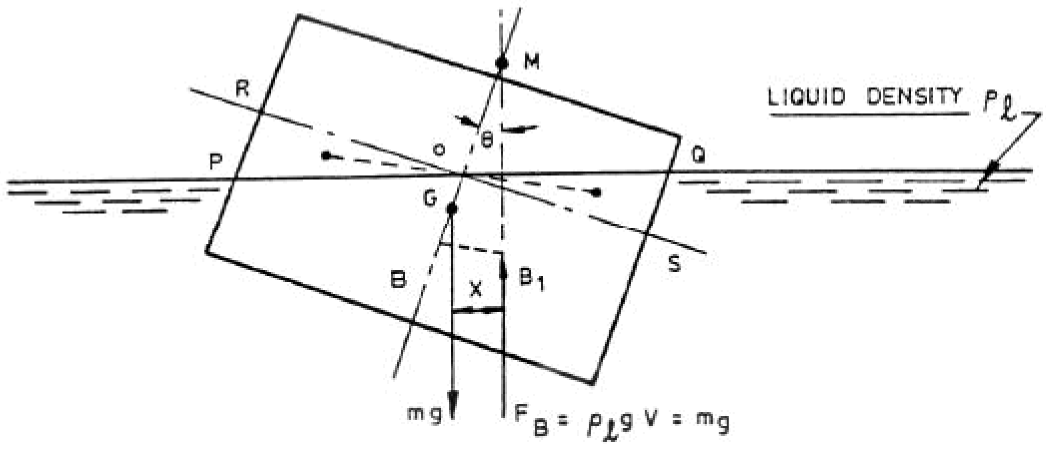
From the analysis in Buoyancy above, it should be clear that if a body is floating freely and is, therefore, in equilibrium, the following two conditions must be satisfied :

1. The upthrust must equal the gravitational force on the body.
2. The centre of gravity of the body and the centre of buoyancy must be in the same vertical line. In addition, consideration must also be given to the effect of linear and angular displacement of the body.

A floating body is said to be in a stable equilibrium if for any change from its original position, there exists forces or moments tending to restore the body to its original position. This condition will be satisfied in all cases when the centre of gravity of the body lies below the centre of buoyancy. For, as shown in the figure below, if the body receives a small angular displacement there will always exist a moment tending to restore the body to its original position.



The equilibrium of floating bodies is not confined to those cases where the centre of gravity of the body lies below the centre of buoyancy. There are, in practice, a large number of cases in which the centre of gravity is above the centre of buoyancy.



A body of rectangular section is shown in the figure above. The original free surface of the liquid is RS, and the centre of buoyancy is at B on the same vertical line as the centre of gravity of the body G, but it is below the centre of gravity. When the body is subjected to a small angular displacement 0, the liquid level changes to PQ, and hence the shape of the immersed section of the body changes, causing the centre of buoyancy to move from B to B1. When the body heels over, due to the movement of the centre of buoyancy from B to B1, a wedge of the body, ORP, emerges. The line joining B to B1 will be parallel to the line joining the centres of gravity of the wedges OQS and OPR, as shown by the dotted lines in the figure above. The upthrust FB acts vertically upward through BG at M. In this position, the body is in stable equilibrium since a righting moment of magnitude mgx exists, tending to restore the body to its original position.

When θ is small $x = GM \cdot \theta$

$\therefore$ the righting moment = $mg \cdot GM \cdot \theta$

The point M is termed the metacentre, and it was defined by Bougier as the point at which the vertical line through the centre of buoyancy intersects the centre line of the body after an infinitely small angle of heel. Clearly, the position of the metacentre, relative to the centre of gravity of the body, governs its stability. Therefore, the conditions governing the stability of floating bodies in which the centre of gravity is above the centre of buoyancy, are as given below.

1. When the metacentre is above the centre of gravity, the body is in stable equilibrium.

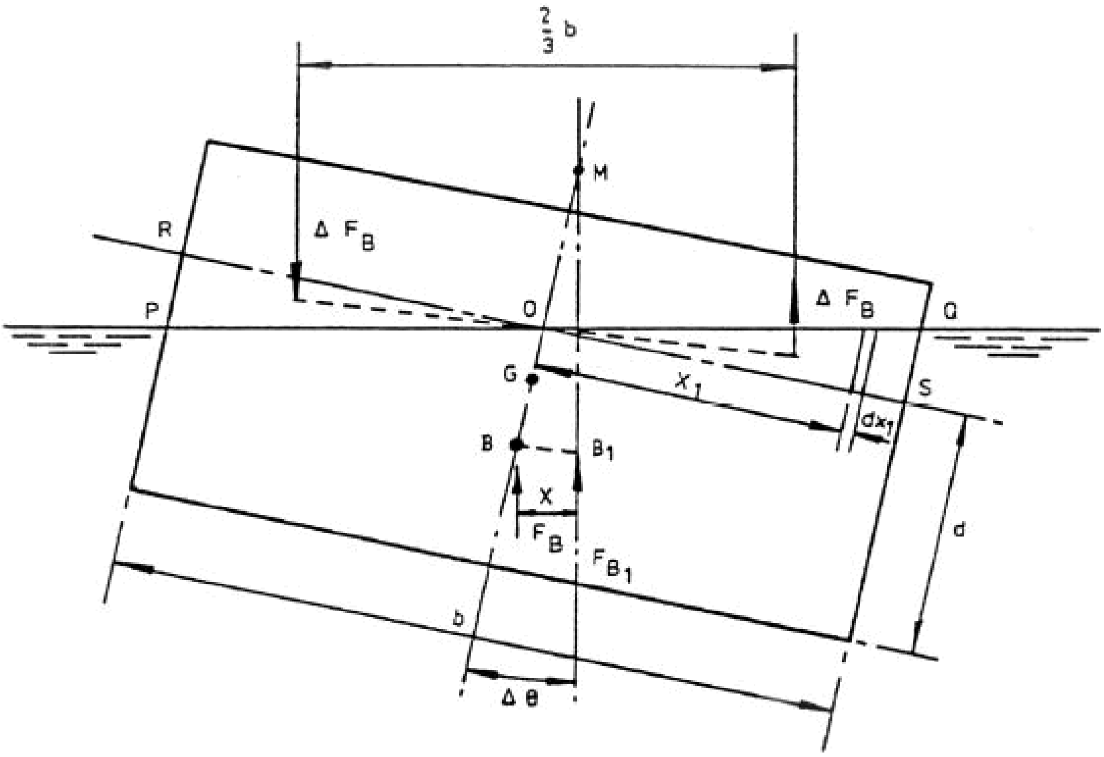
2. When the metacentre coincides with the centre of gravity, the body is in neutral equilibrium.

3. When the metacentre is below the centre of gravity, the body is in unstable equilibrium.

The distance GM is termed the metacentric height, and it must always have a position value, if the body is to be stable. The metacentric height is of importance to naval architects in the design of ships, for if its value is too large, the vessel is said to be ‘stiff’, that is, it tends to roll badly, particularly in rough seas. Commercial vessels, particularly liners, are generally designed to have a relatively small metacentric height of between 0.3 and 0.6 metres for rolling displacements about longitudinal axis, whereas, the corresponding values for pitching, will, in both cases, be much larger.

Analytical Determination of Metacentric Height

The figure below again shows the rectangular body after small angle of heel $\Delta\theta$. As stated in the proceeding section, this causes a wedge of the body, OQS, to become immersed, while an equal wedge, OPR, emerges. The effect of this is to transfer the buoyant force from B to B_1.



Let F_B = initial buoyant force acting at B.

F_{B1} = buoyant force after heeling, acting at B1.

ΔF_B = buoyant force due to immersion of wedge OQS, and emergence of wedge OPR, both acting at the centre of gravity of the respective wedges.

To find the position of B_1, it is convenient to express the buoyant force F_{B1} as follows:

$F_{B1} = F_B + \Delta F_B - \Delta F_B$

Taking moments about B

$$F_{B_1}X = \Delta F_B \frac{2}{3} b$$

hence the centre of buoyancy has moved from B to B1 through a distance

$$\frac{\Delta F_B}{F_{B_1}}\frac{2}{3}b = \frac{\Delta F_B}{F_B}\frac{2}{3}b \quad \text{since} \quad F_{B_1} = F_B$$

$$= \frac{\text{Moment of buoyant force due to transference of wedges}}{\text{Gravitational force on mass of liquid displaced}}$$

Since the position of B1 varies with the angle of heel $\Delta\theta$, it is more convenient to work in terms of the metacentre M, which remains fixed for small angles of heel.

The moment of buoyant force due to transference of wedges can be expressed more conveniently by considering a small element of the wedge OQS distance x_1 from 0.

Let the element have a thickness dxL, and a length dL in the direction of the longitudinal axis through 0.

height of element = $x_1\Delta\theta$ since $\Delta\theta$ is small

volume of element = $dL\Delta\theta\ x_1dx_1$

gravitational force on mass of liquid displaced by element = upthrust due to element $dF_B = \Delta_1 gdL)\theta x_1 dx_1$

Moment due to upthrust on element $dM = \Delta_1 gdL)\theta x_1^2 dx_1$

$\therefore$ Moment of buoyant force due to transference of wedge.

$$\int dM = \rho_1 g\Delta\Theta\int x_1{}^2 dx_1 dL \quad \text{now} \quad \int dM = \Delta F_B\frac{2}{3}b$$

$$F_B\frac{2}{3}b = \rho_1 g\Delta\Theta\int dAx_1{}^2 \quad \text{since} \quad dx_1dL = \text{area of element}$$

but $\int dAx_1{}^2 = \text{2nd moment of area about the longitudinal axis through 0}$

$= I$

$$\therefore F_B\frac{2}{3}b = \rho_1 g\Delta\Theta I \quad \text{but} \quad \Delta F_b\frac{2}{3}b = F_{B_1}x = F_Bx$$

hence, $x = \dfrac{\rho_1 g\Delta\Theta I}{F_B}$ but $F_B = \rho_1 gV$

where V = volume of liquid displaced

$$x = \Delta\Theta \frac{I}{V}$$

now x = BM$\Delta\theta$

$$\therefore BM\Delta\Theta = \Delta\Theta \frac{I}{V}$$

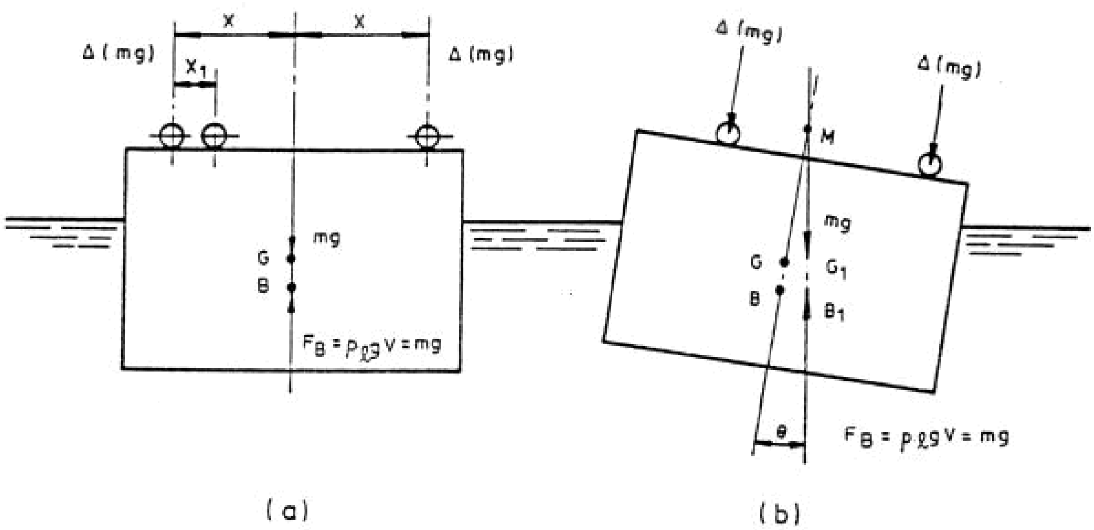
$$BM = \frac{I}{V} \qquad .....4.4$$

Then the metacentric height $\overline{GM} = \overline{BM} - \overline{BG}$.

In practice, Eqn 4.4 may be used for all cases where the angle of heel $\Delta\theta$, measured in radians, is approximately equal to tan $\Delta\theta$, and thus the optimum angle of heel is between 10° and 15°.

Experimental Determination of Metacentric Height

The body whose metacentric height is required is floated in a liquid and small masses of magnitude m are placed equidistant from the vertical axis at a convenient position on the body; as shown at (a) in the figure below. One of these masses is then moved a short distance in towards the centre, causing the body to heel through an angle 0; as shown at (b) below.



The angle of heel is measured by the apparent movement of a plumb bob suspended from a suitable point in the body. The body heels over until the upthrust and the gravitational force on the mass m, which now acts through the new position of the centre of gravity G_1, are in line.

Then, taking moments about G, since the moment of the resultant = sum of the moments of the parts.

$mgGG_1 = (\Delta mg)x - (\Delta mg)(x-x_1)$

where mg = gravitational force on the mass of liquid displaced

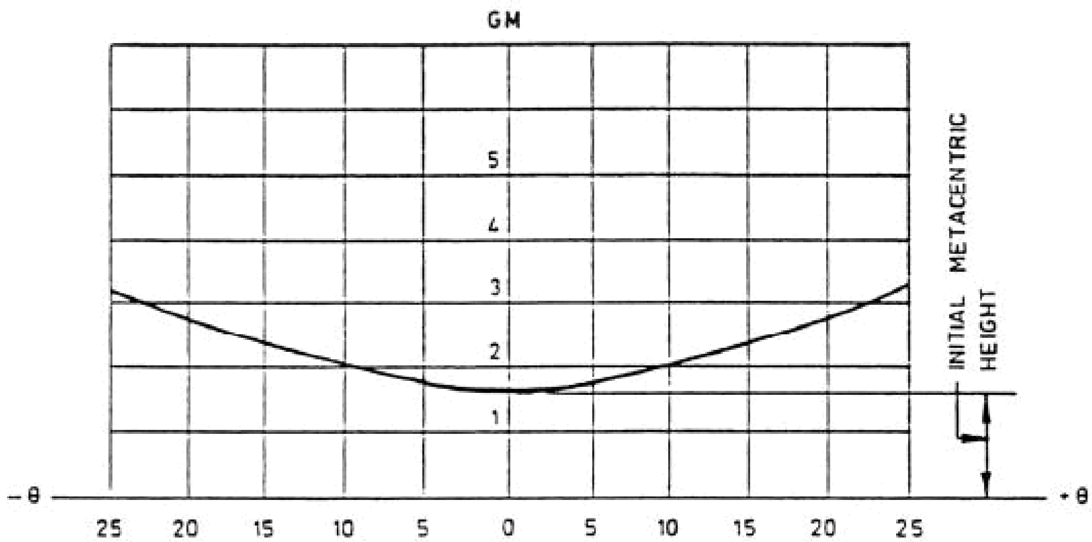
= gravitational force on body + 2 (Δmg)

$$GG_1 = \frac{\Delta mg}{mg}.x_1$$

but $$GG_1 = GM\tan\Theta = \frac{\Delta mg}{mg}.x_1$$

$$\therefore GM = \frac{\Delta mg.x_1}{mg \quad \tan\Theta} = \frac{\Delta m}{m}.\frac{x_1}{\tan\Theta} \qquad ......4.5$$

The value of the metacentric height is determined for a series of values of x_1, and by plotting a curve of GM, against θ, as shown below, the initial metacentric height can be obtained by reading the value of GM when θ is 0.



Exercise A - Measurement of densities and specific gravities

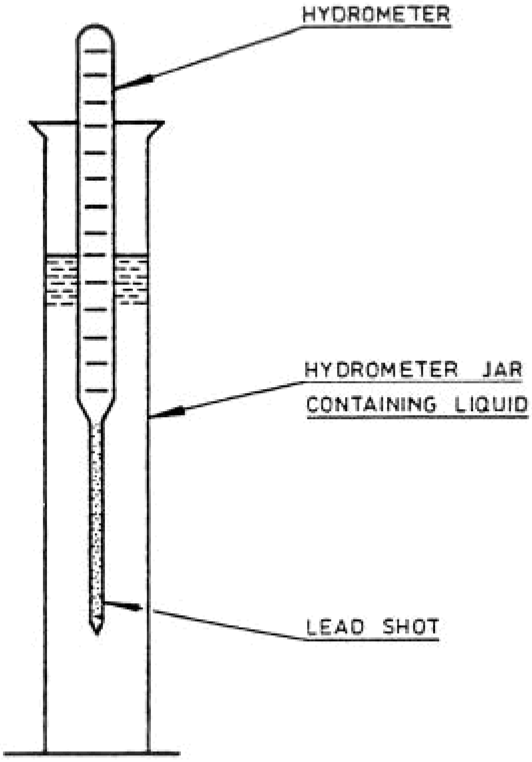
Objective

To determine densities and specific gravities.

Equipment required

Universal Hydrometer (item 1 see Figure 1)

4 off Hydrometer Jars (item 2 see Figure 1)



The Hydrometer

Theory

The specific gravity is read directly from scale. See The Hydrometer within [Properties of Fluids] for the principle on which the instrument works.

Method

a. Fill one hydrometer jar with sufficient water to float the hydrometer and check that the scale marking corresponding to depth of immersion reads 1.00.

b. Fill three hydrometer jars with the liquids to be tested with sufficient of the liquids to float the hydrometer and note for each liquid the scale reading.

Note: It is suggested that the liquids should be those to be used in Experiment B for determining the viscosity of liquids: an engine oil, glycerol and castor oil.

Results

Barometric pressure ____________ mm of Hg,

temperature __________ °C.

Liquid	Scale Reading = Specific Gravity, s
Water	
Engine Oil	
Glycerol	
Castor Oil	

since $s = \frac{\text{density of liquid}}{\text{density of water}} = \frac{\rho_1}{\rho_w}$ (Eqn 1.2 in Specific gravity or relative density, see Properties of Fluids.

$$\therefore \rho_1 = S.\rho_w$$

and $\rho_w = \frac{gm}{m1} = \frac{1}{10^3} x10^6 = 10^3 \frac{kg}{m^3}$

	Density ρ	
Liquid	gm/ml	kg/m^3
Water		
Engine Oil		
Glycerol		
Castor Oil		

Exercise B - Measurement of Viscosity

Objective

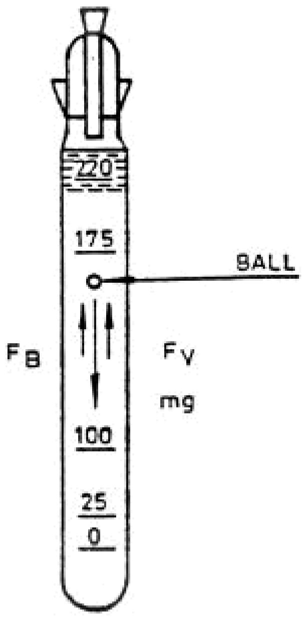
To determine the viscosity of various liquids at atmosphere pressure and temperature.

Equipment required

The Falling Sphere (Ball) Viscometer (item 3 see Figure 1)

The stop clock (item 15 see Figure 1)

Hydrometer (item 1 see Figure 1)



Falling sphere viscometer

Theory

From the figure above; when the ball is moving with a uniform velocity u, then forces acting on the sphere are:

a. the gravitational force on the ball mg.

b. the buoyant force or upthrust F_B

c. the viscous force resisting motion F_V

Since the velocity of fall is uniform, then algebraic sum of these forces must be zero.

$$\therefore mg - F_B - F_V = O$$

The gravitational force on the ball $mg = \rho_s g \frac{4}{3}\pi r^3$

where

ρ_s = density of ball

r = radius of sphere

The buoyant force $F_B = \rho_1 g \frac{4}{3}\pi r^3$

where ρ_1 = density of liquid.

The viscous force FV = $6\pi\mu ru$ from Stokes Law,

where μ = coefficient of viscosity and u = mean velocity of ball

$$\therefore \rho_s g \frac{4}{3}\pi r^3 - \rho_1 g \frac{4}{3}\pi r^3 - 6\pi\mu r u = 0$$

$$\therefore \mu = \frac{4\pi r^3 g}{3x6\pi r u}(\rho_s - \rho_1) = \frac{2}{9} r^2 g \frac{(\rho_s - \rho_1)}{u}$$

Method

a. Fill the three tubes with the liquids under test to a level of just below the exit from the capillary tube as shown in the figure above.

The liquids under test being:

i. An Engine Oil (eg. Castrol XXL)

ii. Glycerol

iii. Castor oil

Note: Since glycerol absorbs moisture easily from the atmosphere, a small amount of cotton wool should be placed in the top of the capillary tube if the tube is left full for any length of time.

b. Use three balls of different diameters with each liquid; measure diameters of the balls. Nominal size of balls supplied: 1.59mm, 2.38mm, 3.175mm.

c. Using the universal hydrometer, obtain the specific gravity of each liquid.

Results

Barometric pressure ___________ mm Hg,

Temperature _________ °C.

Measured diameter of balls: 1.59mm,

2.38mm,

3.175mm,

Specific gravity of steel: 7.8

Specific gravity of liquid:

Engine oil 0.89 (figure quoted for Castrol XXL)

Glycerol 1.25

Castor Oil 0.95

Mean velocity of ball $u = \frac{\text{Distance through which ball falls}}{\text{average time}}$

$= \frac{7.5}{t}$ cm/s where t - average time

$= \frac{.075}{t}$ m/s

Then $\mu = \frac{2}{9}\frac{r^2 g(\rho_s - \rho_1)}{u}$

Note r in metres, g in m/s^2

ρ in kg/m^3, u in m/s

and kinematic viscosity $\upsilon = \frac{\mu}{\rho}$

Fluid	Coefficient of Viscosity $\mu = \frac{kg}{m.s}$	Average μ	Kinematic Viscosity υ $\frac{m^2}{s}$
Engine Oil			
Glycerol			
Castor Oil			

Check from standard tables the accuracy of the results obtained for Glycerol and Castor Oil.

Note that with the Engine Oil, since it is considerably less viscous than either Castor Oil or Glycerol only, the 1.59mm ball can be used. With a larger size ball the time to fall 75mm is too short. If a smaller size ball is used it cannot be seen falling through the oil. Further, because the time is so short, the accuracy must be suspect.

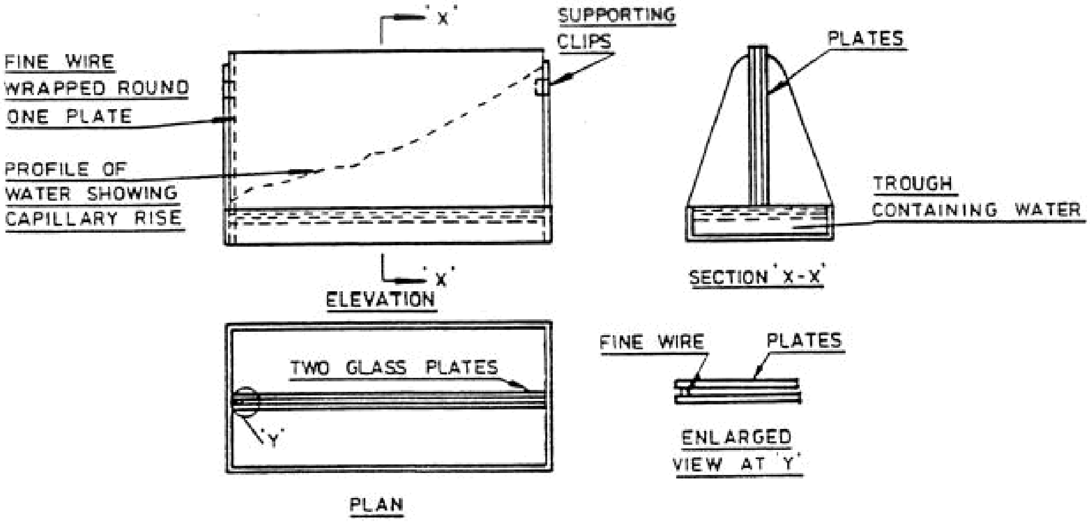
Exercise C - Observation of effect of capillarity

Objective

To observe the effect of the size of the gap between two flat plates on capillary elevation.

Equipment required

Parallel Plate Capillary Apparatus (item 16 see Figure 1)



Method

a. Thoroughly clean the two plates and wrap a length of fine wire around one plate near one end.

b. Fill trough with water,

c. Place the two plates between the supporting clips and slide to the bottom of the trough.

d. Note the pattern of the capillary rise as indicated in the figure above.

It should be noted that where the gap is at its smallest the rise is greatest, and conversely where the gap is widest the capillary rise is at its smallest.

Exercise D - Measurement of Capillary elevation

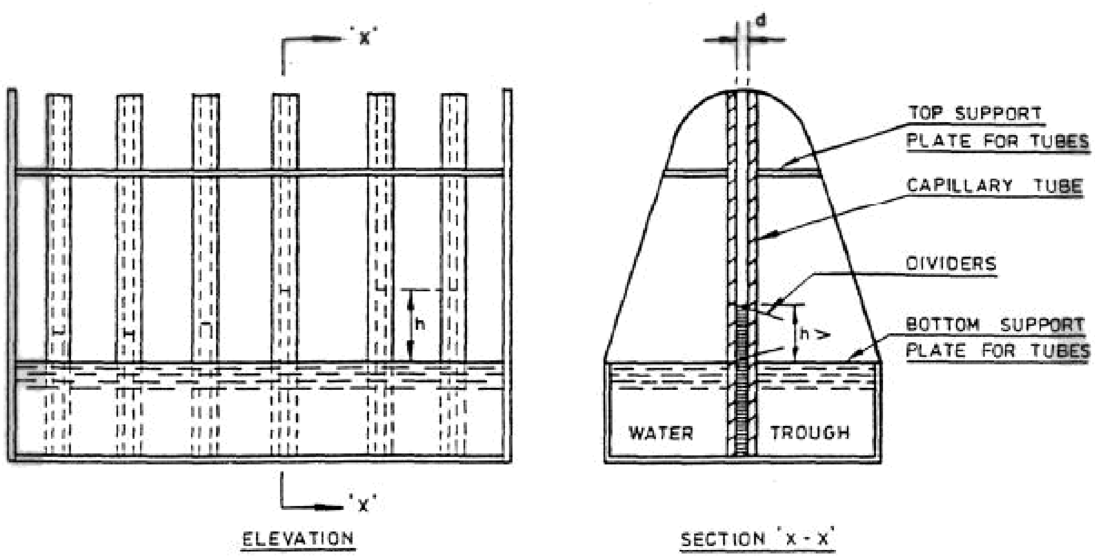
Objective

To measure the capillary elevation produced by various sizes of capillary tube.

Equipment required

Capillary Tube Apparatus (item 17 see Figure 1)

Dividers (not supplied)



Theory

From Eqn 1.8 in Capillarity in Properties of Fluids.

$$h = \frac{4\sigma}{\rho g d}$$

Method

a. Make sure the capillary tubes are thoroughly clean.

b. Fill the water trough to the level of the bottom support plate and insert the capillary tubes.

c. Place a card behind the capillary tubes.

d. Mark the card with the height of the capillary elevation in each tube.

e. With a pair of dividers, take off the capillary rise “h” for each tube and measure each height.

Results

ID of Tube (mm)	Measured Capillary Rise, h (mm)	Calculated Capillary Rise, h (mm)
0.5		
0.8		
1.1		
1.7		
2.0		
2.2		

Surface tension of water σ = .074N/m

Note: Comment on the difference between the measured and calculated capillary rise.

Exercise E - Free Surface of Static Liquid

Objective

To show that the free surfaces of a static liquid is horizontal.

Equipment required

See Introduction in Static Pressure. Use tanks no. 1 and 2, and tubes “a”, “b” and “c” (item 4 see Figure 1)

Theory

From introduction; since the only physical factor involved with a static fluid is gravity, the free surface will always be horizontal.

Method

a. Make sure valves V3 and V4 are closed

b. Open valves V1, V2 and V5.

c. Using the hand pump, transfer water from tank 1 into tank 2 until the level coincides with the first horizontal line on the tank wall.

d. Note that the level in each of the three tubes, “a”, “b” and “c”, is the same and in line with the first horizontal line on the tank.

e. Repeat for the second, third and fourth horizontal lines noting that the level of the water is always horizontal, irrespective of tube size or shape.

f. Drain the water from tank 2 by opening valve V3 and re-establish the level at the first horizontal line.

g. Close valve V3 and ensure that valve V1 is open. Close valve V5 at the top of tube “a” (tube “a” no longer has a free surface).

h. Using the hand pump (A), transfer water from tank 1 into tank 2. Raise the level in tank 1 to the second, third and fourth horizontal lines. Note that the level in tube ”a” remains depressed whilst “b” and “c” follow the level in the tank as (e).

Exercise F - Effect of Flow on Free Surface

Objective

To study the effect of flow on the free surface.

Equipment required

As for Exercise E.

Theory

Considering energies above datum at free surface in tank No. 2 and at point P (Note dimensions in metres).

Potential energy at free surface of tank No. 2 above datum = h.

Energy at P is made up of

a. $\text{pressure energy} = \frac{P}{\rho g}$

b. $\text{kinetic energy} = \frac{U^2}{2g}$

from the law of conservation of energy, since energy cannot be created or destroyed

$$h = \frac{P}{\rho g} + \frac{u^2}{2g} + \text{Losses}$$

Now losses may be expressed as $K.\frac{u^2}{2g}$

$$\therefore h = \frac{P}{\rho g} + \frac{u^2}{2g}(1+K)$$

$$\therefore \frac{P}{\rho g} = h - \frac{u^2}{2g}(1+K)$$

From Introduction in Static Pressure $\frac{P}{\rho g} = h_1$ and $\frac{u^2}{2g}(1+K) = y$

$$\frac{P}{\rho g} = h_1 = h - y \qquad \text{......2.1}$$

Method

a. Ensure that valves V3 and V4 are closed.

b. Open valves V1, V2 and V5.

c. Using the hand pump (A), transfer water from tank 1 into tank 2 until the level coincides with the fourth horizontal line. (Note that the system static, the levels in tubes “a”, “b” and “c” also coincide with the same horizontal line).

d. Open valve V3 so that the water flows from the system to drain. Make sure that the level in tank 2 remains constant by operating the hand pump.

e. Observe that the level in tubes “a”, “b” and “c” falls below the level in tank 2. This loss in head corresponds to the frictional liquid. All three tubes indicate this same level since they are connected to the same point in the system with no flow between them.

f. Close valve V3 and open valve V4 so that water flows along the interconnecting pipework to drain. Make sure that the level in tank 2 remains constant by operating the hand pump.

g. Observe that the levels in tubes “a”, “b” and “c” are progressively lower than the level in tank 2. This is due to the fact that motion of the liquid along the interconnecting pipe results in frictional losses between the tubes. Loss between the tubes “a” and “b” is small compared with the loss between “b” and “c” due to the relative lengths of interconnecting pipe.

Exercise G - Measurement of Liquid Levels

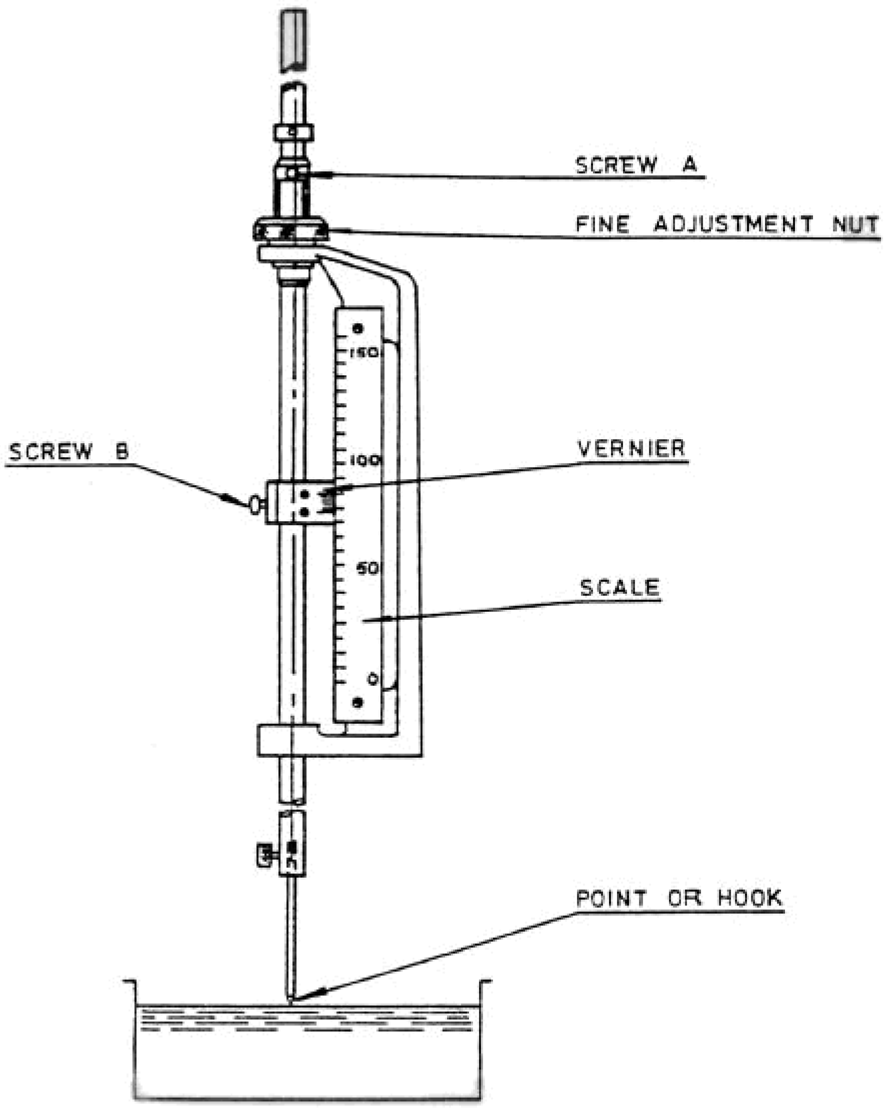
Objective

To measure a change in liquid levels using the Hook Gauge.

Equipment required

Hook and Point Gauge (item 5 see Figure 1)

600ml Beaker (item 14 see Figure 1)



Method

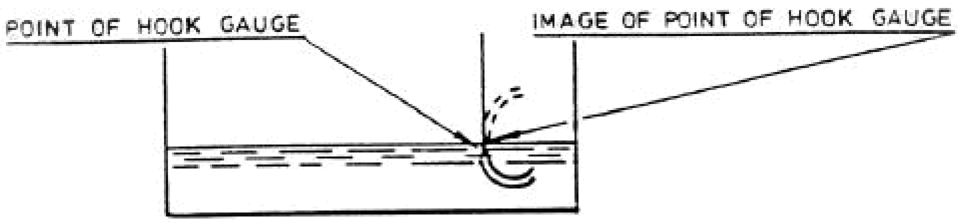
a. Attach a short length of flexible tube to pump B.

b. Using the hand pump, B, partially fill the 600ml beaker.

c. Place the beaker beneath the hook and point gauge which is attached to the backboard.

d. (Use just the hook.) Adjust the point of the hook gauge to just break the surface. That is when the hook and its image just touch (see below).

   The adjustment is made by slackening screw “A” and lowering the hook until it is near the free surface. Then use the fine adjustment nut to get the point of the hook gauge and its image to just touch.



e. Release screw “B”. Set the zero of the Vernier in line with a convenient point on the scale, (say O), tighten screw “B” and note the reading.

f. Using the flexible tube, increase the level of the water in the beaker by operation of the hand pump.

g. Adjust the level of the hook gauge to just break the new free surface in the manner described in (d) above.

h. Note the new reading on the scale.

i. Substitute the point for the hook and repeat the exercises, so that the point just breaks the surface of the water.

Results

Increase in depth = final scale reading - initial scale reading.

Note: This type of depth measuring device can read changes accurately to 0.1mm.

Exercise H - Intensity of Liquid Pressure

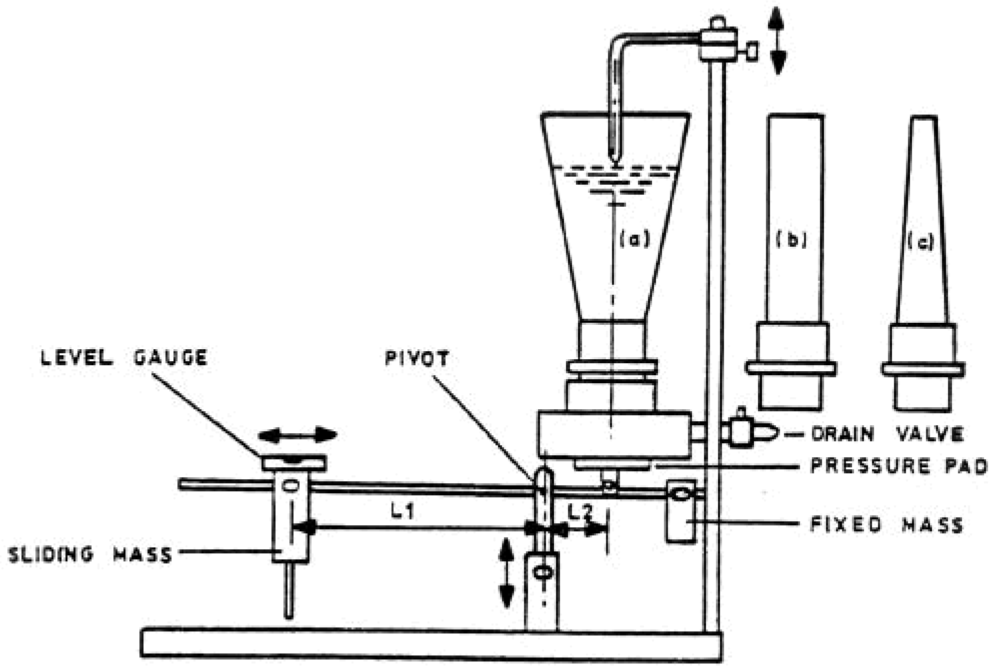
Objective

To show that the intensity of liquid pressure depends only on depth.

Equipment required

Pascal's Apparatus (item 13 see Figure 1)

Weight (item 18 see Figure 1)



Theory

Total pressure of water on sealing pad $P = \rho_1 gAh$

When the moment due to total pressure on pressure pad about the Pivot is just equal to the moment due to the gravitational force on the sliding mass about the Pivot the apparatus is just in balance.

ie. $mgL_1 = \rho_1 gAhL_2$ 2.3

Now intensity of pressure $p = \frac{P}{A} = \rho_1 gh$

When the point of balance is found for, say, tube "a" mark the height h with the pointer. Change the tube for "b" and "c" in turn, and fill each of these tubes to the same level. Then if the intensity of pressure depends only on depth, when each of the other tubes is filled to the prescribed depth the apparatus should again be in balance, and Eqn 2.3 still holds.

Method

a. Take the apparatus from the bottom shelf and place it on the bench.

b. Calibrate the beam by moving the sliding mass to the nearest graduated mark to the pivot, adjust the fixed mass until the beam is balanced, observe the spirit level gauge. **Note:** the pivot post will need to be able to move freely ie. not touching the pressure pad cross pin or the sliding mass support leg.

c. Raise the pivot post until the beam just touches the cross pin attached to the pressure pad.

d. With any tube (i.e. “a”) in position, carefully add water until desired height. **Note:** do not fill too high.

e. Adjust the sliding mass away from the pivot until the beam is in balance note the spirit level gauge.

f. Mark the water level in the tube with the pointer.

g. Leave the sliding mass and the pointer collar in the same position. Repeat using other tubes (ie. “b” and “c”) until the beam is in balance and observe the same height by sliding the pointer back in to the tube so that it rested back onto its collar, or:

h. Still leaving the sliding mass and the pointer collar in the same position slide the pointer back onto its collar so that the point is in the tube and fill to the same height and observe the balance of the beam.

Note: The experiment can be repeated for different positions of the sliding mass.

Exercise I - Centre of Pressure on a Plane Surface

Objective

To determine the position of the centre of pressure on the rectangular face of the toroid.

Equipment required

Hydrostatic Pressure Apparatus, F1-12, (item 12 see Figure 1)

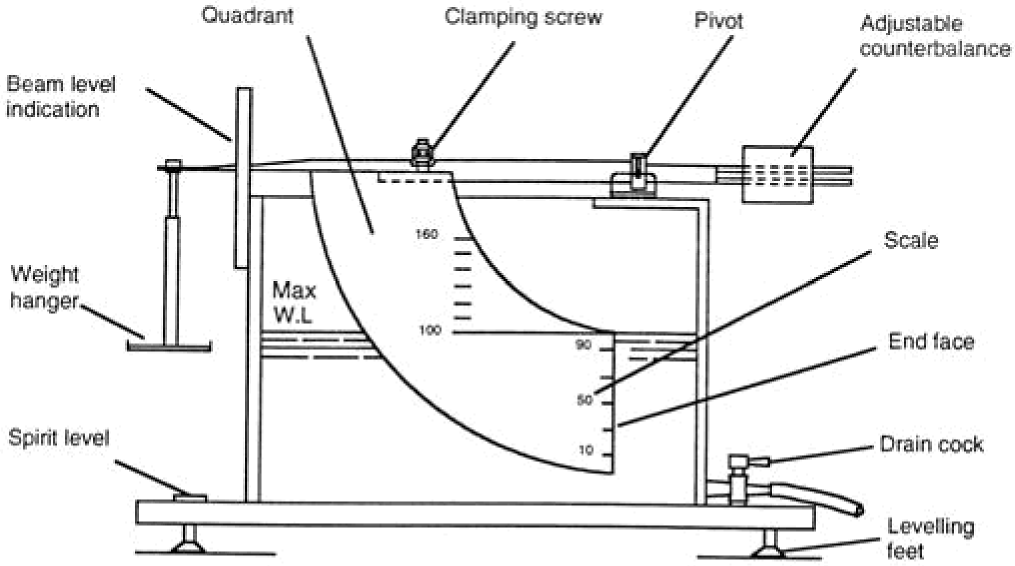


Figure a

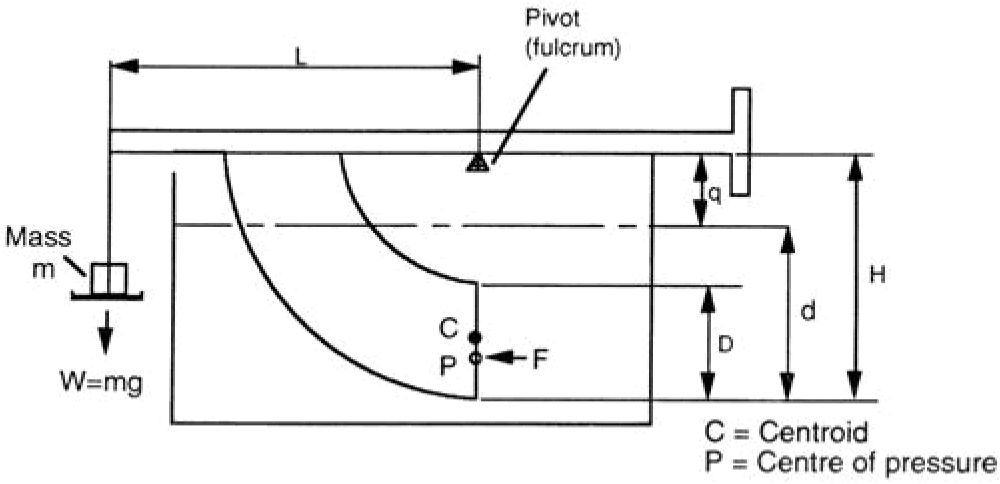


Figure b

Theory

From the theory section (see Pressure on a Surface Immersed in a Liquid in Static Pressure)

For a partly submerged vertical plane surface:

Hydrostatic Thrust $F = \frac{\rho g B d^2}{2}$ (Newtons)

Experimental position of Centre of Pressure $h'' = \frac{2mL}{\rho B d^2}$ (metres)

Theoretical position of Centre of Pressure h" = h' + H - d (metres)

For a fully submerged vertical plane surface:

Hydrostatic Thrust F = ρgBD(d - D/2) (Newtons)

Experimental position of Centre of Pressure $h'' = \frac{mL}{\rho BD\left(d - D/2\right)}$ (metres)

Theoretical position of Centre of Pressure $h'' = \frac{D^2/2 + \left(d - D/2\right)^2 + H - d}{d - D/2}$ (metres)

Method

a. Measure the dimensions B and D of the quadrant end face and the distances H and L, see figure b above. Position the empty plastic tank on the bench. Ensure that the toroid is located on the dowel pins and the central clamping screw is tightened.

   Position the assembled balance arm on the knife edges.

b. Locate the weight hanger in the groove at the end of the balance arm. Ensure that the drain valve is closed. Attach a length of hose to the drain cock and direct the free end to the sink. Remove the free end of the flexible delivery pipe which supplies water to tank 2 and place the free end in the triangular aperture on top of the plastic tank.

c. Level the tank using the adjustable feet and the integral spirit level. Move the counter-balance weight until the balance arm is horizontal (flat underside of balance arm level with the beam level indicator).

d. Add a small mass to the weight hanger. Pump water from tank 1 to the clear acrylic tank using the hand pump (A) provided. Continue to add water until the hydrostatic thrust on the end face of the quadrant causes the balance arm to raise. Ensure there is no water spilled on the upper surfaces of the quadrant or sides, above the water level. Add water until the balance arm is horizontal; you may find it easier to slightly overfill the tank and obtain the equilibrium position by opening the drain cock to allow a small outflow from the tank. Read the depth of immersion from the scale on the side of the quadrant; more accurate results can be obtained from reading below the surface, to avoid the effects of surface tension.

e. Repeat the above procedure for each increment in load produced by adding a further weight to the weight hanger. Continue until the water level reaches the top of the upper scale on the quadrant face. Repeat the procedure in reverse, by progressively removing the weights. Record carefully the factors which you think are likely to affect the accuracy of your results.

Results

Your raw data should be presented in a table using the following headings:

Mass, m (gm)

Depth of immersion, d (mm)

Estimate the likely error associated with each of the quantities measured.

Using the equations from the analysis above, calculate the Hydrostatic Thrust F then calculate the experimental and theoretical position of the Centre of Pressure h" (position of P relative to the pivot) from your experimental results, noting that there are different results for the case when the vertical plane is partly submerged and fully submerged.

The above results should also be tabulated; suggested headings are:

Thrust, F (Newtons)

Depth of Centre of Pressure, h" experimental (mm)

Depth of Centre of Pressure, h" theoretical (mm)

Plot graphs of the thrust against the depth of immersion and the depth of the centre of pressure against the depth of immersion.

Conclusions

1. Comment on the variation of thrust with depth.
2. Comment on the relationship between the depth of the centre of pressure and the depth of immersion.

For both 1 and 2 above, comment on what happens when the plane has become fully submerged.

Comment on and explain any discrepancies between the experimental and theoretical results for the depth of centre of pressure.

Exercise J - Use of a Direct Reading Mercury Manometer

Objective

To read the barometric or atmospheric pressure.

Equipment required

Direct reading mercury barometer (item 6 see Figure 1).

Method

a. With atmospheric pressure acting on the enlarged bowl (see The Barometer in Measurement of Pressure), read the level of the mercury column on the engraved scale.

b. Read the room temperature.

Results

Room temperature ________°C

Barometric pressure ________mm Hg

Comment on the accuracy of this type of barometer.

Exercise K - Calibration of a Bourdon-Type Pressure Gauge

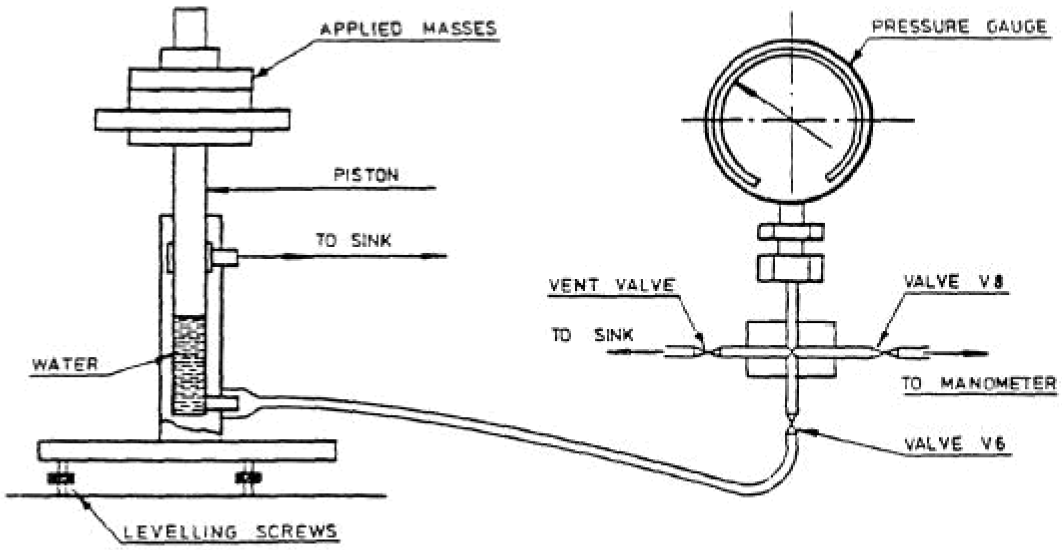
Objective

To calibrate a Bourdon-type pressure gauge using the dead-weight pressure gauge calibrator.

Equipment required

Dead-weight Pressure Gauge Calibrator, F1-11 (item 11 see Figure 1).

600 ml Beaker (item 14 see Figure 1).



Method

a. Close valve V8 and level apparatus.

b. Fill cylinder of dead-weight calibrator with water and insert piston.

c. Open valve V6. Open vent valve to exhaust air from the system.

d. Close vent valve.

e. With piston only in tester, take gauge reading.

   Keep piston rotating to avoid sticking.

f. Load up piston in increments of ½ kilogram, and note gauge reading for each applied mass. Make sure piston is rotated.

   On no account should valve V8 be opened with masses applied to the calibrator since the pressures involved will result in loss of mercury from the manometer.

g. Repeat with decreasing masses.

h. When test is finished, remove and dry piston and lightly coat with “Vaseline”. Drain Cylinder.

   Do not leave piston in cylinder when not in use. Protect piston when not in use by placing it in a cardboard tube or wood block.

Results

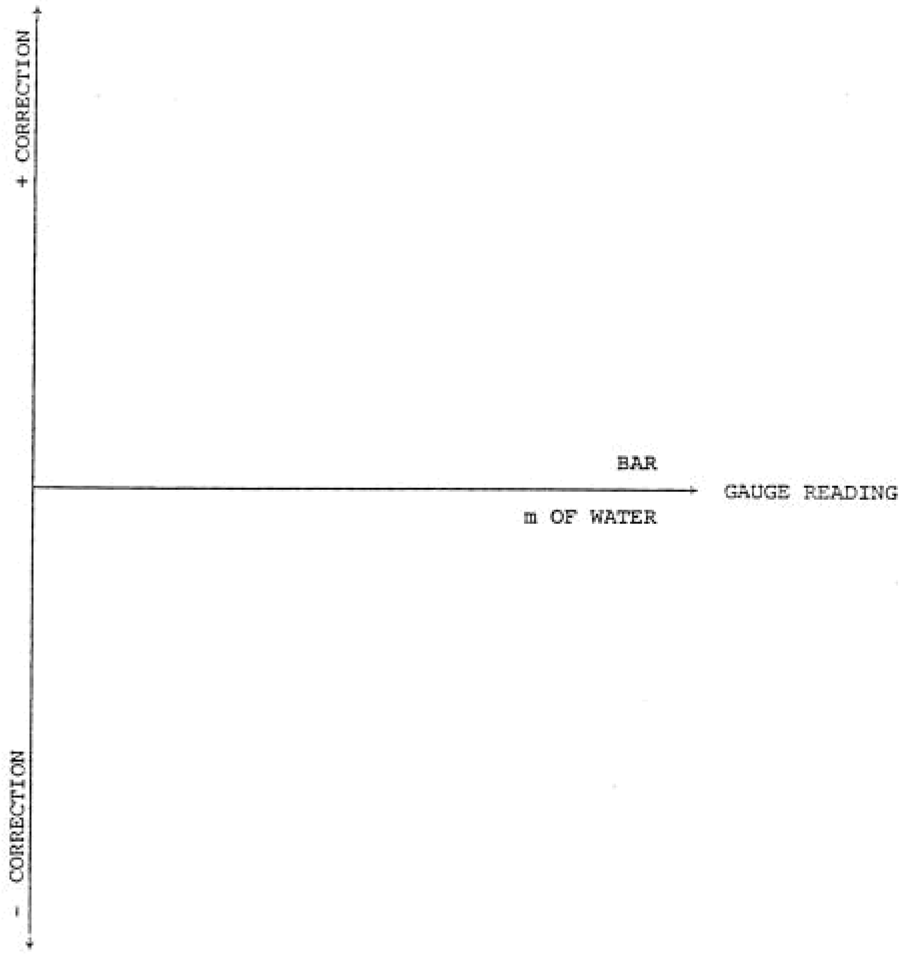
Nominal mass of piston = 0.5 kg

Nominal area of piston = $2.45 \times 10^{-4} m^2$

$$\text{Pressure} = \frac{\text{Force}}{\text{area}} = \frac{mg}{A}$$

$$\text{eg. 1kg mass} = \frac{1x9.81}{2.45x10^{-4}}$$

$= 4 \times 10^4$ N/m^2 = 0.4 bar = 4.08m of water



Output from dead-weight calibrator			Gauge reading load increasing		Gauge reading load decreasing	
Applied mass kg	bar	m of water	bar	m of water	bar	m of water
0.5						
1.0						
1.5						
2.0						
2.5						

Exercise L - Use of a Water over Mercury Manometer

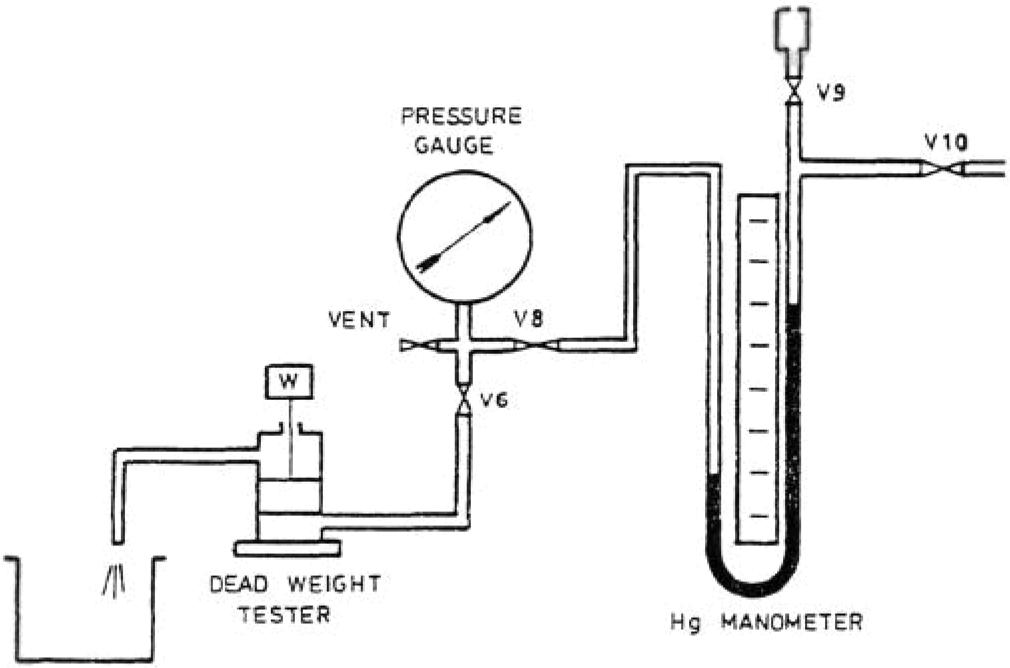
Objective

To use a water over mercury 'U' tube manometer to determine the pressure at a point. To compare the reading of a manometer with a Bourdon gauge.

Equipment required

Dead-weight Pressure Gauge Calibrator, F1-11 (item 11, see Figure 1),

Mercury Manometer (item 8 see Figure 1).



Method

a. Close Valve V10. Open Valve V9.

b. Ensure that the tube connecting the manometer and Bourdon gauge and he respective limb of the manometer, are fully primed with water.

   If air is present in the system, disconnect the tube and fill with water.

c. Level the dead-weight pressure gauge calibrator.

d. Fill cylinder of dead-weight calibrator with water and insert piston.

e. Open Valve V6. Open vent valve to exhaust air from system. Close vent valve.

f. Open Valve V8.

g. Fill dead-weight calibrator with water, insert piston, and note levels of each manometer limb.

h. With piston only in calibrator, note levels of each manometer limb. Note reading on the Bourdon gauge. Keep piston rotating to avoid sticking.

i. Load up piston with 1/2 kg mass and note levels of each manometer limb. Note reading on the Bourdon gauge.

j. Load up piston with 1 kg mass only and note levels of each manometer limb. Note reading on the Bourdon gauge.

   Note: Do not attempt to use the calibrator with masses in excess of 1 kg as this will result in loss of mercury from the manometer.

k. When test is finished, remove and dry piston and lightly coat with “Vaseline”. Drain cylinder.

Exercise M - Use of an Air over Mercury Manometer

Objective

To use an air over mercury ‘U’ tube manometer to determine the pressure at a point.

Equipment required

Air pump (item 23, see Figure 1),

Mercury Manometer (item 9, see Figure 1).

Method

a. Close Valve V10

b. Attach air pump to inlet valve on manometer manifold.

c. Operate hand pump and observe change in manometer level.

d. Release inlet valve and observe that manometer returns to original level.

   Do not exceed the maximum and minimum levels in the manometer limbs.

Exercise N - Use of a U Tube Manometer to determine Pressure Differential

Objective

To use a water over manometer to determine and compare differences in pressures in a water and air system.

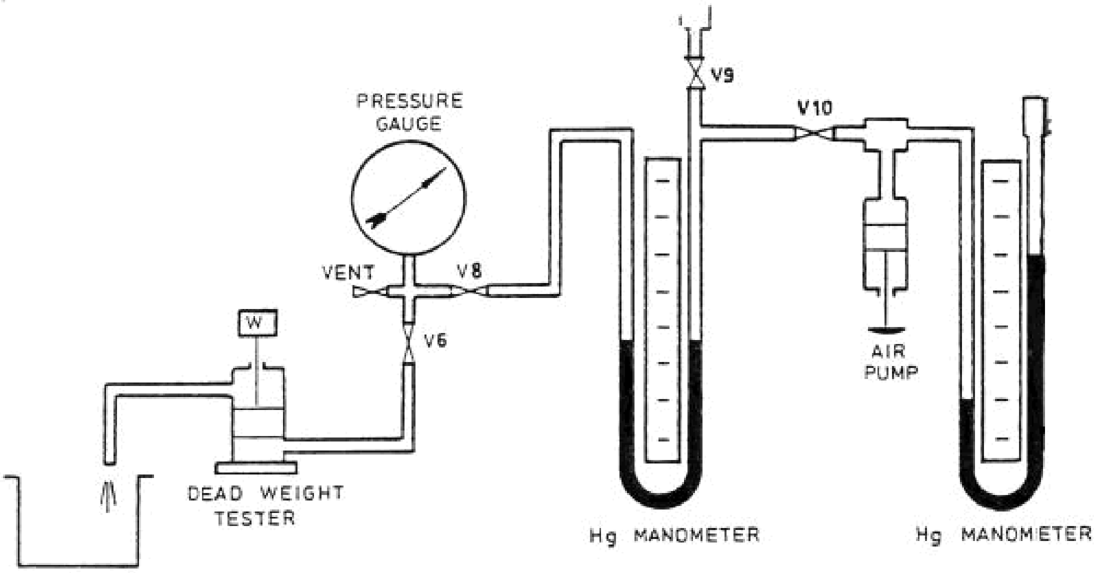
Equipment required

Dead-weight Pressure Gauge, F1-11 (item 11, see Figure 1),

Mercury Manometer (item 8, and item 9, see Figure 1)

Air Pump (item 23, see Figure 1)

and Bourdon Gauge (item 7, see Figure 1).



Method

a. Close Valve V10. Open Valve V9.

b. Ensure that the tube connecting the manometer and Bourdon gauge and the respective limb of the manometer, is fully primed with water.

   If air is present in the system, disconnect the tube and fill with water.

c. Level the dead-weight pressure gauge calibrator.

d. Fill cylinder of dead-weight calibrator with water and insert piston.

e. Open Valve V6. Open vent valve to exhaust air from system. Close vent valve.

f. Open Valve V8.

g. Fill dead-weight calibrator with water, insert piston, and note levels of each manometer limb.

h. Close Valve V9. Open Valve V10 and connect air pump to inlet valve on manometer manifold.

i. Operate air pump until manifold (item 8, see Figure 1) returns to original position. Note Bourdon gauge reading and levels on manometer (item 9, see Figure 1).

j. Repeat i) with ½ kg mass on dead-weight calibrator.

k. Repeat i) with 1 kg mass on dead-weight calibrator.

l. When test is finished, remove and dry piston and lightly coat with “Vaseline”. Drain cylinder.

Note: Do not leave piston in cylinder when not in use.

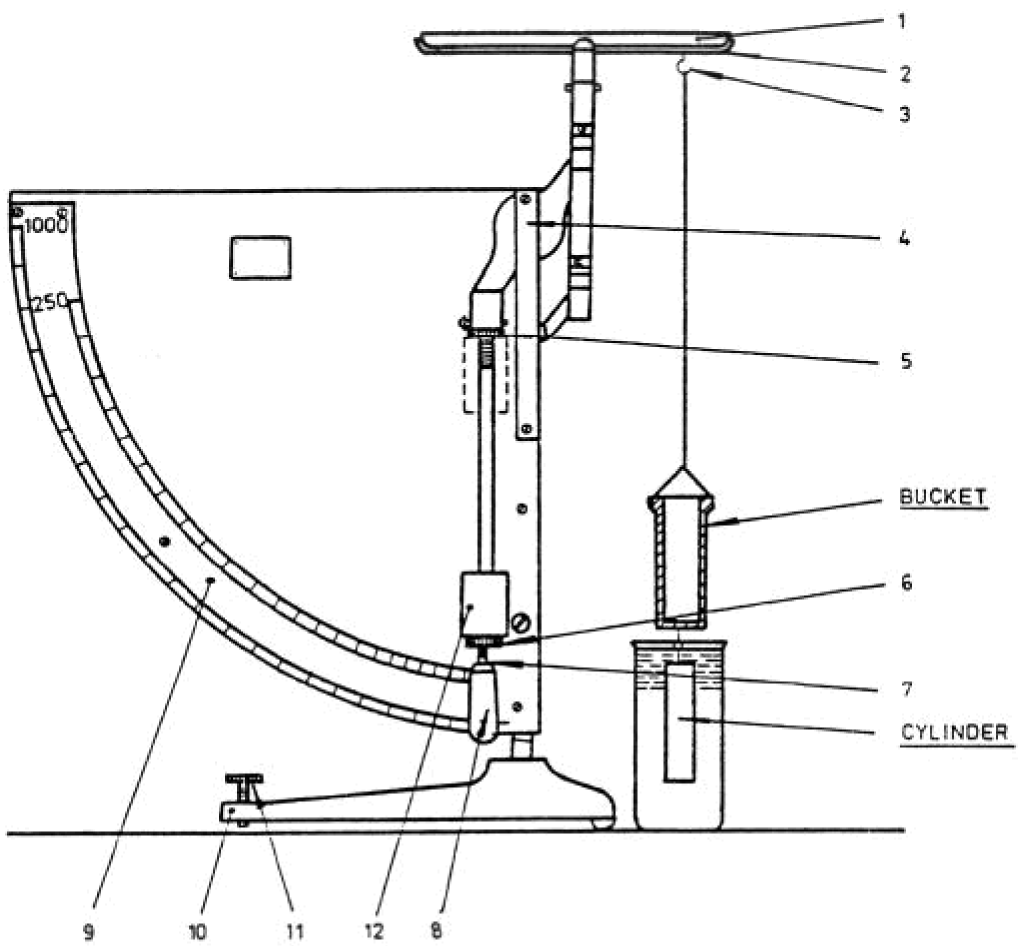
Exercise O - Archimedes Principle

Objective

To verify Archimedes' Principle.

Equipment required

Lever Balance with Displacement Vessel, Bucket and Cylinder (item 19, see Figure 1)



1. 178mm diameter pan
2. Pan carrier
3. Hook for use in buoyancy experiments
4. Central pivot
5. & 6. Calibration collars
7. Lever arm
8. Anti-parallax cursor

9. Double scale 0-0.25 kg, 0-1.00kg
10. Base
11. Levelling screw
12. Bob

If the whole body is considered to be made up of a large number of such prisms, then the net total upthrust on the whole body

$$F_B = \Sigma)F_B = \Sigma(\Delta_{11}gh_1 + \Delta_{12}gh_2)\ )A$$

but $\Sigma h_1\ )A$ = volume of body immersed in lighter fluid

= V1

and $\Sigma h_2\ )A$ = volume of body immersed in heavier fluid

= V2

$$\therefore F_B = \Delta_{11}g\,V_1 + \Delta_{12}g\,V_2 \qquad ......4.2$$

= the gravitational force on the masses of fluid displaced by body.

An examination of Eqn 4.2 will make it clear that when a body is floating freely in a gas and a liquid, such as air water, and since the density of the gas is negligible compared to that of a liquid, then the gravitational force on the mass of the gas displaced by the body will be negligible compared to the gravitational force on the mass of liquid.

$$F_B = \Delta_{12}g\,V_2 \qquad ......4.3$$

= gravitational force on the mass of the liquid displaced by body.

It should be noted that the upthrust is simply the resultant vertical force due to static fluid pressure.

Theory

From Buoyancy in Stability of Floating Bodies Archimedes' Principle states that when a body is wholly or partially immersed in a fluid it experiences an upthrust equal to the gravitational force on the mass of fluid displaced.

Mass of bucket and cylinder in air = m_1 gm

Mass of bucket with cylinder immersed in water = m_2 gm

$$\text{upthrust} = \frac{g(m_1 - m_2)}{10_3} \quad N$$

Mass of bucket = m_3 gm

Filled with water = m_4 gm

Mass of water = $(m_4 - m_3)$ gm

and gravitational force on the mass of water

$$= \frac{g(m_4 - m_3)}{10^3} \quad N$$

From Archimedes' Principle, upthrust = gravitational mass of water displaced by cylinder

$$\frac{g(m_1 - m_2)}{10^3} = \frac{g(m_4 - m_3)}{10^3}$$

$\therefore\ m_1 - m_2 = m_4 - m_3$

Method

a. Suspend bucket and cylinder by a fine thread from hook 3 on the underside of pan 1 of the double range lever balance as shown in the figure above.

b. With balance set to operate on 0-0.25 kg range, note the mass of bucket and cylinder.

c. Immerse cylinder completely in a beaker of water and again note mass.

d. Remove cylinder and beaker of water and note mass of bucket only.

e. Completely fill bucket with water and note mass.

Results

Mass of bucket with cylinder, m_1 = gm

Mass of bucket with cylinder immersed in water, m_2 = gm

Mass of bucket m_3 = gm

Mass of bucket filled with water m_4 = gm

Hence, show that $m_1 - m_2 = m_4 - m_3$

Note: After use ensure the displacement vessel is dried thoroughly.

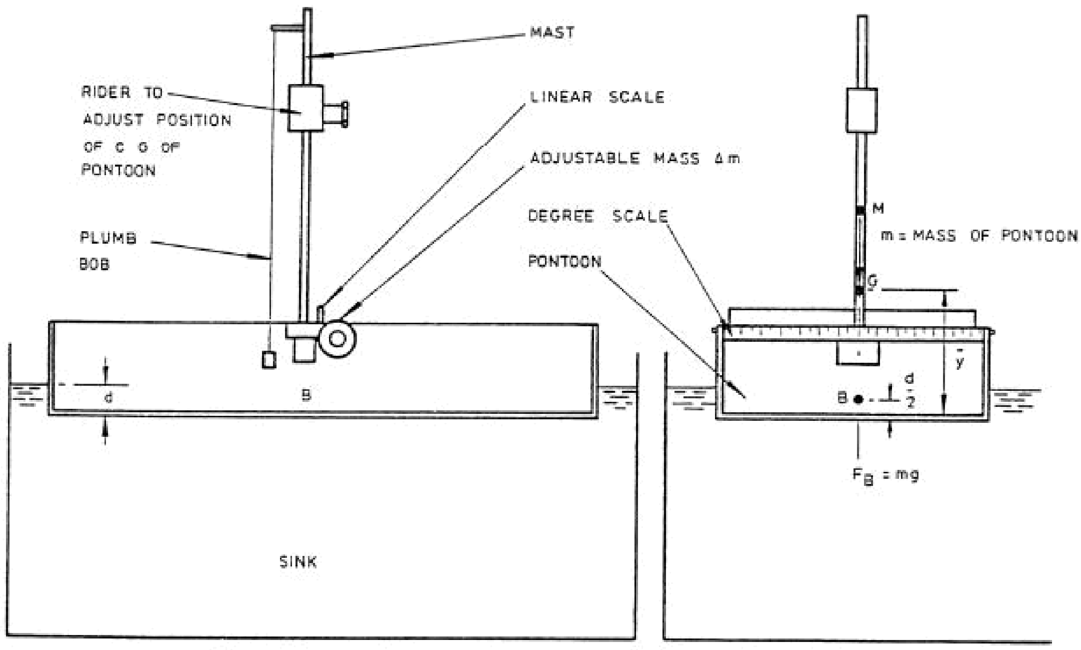
Exercise P - Determination of Metacentric Height

Objective

To determine the metacentric height of a model pontoon.

Equipment required

Metacentric Height Apparatus, F1-12 (item 12, see Figure 1).



Distance of moveable mass Right of centre x mm	Angle of heel θ	Metacentric height GM = $\frac{\Delta m}{m}\frac{x}{\tan\theta}$ mm	Distance of moveable mass Left of centre x mm	Angle of heel θ	Metacentric height GM = $\frac{\Delta m}{m}\frac{x}{\tan\theta}$ mm

Theory

From Eqn 4.5 in Experimental Determination of Metacentric Height, see Stability of Floating Bodies.

$$GM = \frac{\Delta mx}{m \tan \Theta}$$

Where GM = metacentric height in mm

Δm = mass of movable weight in kg.

x = Distance of movable weight from central position in mm.

m = mass of assembled pontoon in kg

θ = Angle of heel in degrees

From Eqn 4.4 in Analytical Determination of Metacentric Height, see Stability of Floating Bodies.

$$BM = \frac{I}{V}$$

where I = 2nd moment of area of water plane about longitudinal axis

$$= \frac{L.b^3}{12}$$

V = volume of water displaced

BM = Distance between centre of buoyancy and metacentre

Then GM = BM - BG

Method

a. Obtain mass of the transversely movable weight.

b. Assemble pontoon with rider near to top of the mast, and obtain mass of the assembled pontoon.

c. Determine the position of the centre of gravity of the pontoon by obtaining the point of balance, either by using a knife-edge or by suspending it from a suitable position by a light string.

d. Fill the sink by operating the hand pump (B).

e. With movable mass in the central position, float the pontoon.

f. Move movable mass to the right of centre in 10mm increments until the full range of scale is covered.

   Note angular displacement of plumb bob for each position.

g. Repeat f) for movement of movable mass to the left of centre.

h. Repeat c), e), f) and g) for the rider in a different position, ie. different centre of gravity.

Results

Dimensions of Pontoon: length 350mm, breadth 200mm, depth 73mm.

Movable mass Δm = _______ kg

Mass of assembled pontoon, m = ________ kg

Position of CG of assembled pontoon from base y = ________ mm

From the mass and plan area of the pontoon, deduce V and hence the

Depth of immersion, d = _________ mm

Position of CB from base,

$$\frac{d}{2} = \_\_\_\_\_\_\_\_ \text{mm}$$

Plot GM against θ - See graph in Experimental Determination of Metacentric Height, see Stability of Floating Bodies.

and read GM when θ = O

Check by calculation $BM \quad \frac{I}{V} = \frac{L.b^3}{12V}$

Note L and b must be in mm

and $V = \frac{m}{p} \quad m^3$

$$= \frac{mx \quad 10^9}{10^3} = mx \quad 10^6 \quad \text{mm}^3$$

GM = BM - BG

$$= \frac{1}{V} - y - \frac{d}{2}$$

Conclusion

Does the position of the metacentre depend on the position of the Centre of Gravity?

Does the metacentric height vary with Angle of Heels?

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