Design of Testing Equipment of Ultra Low Head Hydraulic Turbine Model to Support Implementation the Laboratory Work of Machine Performance at Mechanical Engineering Department

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Abstract

Mechanical Engineering Department, University of Lampung has been established since 1998 and in the implementation of learning process at this departmen supported by ten laboratories, that is: Laboratory of CNC, Laboratory of Drafting, Laboratory of Materials, Laboratory of Manufactured, Laboratory of Computer, Laboratory of Industry Metrology, Laboratory of Structural Mechanics, Laboratory of Thermodynamics, Laboratory of Fluid Mechanics, and Laboratory of Combustion Engine. These laboratories are used as research means for the lecturers and the students and also for the implementation of the subject of available laboratory work in the curriculum of Mechanical Engineering Department, University of Lampung, One of the subjects of laboratory work is machine performance, where this laboratory work is carried out in three laboratories, that is Laboratory of Thermodynamics, Laboratory of Fluid mechanics, and Laboratory of Combustion Engine. The testing equipments are available until now, namely, vapour compression refrigeration system, Pelton turbine, and combustion engine, and these testing equipments need for the addition to support this laboratory work. However the funding from university is very limited. Therefore addition testing equipment must be made. In this paper design of a testing equipment of ultra low head hydraulic turbine model is presented to be used for laboratory work of machine performance in Mechanical Engineering Department, University of Lampung.

Keywords: Hydraulic Turbine, Helical Turbine, Ultra Low Head, Laboratory Work, Machine Performance

1. Introduction

The Department of Mechanical Engineering is one of the departments located in the Faculty of Engineering, University of Lampung, and this department was established in 1988 with supporting fund from EEDP and HEDS-Project, especially in development of human resources, laboratories, physical buildings and learning process and office facilities. The goal of establishing of this Mechanical Engineering Department is:

1. To develop graduates who have a reasonable, logical and rational mindset with the basic knowledge of Mechanical Engineering to be able to analyze and synthesize machine characteristics.

2. To develop graduates who have the ability to create new solutions, adopt old solutions, and use the knowledge gained in the science of energy conversion, design and construction, materials and manufacturing.

3. To develop graduates who can model and predict the behavior of engineering equipment through the application of scientific and technological principles.

One of the missions to achieve this goal is to carry out an effective and efficient learning process by improving facilities and infrastructure to support the learning process including laboratory equipment.

The learning process carry out at the Mechanical Engineering Department of Faculty of Engineering, University of Lampung is currently supported by 10 laboratories, namely: Laboratory of CNC, Laboratory of Drafting, Laboratory of Materials, Laboratory of Manufactured, Laboratory of Computer, Laboratory of Industry Metrology, Laboratory of Structural Mechanics, Laboratory of Thermodynamics, Laboratory of Fluid Mechanics, and Laboratory of Combustion Engine. These laboratories are used as research facilities for lecturers and students and also for the implementation of laboratory work courses in the curriculum of the Department of Mechanical Engineering, Faculty of Engineering, University of Lampung. One of the laboratory work courses is the laboratory work of machine performance. This laboratory work is carried out so that students are able to determine and measure the performance parameters of energy conversion machines by applying theories that have been obtained in the courses of Fluid Mechanics, Thermodynamics, and Energy Conversion Machines. However, the testing equipment to carry out the laboratory work of machine performance is still lacking, where the testing equipments are available until now, combustion engine, Pelton turbine and Air Conditioning (AC). This is caused by the limited funds provided by the university to supply the testing equipment in the laboratory. So it is necessary to develop additional testing equipment to support the implementation of this laboratory work. In this paper is given the design and development of testing equipment of ultra low head hydraulic turbine model to support implementation the laboratory work of machine performance in Mechanical Engineering Department, University of Lampung.

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1.1. **Hydraulic Turbine for Very Low Flow Head**

For decades scientists have tried to use conventional turbines for low flow heads. Highly efficient water turbines for high flow heads are very expensive when applied to hydropower stations with low or very low heads. The main types of water turbines currently used to harness hydropower are: Kaplan, Francis, Pelton, and cross flow turbines. The Kaplan turbine is one of the water turbines which technically can be used for a two meter head height or a lower water head but the turbine operating unit cost increases up to about four times when the water heads fall from 5 to 2 meters.

In 1931 Darrieus patented reaction turbine to use low or very low head flow energy (free flow). This turbine has a drum-like shape with a number of straight or curved blades of airfoil and a shaft that is perpendicular to the fluid flow. This turbine allows high torque for slow current flow, and provides a large fluid flow through the turbine without enlarging the diameter. However, the Darrieus turbine has not been acceptable for large applications, mainly due to fluctuations during rotation and relatively low efficiency. Fatigue failure of the blade generally occurs in this turbine due to the nature of the vibration that occurs. This turbine also has an initial operating problem at low rotational speed due to a straight blade that changes the angle of attack.

Gorlov [1] explained the helical turbine has the same advantages as the Darrieus turbine, for example: able to pass a large mass of water for slow flow, kinetic energy capturing, and the low cost turbine for using a very simple rotor blade. The helical arrangement of the rotor blades also makes the performance of the helical turbine better as compare with the Darrieus turbine. It results the characteristics: uniform turbine rotation at high speed in relatively slow fluid flow, unidirectional rotation in reversible fluid currents, high efficiency, no fluctuating torque, no cavitation in water for high rotating speed, self-starting better in slow flow of waters.

An approximation of the vertical axis turbine is used to calculate the power was generated by this helical turbine blade, as can be seen in Figure 1. The resultant velocity vector (W) is the sum of the velocity vector of fluid (V) and the velocity vector of the advancing blade (U).

$$\overrightarrow{W} = \vec{V} + \left(-\vec{\mu} \times \vec{R}\right) \tag{1}$$

where R is the radius of turbine (m), and ω is the angular velocity of turbine (rad/ s).
From the Figure 1, the resulting of fluid velocity varies, the maximum is found for $\theta = 0^{O}$ and the minimum is found for $\theta = 180^{O}$, where θ is the azimuthal or orbital blade position. The angle of attackα is the angle between the resultant vector velocity (W), and

blade's chord. From geometrical considerations, the resultant of flow velocity and the angle of attack are calculated as follows:

$$W = V\sqrt{1 + 2\lambda\cos\theta + \lambda^2} \tag{2}$$

$$\alpha = \tan^{-1}\left(\frac{\sin\theta}{\cos\theta + \lambda}\right) \tag{3}$$

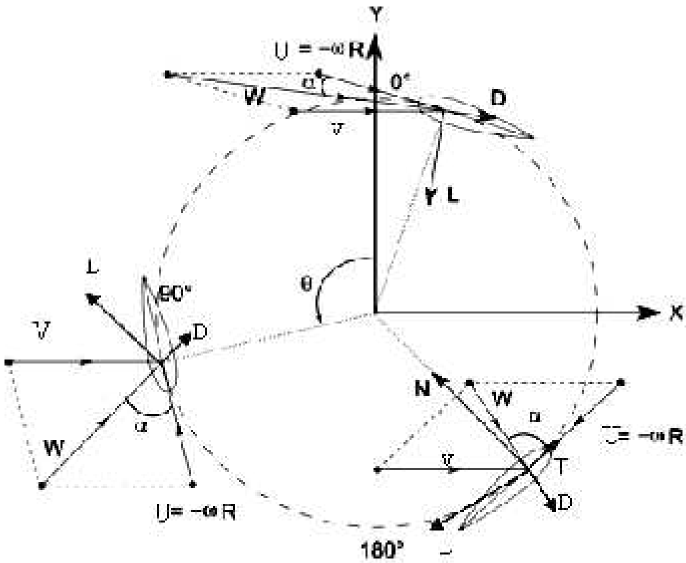


Figure 1.Forces and velocities acting in a vertical axis wind turbine for various azimuthal positions.

where λ is tip speed ratio, and can be calculated by using the following equation

$$\lambda = \frac{\omega R}{U} \tag{4}$$

The resultant aerodynamic force is composed in the lift force (F_L) and drag force (F_d) which these forces can be calculated using the following equation:

$$F_d = \frac{1}{2} C_d \rho V^2 A \tag{5}$$

$$F_l = \frac{1}{2} C_l \rho V^2 A \tag{6}$$

where C_d is the coefficient of drag, C_l is the lift coefficient, ρ is fluid density (kg/ m^3), V is fluid velocity (m/s), and A is cross-sectional area of the hydro foil blade (m^2).

The force perpendicular to the arm (radius) of turbine, the torque by projecting lift and drag forces can be calculated using the following equation:

$$T = (F_l.\sin\sim - F_d.\cos\sim) \times R \tag{7}$$

where T is the torque (N.m), F is the force perpendicular to the arm (N), and R is the radius (m). From Equation 7, the shaft power P_b (W) can be calculated using the equation:

$$P_b = T\mu \tag{8}$$

1.2. **Mathematical Model for Design of Helical Turbine**

In Figure 2 [4], It can be seen helical blades formed AME lines on the surface of a cylinder having height L and radius R. The helical blade equation is defined by:

$$X = R\cos\ddot{} \quad Y = R\sin\ddot{} \quad Z = R\ddot{}\ \cos¢ \tag{9}$$

where x, y and z are the coordinates of the point M of the helix, and δ is the angle of inclination of the blade to the XOY plane.

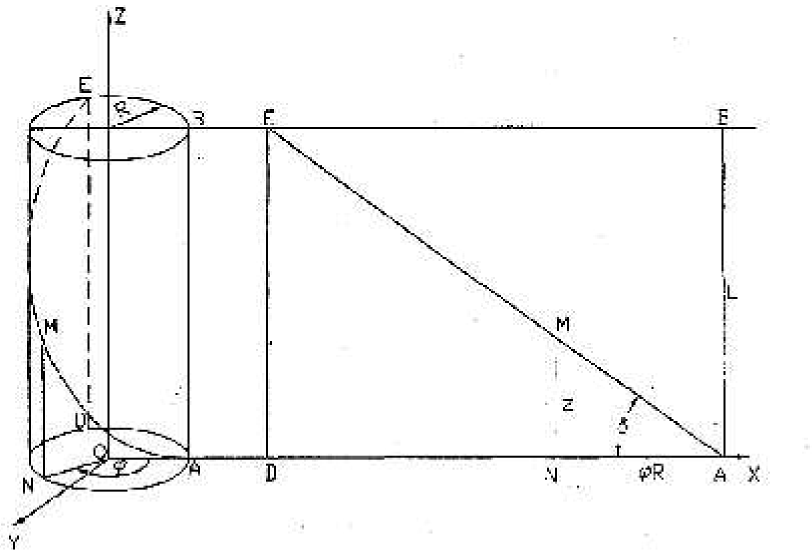


Figure 2. Projection of the blade line on vertical plane.

As an approximation that the cross section of the blade has the shape of an infinitely thin rectangle with its length equal to the chord c of the blade's airfoil. This does not change the proportion between lifts and drags after resolution of the reaction force F which can be calculated as:

$$F = k_o A V^2 \qquad (10)$$

where: ko is a constant, ρ is water density, A is projection of the frontal area of the blade on the plane perpendicular to the water flow, and V is velocity of water.

The total starting torque developed by the turbine blades in the water flow can be expressed by the equation

$$T = k_2 \frac{\sqrt{1+q^2}}{2} \sin^2\left(\frac{L}{R\,q}\right) \qquad (11)$$

where $k_2 = \frac{1}{2} k_1 R$, $k_1 = k_0\, b V^2 R$, $q = \tan ¢ = \frac{L}{¨_0 R}$, and l is the length of the blade.

In dimensionless can be written

$$T_1 = \frac{T(q)}{k_2} = \frac{\sqrt{1+q^2}}{2} \sin^2\left(\frac{L}{R\,q}\right) \qquad (12)$$

Figure 3 [2] shows the torque T, as a function of angle of blade inclination δ and the ratio of the turbine height to its radius L/R.

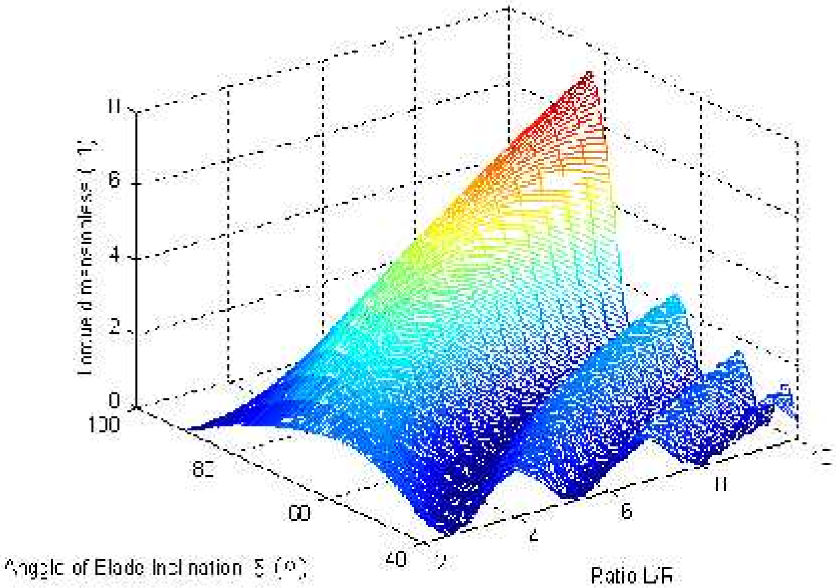


Figure 3. The torque relation T_1 as a function of angle of blade inclination δ and the ratio of the turbine height to its radius L/R.

2. Materials and Methods

2.1 Determining the Turbine Parameters

The model of designed turbine to be used in the testing equipment is shown in Figure 4. The parameters of turbine to be determined: height of turbine L, diameter of turbine R, shape of blade, number of blades n, and angle of blade inclination δ.

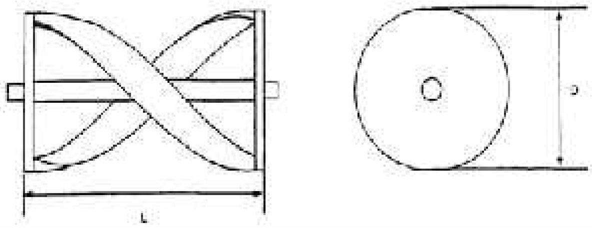


Figure 4. Scheme of helical turbine model

Determining dimensions of the testing equipment system and the parameters of the helical turbine to be used should consider the Fluid Mechanics Laboratory conditions and the available measurement instruments. The measurement instruments used to execute this laboratory experiment are torque meter to measure the torque produced by shaft turbine (N.cm), with the maximum torque meter of 147 N.cm, tacho meter to measure the speed of turbine rotation (rpm) and propeller flow meter to measure the velocity of flow (m/s).

(a)

(b)

(c)

Figure 5. Photograph of measurement instruments: a. tacho meter, b. torque meter, and c. propeller flow meter

2.2. Construction of Testing Equipment

Scheme of the testing equipment design can be seen in Figure 6. This device transforms kinetic energy derived from flow of low head, to turn a turbine to produces mechanical energy of rotation and whose primary function is to drive a electric generator.

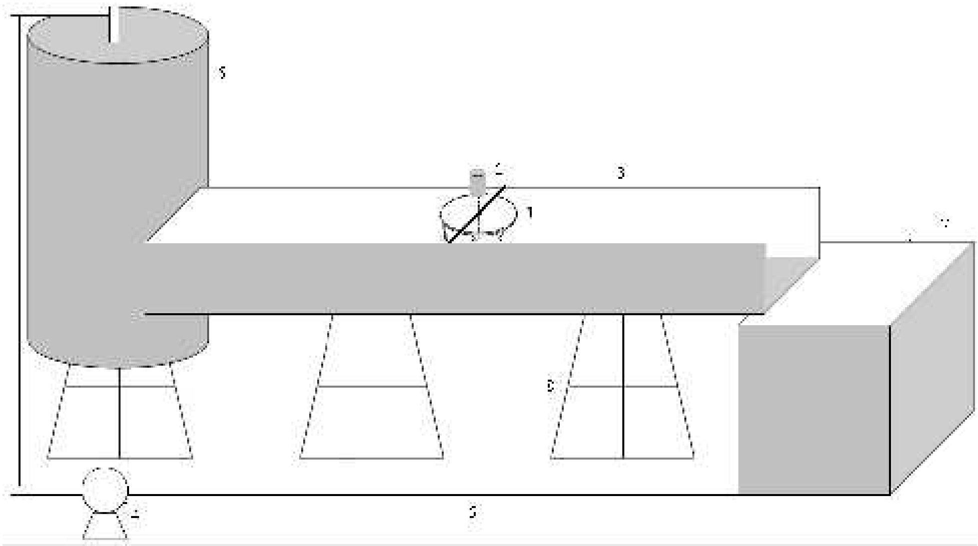


Figure 6. Schematic of testing equipment system

Caption:

1. Helical turbine	2.Torque meter
3. Channel	4. Pump
5. Pipe	6. Tank
7. Reservoir	8. Testing equipment supporting

The efficiency η_t of helical turbine model can be calculated using the equation:

$$\eta_{sys} = \frac{P_t}{0{,}5 \cdot \rho . A_t . V^3} \tag{13}$$

Where P_t is power generated by turbine shaft (W), it can be calculated using the Equation 7, ρ is water density (kg/m^3), V is velocity of water flow (m/s), and A_t is cross sectional area of helical turbine (m^2).

3. Results and discussion.

3.1. Model of Testing Equipment System

According to the conditions of space of the Fluid Mechanics Laboratory, dimensions of thank and cross-sectional area of channel were determined 1 m x 1 m x 1 m and 20 cm x 30 cm respectively. The available head of flow is 1 m to run the experiment. The velocity of flow in channel was measured by propeller flow meter and it can be varied to 1.37 m/s, 1.56 m/s and 2.1 m/s.

Figure 5. System of testing equipment

3.2. Turbine Design

Generally helical turbine uses blade's airfoil, due to its high efficiency and produces a large pressure difference between two sides of blade to rotate with a considerable force moment in which the force moment is generated by lift and drag force. The lift and drag forces that occur in the airfoil sections are influenced by the shape of blade and the angle of attack. The symmetry airfoils of NACA 0030 [3] was used for the turbine blades.

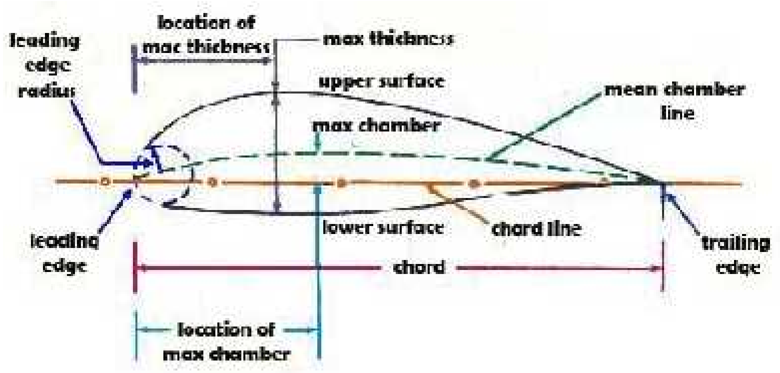


Figure 8. Parameters of NACA airfoil

According to conditions of the channel, helical turbine to be used has 10 cm in diameter and 20 cm in height. Using equation 12, for the ratio of height to radius of turbine L/R of 4, it was obtained the angle of blade inclination δ of 72^o.

The performance of helical turbine operation is also influenced by relative solidity. It can be calculated using the equation [4]:

$$\pm = \frac{S}{2LR} \tag{14}$$

where σ is parameter of relative solidity, S is solidity of the helical turbine, L is height of the turbine, and R is radius of the turbine. solidity of the helical turbine can be calculated using the equation:

$$S = \frac{2nLR}{®}\left(d + \sum_{k=1}^{n} \sin\left(\frac{® k}{n} - d\right) - \sin\frac{® k}{n}\right) \tag{15}$$

where n is the number of blades, and d is half of the blade’s chord in radians with respect to the axis of rotation.

Figure 9 [5] is shown the effect of tip speed ratio λ to coefficient of performance Cp (efficiency) for each relative solidity σ of hydrokinetic turbine (HKT) Darrieus with straight blade.

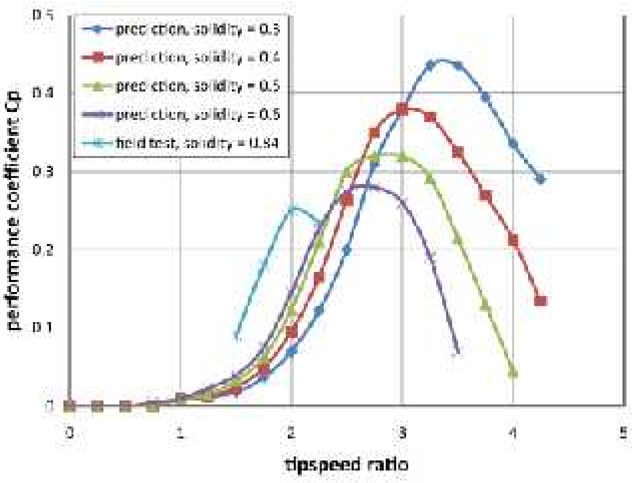


Figure 9. Predicted and measured performance of Darrieus HKTs of varying solidity

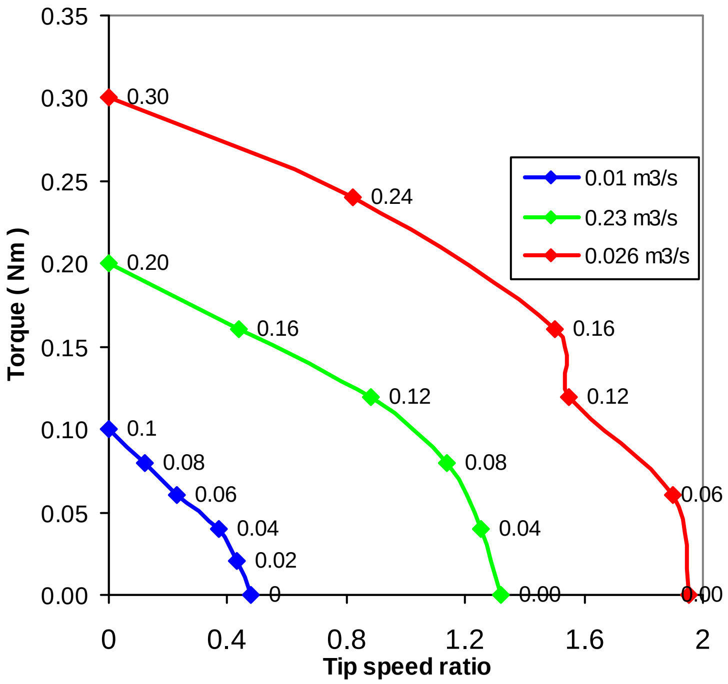
The tip speed ratio of turbine operation was determined λ = 3 [4], this is to prevent cavitation during turbine operation. From Figure 10, for tip speed ratio λ = 3, it was obtained the relative solidity σ ≈ 0.4 as proposed by Shiono et. all.[6|. Based on previous study [7], operating the helical turbine with tree blades was given the maximum efficiency, however to see the influence of the number of blades on performance characteristic of turbine, turbine with two blades also developed. Using Equation of 14 and 15, it was found the length of chord’s blade of 3.2 cm.

Figure 10. Model of helical turbine with tree blades

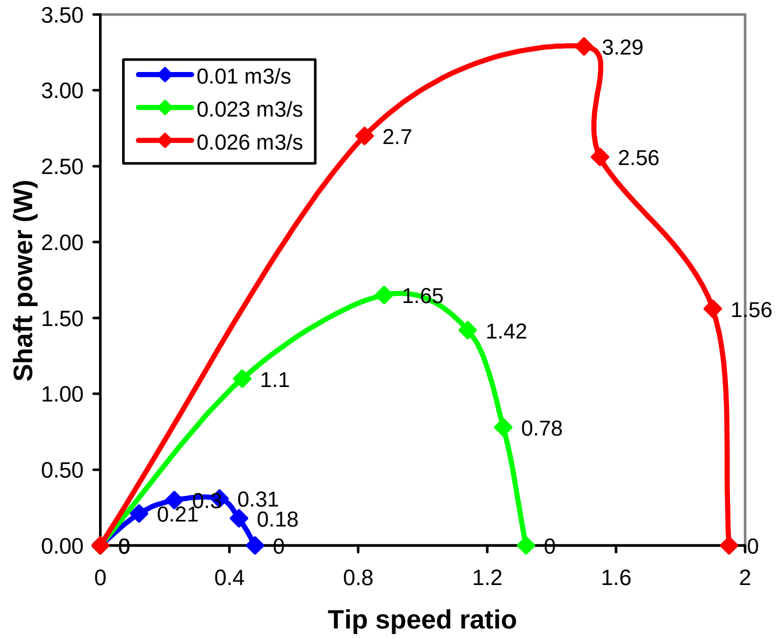
3.4. Testing Results and Discussion

Figure 12 and 13 are given the testing results of the testing equipment of helical turbine. From the testing results in Figure 13, the turbine using 3 number of blades give the highest efficiency and shaft power, where these values of efficiency and power were found 28.03 % and 9.46 W respectively. It was better as compare with the using 2 number of blades of turbine. This is due to the operation of turbine using 3 blades produced greater lift forces compared with the 2 number of blades. The best operation of this turbine was at the tip speed ratio of 0.89.

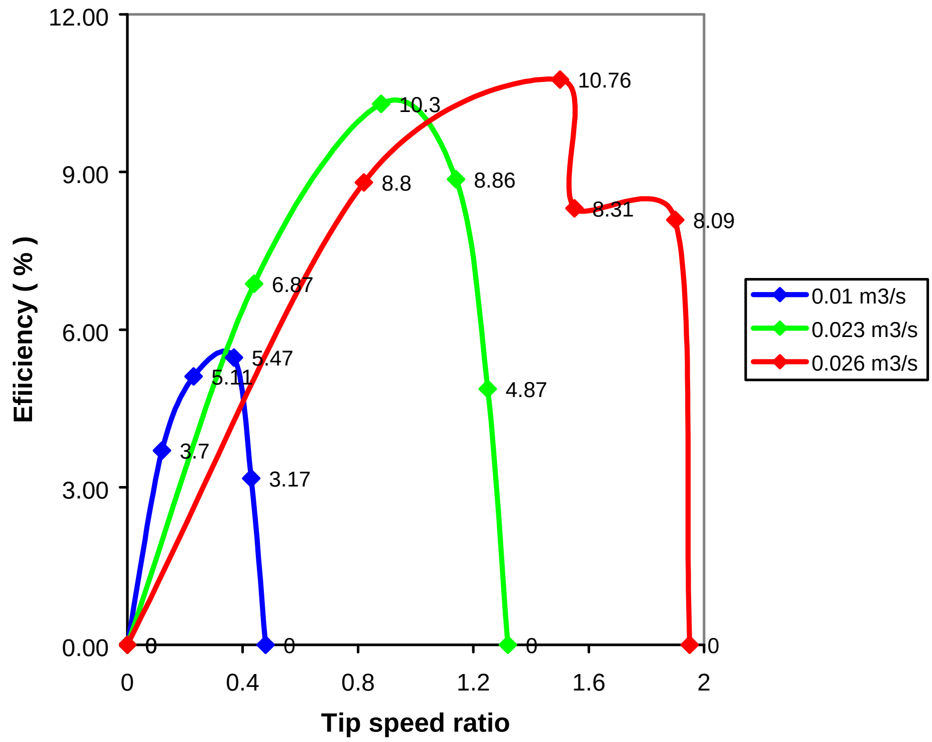
Figure 11. Testing of the developed testing equipment



a. Influence of volume flow rate on the torque

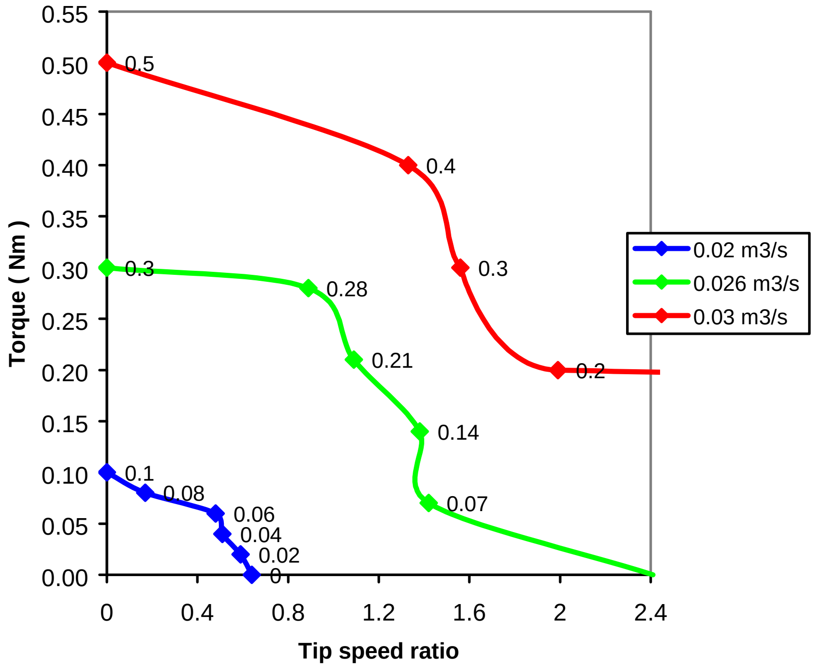


b. Influence of volume flow rate on the shaft power

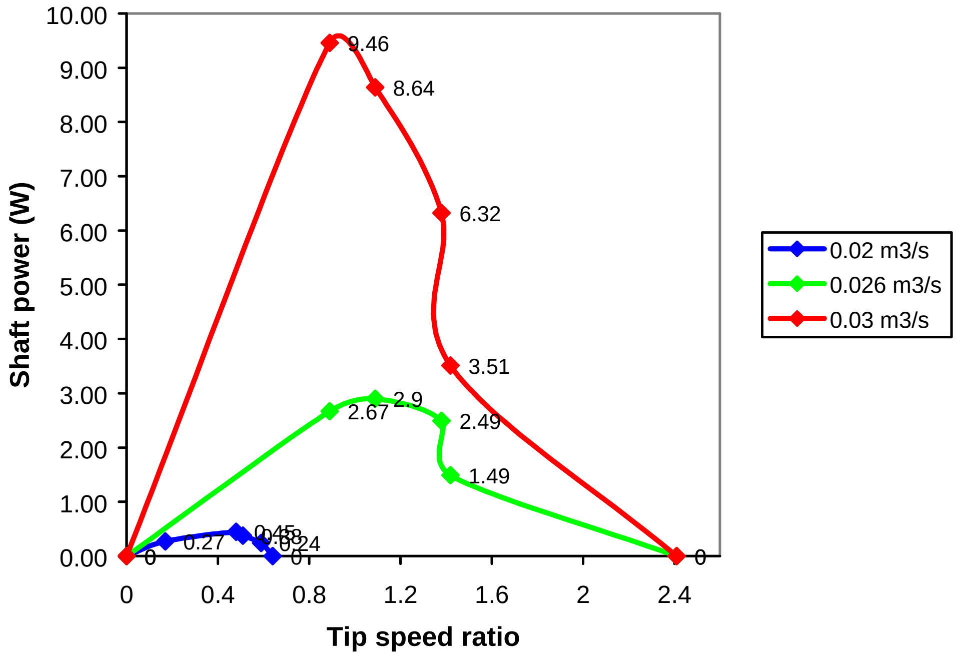


c. Influence of volume flow rate on the efficiency

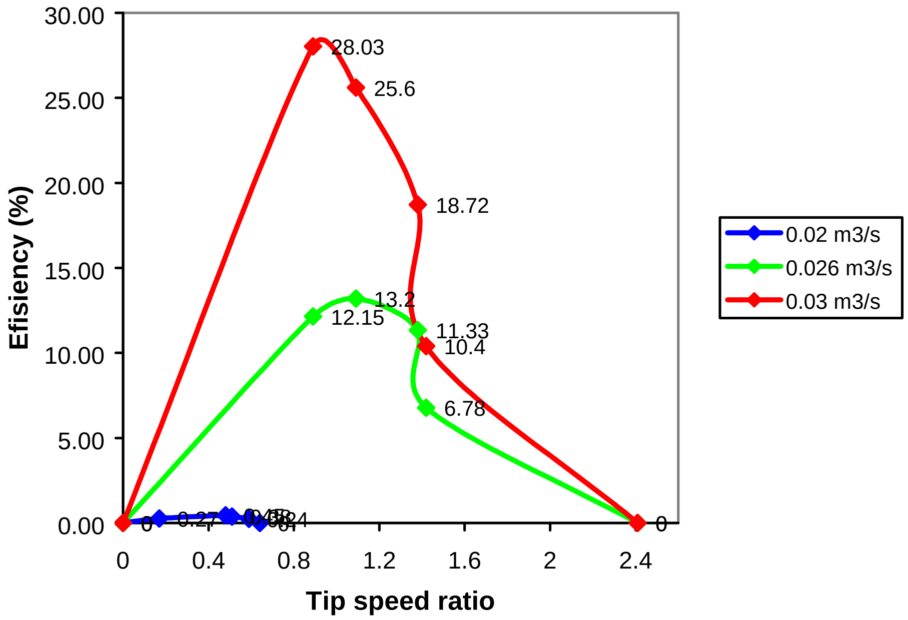
Figure 12. The testing results of helical turbine model with using 2 number of blades



a. Influence of volume flow rate on the torque



b. Influence of volume flow rate on the shaft power



c. Influence of volume flow rate on the efficiency

Figure 13. The testing results of helical turbine model with using 3 number of blades

The developed testing equipment of ultra low head hydraulic turbine model can perform the performance characteristics of helical turbine. Using this testing equipment will help the students to understand how the working principle of helical turbine to convert kinetic energy of water flow into mechanical energy. The testing results also show how the number of blades and velocity of flow influence the performance characteristics of helical turbine. Therefore this testing equipment of ultra low head hydraulic turbine model can be used to support implementation the laboratory work of machine performance in Mechanical Engineering Department. This testing equipment will also help the students who interested in studying the performance of this turbine when it is applied in the system of hydro electric power generation to utilize kinetic energy derived from flow of low head or stream of water.

4. Conclusions

Based on the results that have been obtained and described earlier, it can be taken some conclusions:

1. In this research is given design method of the testing equipment of ultra low head hydraulic turbine model to support implementation the laboratory work of machine performance in Mechanical Engineering Department.

2. The developed testing equipment of ultra low head hydraulic turbine model can perform the performance characteristics of helical turbine to utilize the stream flow energy which has very low head or only kinetic energy.
3. The test results show the number of blades and velocity of flow influence the performance characteristics of helical turbine where using 3 number of blades gives the maximum of turbine efficiency of 28.03 %.
4. The course of this laboratory work will provide an opportunity for students to develop their competency in design and execution of laboratory experiments, analysis and interpretation of data use information from the engineering literature including basic concepts from the courses have introduced by the lecturer especially fluid mechanics, energy conversation and fluid machinery subject.

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