DESIGN, CONSTRUCTION AND PERFORMANCE TESTING OF A FORCED VORTEX EQUIPMENT FOR USE IN THE FLUID MECHANICS LABORATORY

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ABSTRACT: *The study of fluid flow phenomenon is a very important one in the education of engineering students and one of the equipment that can help in doing this is the forced vortex equipment. This equipment has been designed and constructed to verify the turbulent flow caused by fluid rotation at constant angular velocity. Results obtained showed a parabolic profile of liquid surface in the equipment, which confirmed the type of equation of pressure head normally developed in a forced vortex. The Reynolds number obtained at the flow between minimum and maximum speeds of the impeller (268949 and 462256 respectively) were much greater than 4000 above which flow is turbulent, which also confirmed the turbulence of forced vortex flow. Performance test with the equipment also indicates its average efficiency of 99.18 % as analytical values of pressure head at maximum impeller speed deviated from the experimental values only in the range 0.63 to 1.27 % and at minimum impeller speed, deviation is in the range 0.27 to 1.37 %.*

Key Words: Forced Vortex, Design and Construction, Fluid Flow, Fluid Rotation, Pressure Head, Turbulent, Performance Test.

INTRODUCTION

The study of fluid flow, on which the forced vortex equipment is based, is one of the few areas of engineering that truly crosses the boundaries between the various engineering disciplines. It is of equal importance to mechanical, civil, chemical and process, aeronautical, Environmental and building services engineers. A vortex is described as the mass of whirling fluid or wind and vortex motion is the curvilinear flow of real fluids (Featherstone and Nalluri, 1985). An ideal flow is a purely theoretical concept; as such flows pose no viscosity, compressibility, surface tension or vaporisation pressure limit. However, the mathematical treatment of such flow was fundamental in the development of aerofoil lift, fan/pump blade design and ground water flow predictions.

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The ideal flow theory may also be extended to situations in which fluid viscosity is very small and velocities are high, since they correspond to very high values of Reynolds numbers at which flows are independent of viscosity. Thus, it is possible to see ideal flow as that corresponding to an infinitely large Reynolds number and to zero viscosity. The application of ideal flow theory is found in aerodynamics in accelerating flow, tides and waves. When the type of flow is such that the streamlines are concentric circles, they are known as vortex flows. This vortex motion can be categorized under two main types. They are free vortex and forced vortex. Free vortex motion is the type that occurs naturally in life, as it is independent of any external force or mechanical means for its occurrence and forced vortex is the type that cannot occur naturally, but it requires an external force to set the fluid in motion.

Investigation on forced vortex was carried out in the early period by using simple apparatus. This consists of a transparent cylinder basin and a means of rotation usually a turntable. The setup of the apparatus is by putting the transparent cylinder on a stationary turntable and the cylinder is filled with clear water to some level or height. The coloured water that has a low density compared with the clear water is powered on top of the clear water. The cylinder is then subjected to a constant angular velocity by setting the turntable to a constant rotation. It is observed that the clear water was gradually being ‘spun-up’ to the angular velocity of the cylinder. Liquid spun-up achieved is about 1% by viscous interaction at the cylinder side wall and about 99% by a viscous secondary flow at the cylinder bottom (James, 1993). The forced vortex apparatus has been modified in recent time to a more reliable one, in which reading of various pressure head corresponding with the radius can be made instead of mere observation. More recent vortex equipment are capable of performing experiments on both free and force vortex.

In the recent time of greater discoveries and technological development, the vortex theory has equipped the scientists and experimenters with the knowledge, which led to the inventory of impeller blade designs both in hydrodynamics and aerodynamics by taking into account the actual velocity distribution in the slipstream (Baumeister and Avallone, 1978). According to Velikhov (1980), a large amount of experimental data has been obtained and many mathematical models related to the vortex theory have been devised in hydrodynamics, the foundation of shipbuilding, research in the movement of oceans and seas and also in aviation studies. Although, the principle of operation of the experiment remains the same, rotary motion is important to the fluid by using fluid to drive paddles or by using electric motor to turn the impeller or cylinder, which in turn sets the water into rotary motion (Digdate and Banister, 1971).

This paper presents a report on design, construction, and performance test of a forced vortex equipment for use in the fluid mechanics laboratory to carry out students’ practical tests in relation to fluid rotation. The equipment operates on the principle of using mechanical means to impart motion to the fluid in a cylinder. The motion results in pressure head variation from one stream line to another. Due to this variation in pressure head, fluids develop a parabolic shape at its head. The experimental results are therefore used to verify the concept of turbulence in fluid flow.

THEORETICAL CONSIDERATIONS

Basic Theory: The forced vortex theory relates to a fluid mass in a container, which is made to rotate in a curved path under the action of an external force. The means of this rotation should be continuous and constant so that the entire fluid body will rotate at constant angular velocity. The external force in this case is imparted by an impeller, which is powered by an electric motor. This impeller sets the liquid into motion and moves until the velocity at which the fluid moves equals that of the impeller. Since the angular velocity is constant at any point, $V = \omega r$ ………………………………(1)

Increase in radial pressure is given by

$$\frac{dp}{dr} = \frac{w}{g} \bullet \frac{v^2}{r} = \frac{w}{g} \bullet \omega^2 r \qquad \text{……………………(2)}$$

Where: dp = increase in pressure, Nm^{-2}

dr = increase in the radius of the cylinder, m

v = linear velocity, ms^{-1}

ω = angular velocity, $rads^{-1}$

g = acceleration due to gravity, ms^{-2}

w = specific weight of water, kg

Now, $$\int_{P_1}^{P_2} dp = \frac{w}{g}\omega^2 \int_{r_1}^{r_2} rdr \qquad \text{……………………(3)}$$

If P_1 and P_2 are pressure intensities at radii r_1 and r_2 respectively, we have

$$P_2 - P_1 = \frac{w}{2g}\omega^2\left(r_1^2 - r_2^2\right) \qquad \text{……………………(4)}$$

$v_1 = \omega r_1$ and $v_2 = \omega r_2$

r = 0 when $P = P_o$ at the centre of the vortex

$$\frac{P - P_o}{w} = \frac{\omega^2 r^2}{2g}$$

Since $\frac{P}{w} = h$ also $\frac{P_o}{w} = h_o$, we have

$$h - h_o = \frac{\omega^2 r^2}{2g}$$

$$h = h_o + \frac{\omega^2 r^2}{2g} \qquad \text{………………………………(5)}$$

Eqn. (5) is parabolic when the datum is taken as the base of the parabola; h_o will be equal to zero. So, at $h_o = 0$, Eqn. (5) becomes:

$$h = \frac{\omega^2 r^2}{2g} \qquad \text{...(6)}$$

Thus, since the expression is parabolic, similarly other surfaces of equal pressure will be paraboloids (Douglas et al., 1996). This **h** corresponds to the pressure head at the set angular velocity and radius. Since the equation is parabolic, hence, the liquid surface in a forced vortex takes a parabolic profile too, in which case rise in water level at the ends is equal to the fall in water level at the center. This expression can better be explained by using the figure below in terms of volume of water displaced.

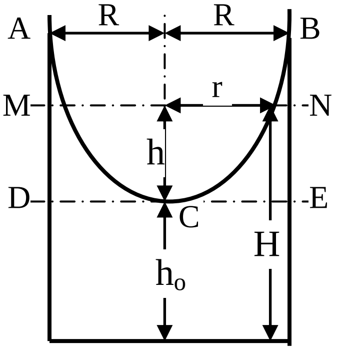


Fig. 1: Parabolic Head developed in a Forced Vortex

In the Fig. 1 above, MN is the initial liquid surface in the cylinder when the system is in absolute equilibrium. When the cylinder is rotated, a parabolic profile ACB is formed on the liquid surface. Volume of liquid above the level DE before and after rotation is equal. Volume above DCE before rotation = $\pi R^2 MD$. Volume above DCE after rotation equals volume of cylinder between DE and AB minus volume of parabolic ACB

$$\pi R^2 AD - \frac{\pi R^2 AD}{2} = \frac{\pi R^2 AD}{2}$$

$$\pi R^2 MD = \frac{\pi R^2 AD}{2}$$

MD = ½AD

MD = AM ....(7)

The above confirms that the rise in liquid level at cylinder wall equals fall in level at the centre.

EQUIPMENT DESIGN

Speed of the Impeller: The diameter of the transparent cylinder to be used for the forced vortex equipment is 290 mm with a height of 600 mm. The maximum initial water level is not to exceed 480 mm from the bottom of the cylinder when operating maximum speed. It shows that when it is to be operated at the maximum speed, 120 mm depth of unoccupied space will still remain. From the theory presented, it was shown that a rise in level at the edge is equal to the fall in level at the centre. That is h = rise in level at the edge + fall in the level at centre, h = space above initial water level x 2, h = 120 x 2 = 240 mm.

But, $$\omega = \left(\frac{2gh}{r^2}\right)^{\frac{1}{2}} \qquad \text{………………………………..…(8)}$$

$$h = \frac{\omega^2 r^2}{2g}$$

Substituting the value of h = 0.24 mm into Eqn. (8), we obtain

$$\omega = \left(\frac{2 \times 9.8 \times 0.240}{(0.145)^2}\right)^{\frac{1}{2}}$$

$$\omega = 14.965 \text{ rad/s}$$

The angular velocity of the impeller is, thus, 14.965 rads^{-1}. This can be converted to number of revolutions (N) per minute thus:

$$\omega = \frac{2\pi N}{60} \qquad \text{…………………………………..…………..…(9)}$$

$$N = \frac{60 \times 14.965}{2 \times 3.142}$$

$$N = 143 \text{ rpm}$$

The implication of this is that if the initial water level is not to exceed 480 mm from the bottom of the cylinder of 600 mm height and 290 mm diameter, the maximum angular velocity of the impeller will be 143 rpm

The Gear Box Ratio: The maximum angular velocity of the impeller is 143 rpm and the speed of the electric motor used for the equipment is 1375 rpm. In order to achieve the required speed, a gear box is required and the ratio, I, of the gear box is given by:

$$I = \frac{\text{Speed of electric motor}}{\text{Speed of the impeller}}$$

$$I = \frac{1375}{143} = 9.61$$

$$I = 10$$

Therefore, the speed of the impeller 137.5 rpm

Selection of Impeller: Impeller is the device through which energy is transferred to the fluid through its rotation or by which energy is transferred from a fluid to set that device into rotation. In the operation of vortex equipment, it requires that the impeller transfers energy to a fluid. Out of the three types of impellers that are available, that is, the simplified radial flow (centrifugal blower), tangential flow (impulse turbine) and axial flow (engine turbine) impellers, it is the simplified radial flow (centrifugal blower) type that can easily achieve the desired result since the Impeller is just to set the fluid into rotation. Also, the impeller is a form of centrifugal pump, which will cause water to be pumped, under centrifugal action, into the small openings under the cylinder that serves as the pressure tapping point where the piezometer is connected so that the pressure head can be read directly on the piezometer tube stand.

The Pressure Head Tapping Radius: For pressure head at different radius to be read directly on a piezometer so as to make comparison between the measured pressure head and calculated pressure head, it is required to fix some points at which the readings should be made; that is, the radii of the pressure tapings from the centre of the vortex. In order to have an accurate shape of the water head, the radii of the pressure tapings are close to one another with an interval of 25 mm. The pressure taping radii are 25, 50, 75, 100 and 125 mm. The holes are drilled of Ø3 mm radially outwards from the centre of the base plate. Two of the arrangements are made at 90^o to each other forming a vee shape of holes.

Calibration of the Speed Control System: Since the operation of the vortex equipment depends mainly on the speed, it is necessary to know the speed of the electric motor at each point in time. A speed regulator is, therefore, provided. It is a form of variable power transformer, which functions by connecting it to the electric motor and by starting from the lowest point in the regulator, the speed corresponding to each point is measured. This is done by switching on the power supply to the electric motor and allowing the motor to run to maximum speed corresponding to the regulator voltage supply. Then the speed of the electric motor is measured with a tachometer that gives the number of revolution per minute of the electric motor at that voltage. This is repeated at different points to get the speed at various points of the regulator setting.

MATERIAL AND METHODS

Equipment Description: Forced vortex equipment consists of the frame, piezometer, impeller, cylinder and electric motor. The frame constitutes the body, which serves as a support for the main part and for the electric motor, which carries the reduction gear box fixed within the frame. The overall dimensions of the frame are 700 mm x 460 mm x 280 mm (Fig. 2). A 12 mm hole is drilled at a point on the frame, which will serve as a centre of the cylinder. This hole will serve as an access way for the impeller shaft to the gear box. Also on the frame, ten holes, which are five on each of the two lines at 900 to each other, are drilled on one side of the frame. These holes will give a free access for the hole that will connect the pressure tapping holes on the base of the cylinder to the piezometer. A 15 mm hole is also drilled on the frame, which serves as a draining hole for the fluid.

The piezometer is part of the forced vortex equipment, which is used for measuring pressure head at different radius of the water in the cylinder. The pressure head is developed by the centrifugal action of the impeller. The piezometer consists of capillary tube, plywood board, metre rule and stand.

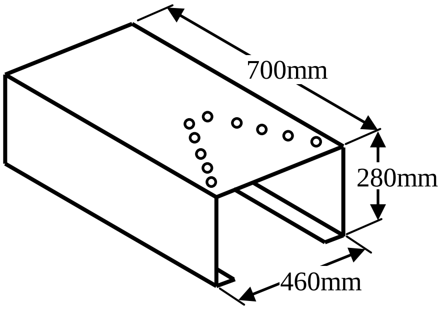


Fig. 2: The Isometric View of the Frame

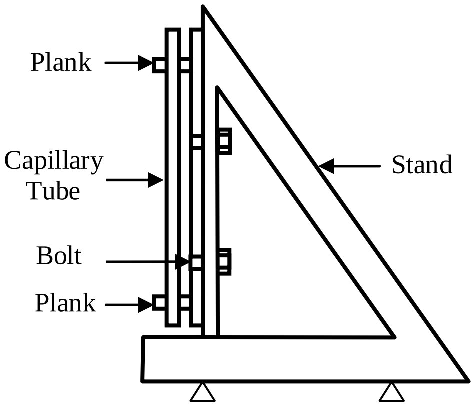


Fig. 3: The Side View of the Piezometer

The impeller is that part used in the vortex equipment to impart centrifugal force to the water in the cylinder, thereby creating a pressure head, which increases with the radius. The impeller is made from metallic material circular in shape, having a diameter of 285mm and 10mm thick. It has blades made of metals having 120mm length, 15mm width and 5mm thickness. The blades are six in number and are welded to the back-plate at 60° to one another. The back-plate is drilled at the centre so that it can be bolted to the shaft through the hole. The shaft, which links the impeller with the electric motor, is made of mild steel rod. The biggest diameter portion is machined to 41 mm with 20mm thickness. Another portion from one end is machined to 12 mm diameter and threaded up to 30mm length. The last portion of the shaft is machined to 15 mm diameter with 200 mm length.

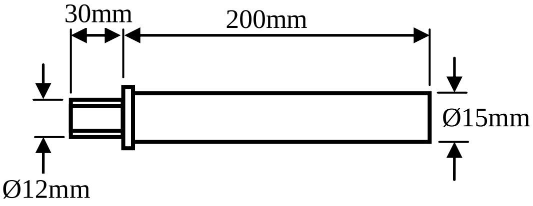


Fig.4: The Impeller Driving Shaft

The cylinder is made up of a transparent plastic so as to allow visible flow of water. And the electric motor used for this equipment is 1.8 horse power 50Hz, having a maximum speed of 1375 rpm.

The Experimental Set Up: Fig. 5 shows the experimental layout of the forced vortex equipment. Most of the parts of the equipment were assembled together with bolts and nuts. The electric motor is bolted to the base of the frame while the cylinder is bolted on top of the frame. The gearbox is coupled to the electric motor by means of a flange coupling and the output shaft of the gearbox is coupled to the impeller shaft by a hollow shaft, which has holes on it at both ends so that the gearbox output shaft and impeller can be together by using pins through the holes and through the holes that are on both shafts. The board of the piezometer is bolted to the stand and capillary tube is fixed to it by using two planks, which have ten holes on them to accommodate the tubes. The tubes are connected to the pressure tapping radii by rubber hoses.

For pressure head at different radius to be read directly on a piezometer so as to make comparison between the measured pressure head and calculated pressure head, it is required to fix some points at which the readings should be made; that is, the radius of the pressure tapings from the centre of the vortex. In order to have an accurate shape of the water head, the radius of the pressure tapings are located close to one another with an interval of 25 mm. The pressure tapping radii are 25, 50, 75, 100 and 125 mnm. The holes are drilled of Ø3mm radially outwards from the centre of the base plate. Two of these arrangements are made at 900 to each other forming a vee shape of holes.

Experimental Procedure: Water is admitted into the cylinder through the open top to a height of 400mm. The drain hole, which has been closed, will prevent the draining off of the water from the cylinder. The desired speed is selected on the speed regulator. The electric motor is then switched on and left to run to its full speed and the piezometer is observed until the water level in each tube is no more fluctuating. When this occurs, the readings are taken. The total head corresponding to each radius is measured; that is, the height of water at each point using the base of the cylinder as the datum from where all readings are taken and measured. The experiment is taken for both maximum and minimum speeds of the impeller as it spins the water inside the cylinder and produces the forced vortex flow.

RESULTS AND DISCUSSION

The readings of total heads (called measured H), at maximum and minimum speed, from the experiments conducted on the forced vortex equipment are given in Tables 1 and 2 respectively. The calculated values of the total head called calculated

H*, are also given in the same tables for the purpose of comparison, thereby indicating the performance of the experiment.

Table 1: Experimental and Analytical Results Showing the Performance of the Forced Vortex Equipment at Maximum Impeller Speed

Tapping Radius	Total Head at Maximum Impeller Speed (137.5rpm)		Deviation between Analytical and Experimental Results (%)
	Calculated H^*_{max} (mm)	Measured H_{max} (mm)	
25	296	294	0.68
50	315	313	0.63
75	349	346	0.86
100	395	390	1.27
125	454	450	0.88

Table 1: Experimental and Analytical Results Showing the Performance of the Forced Vortex Equipment at Minimum Impeller Speed

Tapping Radius	Total Head at Maximum Impeller Speed (137.5rpm)		Deviation between Analytical and Experimental Results (%)
	Calculated H^*_{max} (mm)	Measured H_{max} (mm)	
25	365	360	1.37
50	371	370	0.27
75	385	383	0.52
100	398	396	0.50
125	420	418	0.48

Computation of Reynolds Number

$$\mathrm{Re} = \frac{\rho v d}{\mu} \qquad \text{(10)}$$

(Bacon and Stephens, 1990)

where, Re = Reynolds number

ρ = density of water, kgm^{-3}

d = diameter of the cylinder, m

v = linear velocity of flow in the cylinder, ms^{-1}

μ = dynamic viscosity, Nsm^{-2}

but, kinematic viscosity, $\upsilon = \frac{\mu}{\rho}$, d = 2r and v = ωr

$$\mathrm{Re} = \frac{2\omega r^2}{\upsilon} \qquad \text{(11)}$$

For water, Kinematic viscosity, υ, = 1.31×10^{-6} m^2/s, r = 0.145 m and $\omega = 2\pi N/60$
Eqn. (11) becomes Re = 3361.86N . For maximum speed of impeller, N = 137.5 rpm, therefore, Re = 462256. Also, for minimum speed of impeller, N = 80 rpm, Re = 268949.

Figures 6 and 7 show the variation of total head with the tapping radius measured from the centre of the cylinder for maximum and minimum impeller speeds respectively. The differences between the calculated (analytical) and measured (experimental) values as shown in Figures 6 and 7 are accounted for by the fluctuations produced during flow of the vortex and frictional resistance due to bend and losses. This is true as all calculated values of the pressure head (H) are greater than the measured values of H at both maximum and minimum speeds of the impeller. Again, the results shown in Table 1 and 2 indicate that for maximum impeller's speed of 137.5 rpm, the deviation between analytical and experimental results was in the range of 0.63 to 1.27% meaning, a range of 98.73 to 99.37% performance of the designed forced vortex equipment while for minimum impeller's speed of 80 rpm, it was deviation range of 0.27 to 1.37% and hence, a performance of 98.63 to 99.73% of the forced vortex equipment. The combination of these two results would give an average equipment efficiency of 99.18%.

From his experiments, Osborne Reynolds had found out that laminar flow characterised by smooth motion of fluid elements or laminar past another while turbulent flow is characterised by an irregular and nearly random motion of fluid (Slimes, 1962). Reynolds also discovered that in round pipe, flow is laminar for Re less than 2000 and turbulent for Re greater than 4000. The transition zone lying between these two values has flow, which is unstable, and indeterminate (Bacon and Stephens, 1990). However, from the computation of the Reynolds number for both maximum and minimum speeds of the impeller spinning the water contained in the cylinder, it is obvious that the vortex flow is turbulent since both values are even much greater than 4000.

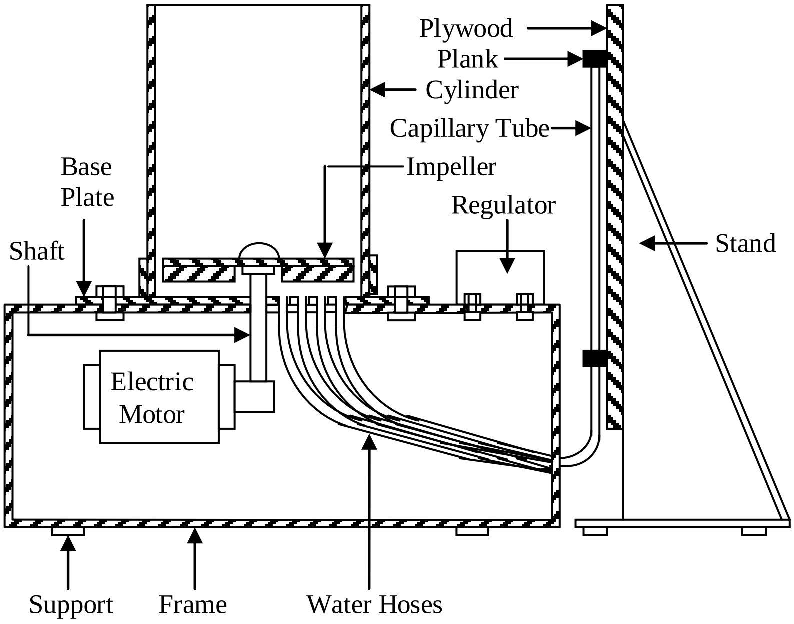


Fig. 5: Experimental Layout of the Forced Vortex Equipment

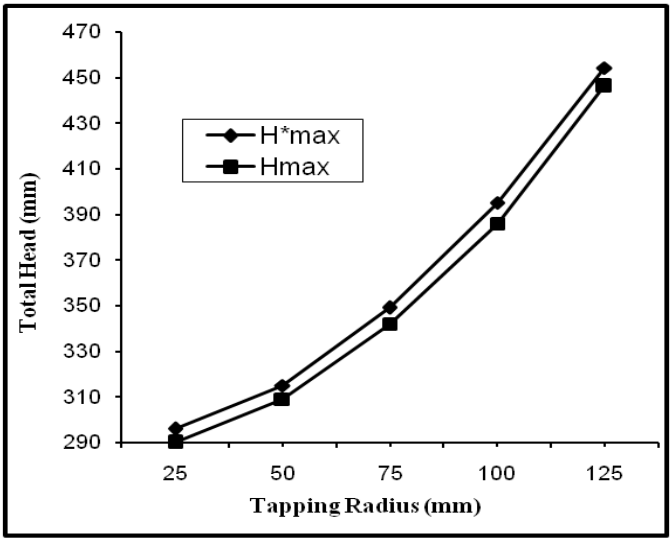


Fig. 6: Variation of Total Head with the Tapping Radius for Maximum Impeller Speeds

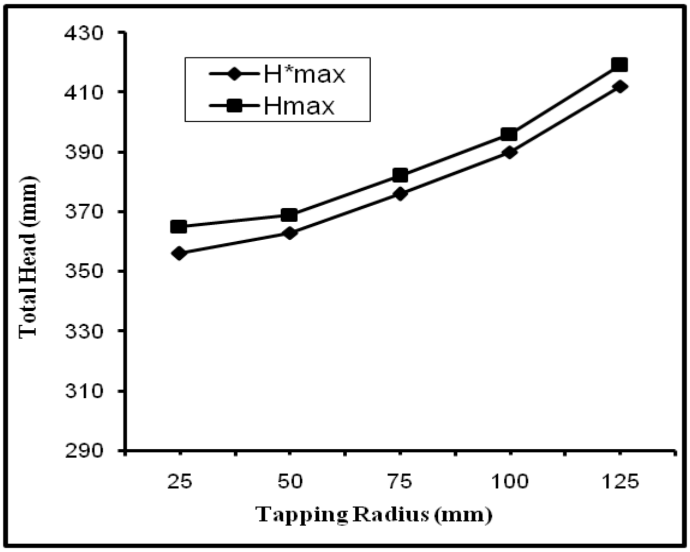
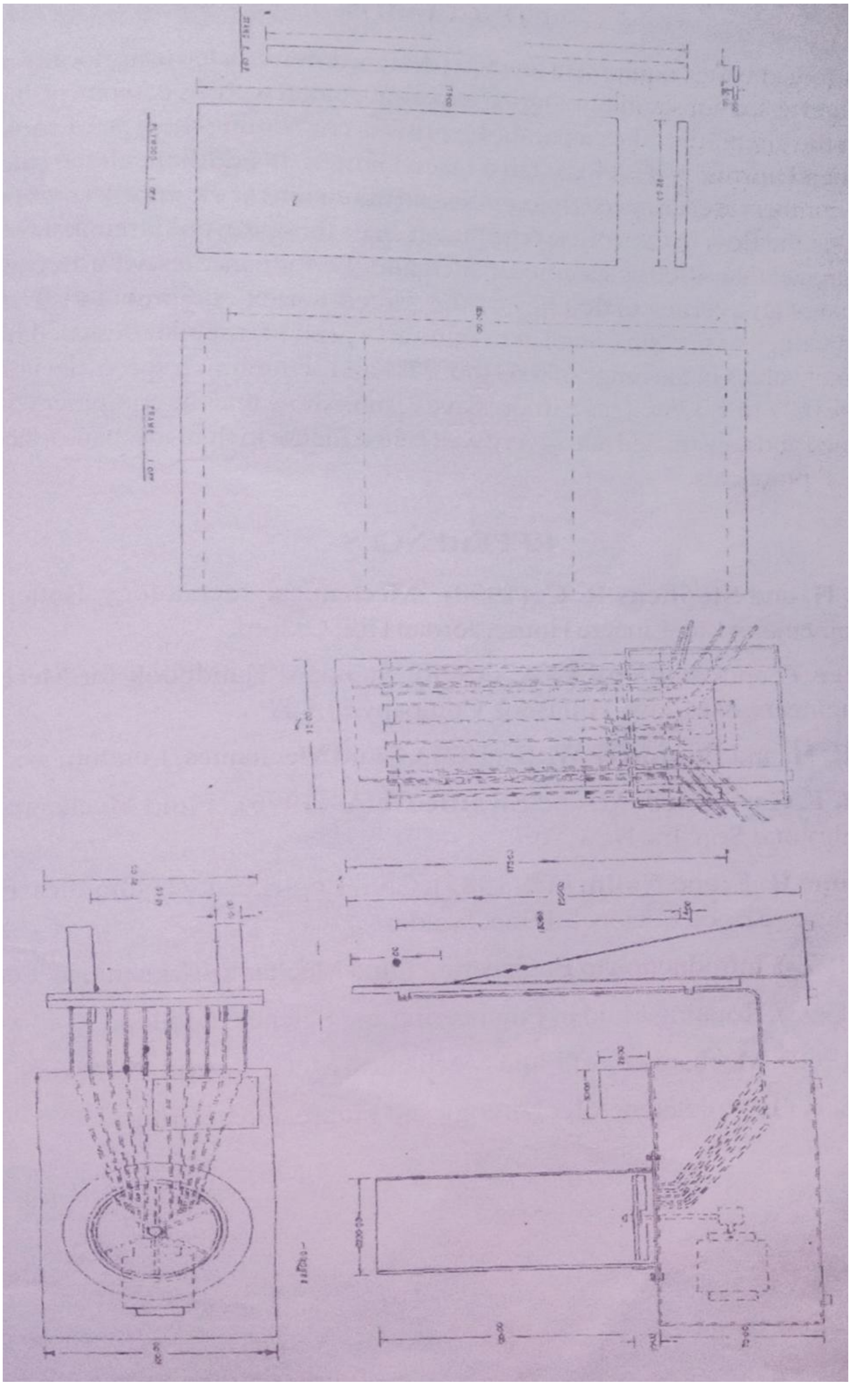


Fig. 7: Variation of Total Head with the Tapping Radius for Minimum Impeller Speeds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CONCLUSION

A forced vortex equipment has been designed, constructed using locally-sourced materials and tested substantially. During experimentation with the equipment, the liquid surface in the apparatus takes a parabolic profile, confirming the type of equation of pressure head normally developed in a forced vortex. In addition, all the calculated Reynolds numbers at each speed (maximum and minimum) of the impeller are very high, showing that the flow in the vortex is turbulent since those Reynolds numbers obtained are much greater than 4000 as specified in literature. Performance test with the equipment also indicates an average efficiency of the forced vortex equipment oft 99.18% as calculated values of pressure head at maximum speed of impeller deviated from the experimental values in the range of 0.63 to 1.27% and at minimum speed, deviation was in the range 0.27 to 1.37%. These impressive results show that the equipment has been well designed and constructed and is very well suited for use in fluid mechanics laboratory for students' practical.

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