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Research Article

Fluid Flow Phenomenon in a Three-Bladed Power-Generating Archimedes Screw Turbine

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Abstract

Experimental studies of the Archimedes screw turbine are applied as a micro hydro power plant for low head focused on the fluid flow. Fluid flow on a screw turbine is not completely filled water flow there is still a free surface between the water fluid and atmospheric air. Except the screw geometry, the turbine screw free surface allows the flow phenomena that are important in the process of turbine screw power generation. The Archimedes screw turbine main driving force is the fluid-gravity weight, which is affected by the inflow depth, inflow velocity and the turbine shaft's slope. The dimensionless parameter Froude number (Fr) is connected to analyze the screw turbine efficiency. The purpose of this study is to figure out the fluid flow role when power generated by a three blades Archimedes screw turbine observed visualized, and also observed the turbine rotation and torque. The observed parameters are varied in inflow depth as the characteristic length (y) of Froude Number, inflow velocity (co), and the turbine shaft slope (α). The screw turbine model, were made under a laboratory scale and made from acrylic material. The geometric form is the three bladed screws which have seven screw respectively, the number of helix turns is 21, the angle of screw blade is 30°, radius ratio of 0.54 with a pitch distance of 2,4 Ro. The result from this study revealed a phenomenon of fluid flow between the screw blades a whirlpool wave occurs or vortex due to the linear momentum in a form of the hydrostatic force against the blade screw which occurs in two opposite directions and the effect of the turbine shaft angular momentum. The vortex would affect the screw turbine power generation process as most of the kinetic energy that goes into the screw turbine sucked into the vortex between the screw blades, but this phenomenon can be reduced by reducing the turbine shaft slope. The highest turbine efficiency of 89% occurred in the turbine shaft's slope of 25° and a flow rate of 0.5 m/s and a 1Ro characteristic length and a 0,12 Froude number.

Keywords: screw turbines, flow phenomena, vortex, power generation, efficiency

1. Introduction

This research was done as a major concern with the electric energy crisis problem. Renewable energy sources such as streams and irrigation channels can be used to become electrical energy generators through a screw turbine as a micro hydro power plant. The screw turbine is adopted from the Archimedean screw theory which is used as a pump. The implementation of an Archimedes screw pumps into the new turbine is a breakthrough and has the possibility for a wider application [1]. The advantage of this screw turbine is that it can operate at a low head (H< 10 m), no penstock is needed, easy installation, easy maintenance and does not damage the river ecology of or fish-friendly [2]. Archimedes screw turbine also could be applied at sea and tidal current for electric power generation [3]. The water flow kinetic energy and potential energy are transformed into mechanical energy on the screw blade and produces a turbine shaft rotation that can be converted into electrical energy in a generator through a transmission device. The water density on the blade which causes the screw to be rotated, assuming that there is no loss of all potential energy in the flow and could produce a maximum efficiency of 100% [4].

Nowadays, the screw turbine research is being developed in terms of both theoretical and experimental designs related to the efficiency of screw turbine. The numerical optimization of the design of screw's geometric shapes [5] with a pitch ratio results depends on the blade number and radius (R_1/R_0) which was 0.54 on the optimal pitch ratio. The screw turbine efficiency is influenced by the turbine geometry and flow loss [4]. Furthermore, [6] introduces an analytical model of screw turbine inlet flow by taking into account the possibility of flow leaking on the gap between the screw and the outer cylinder (casing) and also the excess water on the center of the pipe. A MATLAB screw turbine simulation for hydroelectric power plants on the

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lower head already carried out [7]. The modeling and theoretical result of Müeller [4], Nuernbergk [6] and Raza Ali [7] was then compared with the first [8] and second [9] experiment of Brada.

The experimental screw turbine study still needs to be developed to get real information in order to apply the screw turbines optimally. Screw turbine is applied on river flows and irrigation canals, which they are in open surface condition. Prime mover of the open flow is the weight of fluid that influenced by gravitation and its pressure distribution is hydrostatic. Character of the open flow could be indicated by dimensionless parameter; it is called by Froude Number (Fr).

This research is important because the water flow is the source of kinetic and potential energy which was used in screw turbine power generation system. The experimental screw turbine was made in a laboratory scale using acrylic material. The aim of this is to determine the screw turbine efficiency by observing the effects of the Froude number (*Fr*) and the flow phenomenon.

2. The screw turbine power Generation principle

The Archimedes screw turbine power is the turbine torque linear to the angular velocity. Torque is the moment of a force on an axis. Based on Newton's second law of motion produces the relationship between the tangential force with the linear flow momentum. From the linear momentum equation, it can be developed an equations moment of the momentum by connecting the torque and the angular momentum flow of a control volume. By assuming a one-dimensional flow conditions distributed uniformly with an average speed on each section, and a steady flow condition.

The linear momentum flow equation application on a one-dimensional control volume of a screw turbine blade is the hydrostatic force toward the blade screw, shown in Figure 1. The screw turbine hydrostatic force is the resultant between the hydrostatic force along the turbine axis with the number of helix turns *m* and *S/N* (pitch per number of blades).

$$\int_{cs} V\rho V.\hat{n}dA = \sum F_{hyd} = \frac{(y+\Delta y)^2-y^2}{2}.\gamma.\left(\frac{S}{3}\right).m \quad (1)$$

The shaft torque (moment) working on a control volume is equal to water flow speed moment-momentum (angular momentum) through the control surface, the equation is:

$$\sum(r\ x\ F) = \int_{cs}(r\ x\ V)\rho V\ \hat{n}.dA \quad (2)$$

The screw turbine shaft torque is the resultant of the hydrostatic force (linear momentum) toward the screw turbine blades producing a tangential reaction of the turbine shaft, so that the shaft rotation is directly proportional to r_m the arithmetic radius average ($R_o/2$).

$$T = r_m.\sum F_{hyd} \quad (3)$$

Turbine shaft power related to the turbine shaft torque (torque) and angular velocity ω. Theoretically, the screw turbine's power is calculated by using the following equation:

$$P_t = T.\omega = (r_m.\sum F_{hyd}).\omega \text{ (Watt)} \quad (4)$$

The screw turbine shaft power is experimentally given by,

$$P = T.\omega = (F.\ r)\ .\ \omega \quad \text{(Watt)} \quad (5)$$

Where, F is braking force in spring scale, r is radius of pulley that connected turbine shaft and spring scale.

The hydraulic energy result is then converted into Archimedes screw rotation energy which is the water volume in each bucket Vb. The water flow rate getting into the turbine is divided into Q_w that is hitting blade and Q_G that is passing through the gap between the screw and the turbine casing. The flow rate Q_w that produces torque [6] is as follows:

$$Q_w = V_u\frac{n}{60} \quad (m^3/s) \quad (6)$$

V_u is the volume of every NVb bucket. V_u is depending on the blade numbers, the radius ratio and the pitch.

$$V_u = \frac{2\pi^2 R_o^3}{\tan\beta}\lambda v \quad (m^3) \quad (7)$$

Where λv is the ratio of the volume of each rotation for $N = 3$, [5]. The leakage fraction is the ratio between the flow rate that passes between the screw and the casing Q_G and the water flow rate that produces torque Q_w. The leakage fraction $Q_G/\ Q_w$ is between 0.02 and 0.06 [6]. The total flow rate equation Q is:

$$Q = Q_w + Q_G. \quad (8)$$

The Hydraulic power (P_{hyd}) of the Archimedes screw turbine is:

$$P_{hyd} = \rho.\ g.\ Q.\ H = \rho.\ g.Q.m\ .\Delta y \quad (9)$$

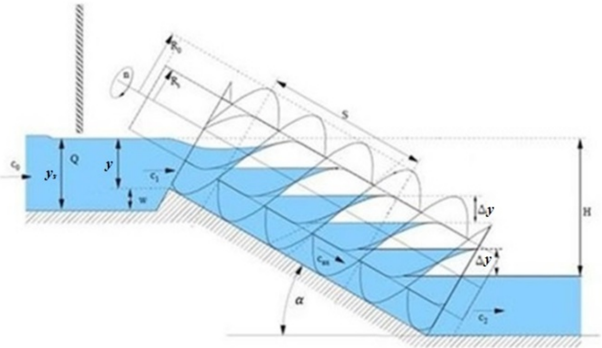

Fig. 1. Flow model on Archimedes screw turbine blade [6].

Theoretical efficiency of screw turbine is:

$$\eta_{th} = \frac{Pt}{P_{hyd}} .100\ \% \tag{10}$$

Efficiency of screw turbine is:

$$\eta_{real} = \frac{P}{P_{hyd}} .100\ \% \tag{11}$$

3. Research Method

3.1 The experimental equipment diagram

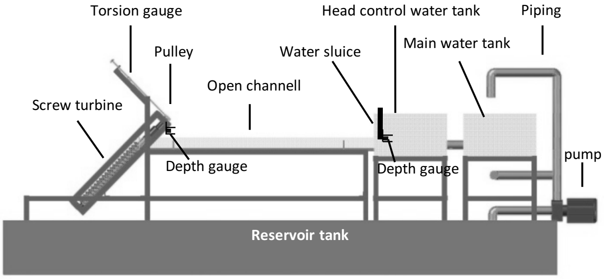

Fig. 2. The screw turbine Installation [12]

Screw turbine model parameters :

Parameter	Value	Description
R_o	0.055 m	Outer radius
R_i	0.030 m	Inner radius
S	0.132 m	Pitch
N	3	Number of blades
m	21	Number of helix turns
β	30°	The angle of screw blade
λv	0.059	Normalized volume/turn
α	25°, 35°, 45°	Turbine shaft slope
h_o	$1/2R_o, 2/3R_o, 1R_o$	Characteristic length
c_o	(0.3, 0.4, 0.5) m/s	Inflow velocity

3.2 Experimental Procedure

In this experimental, an Archimedes screw turbine model is made as shown in Figure 3a.The installation is made in a laboratory scale testing as seen in Figure 2. The working fluid is water. The geometric form is the three bladed screws which have seven screw respectively, the number of helix turns is 21.

The screw blade material is made from acrylic with a 60 mm pipe diameter of the turbine shaft, 25 mm for the blade height, a screw lead distance of 2,4R_o, a radius ratio (R_1/R_o) of 0.54 and an angle of the screw blade is 30^o. Before the data taken, first is set the installation with the appropriate with parameter settings are determined and calibrate the measuring devices. Since the first running test is pumping the water into the tank by controlling the water flow rate with the valve settings.

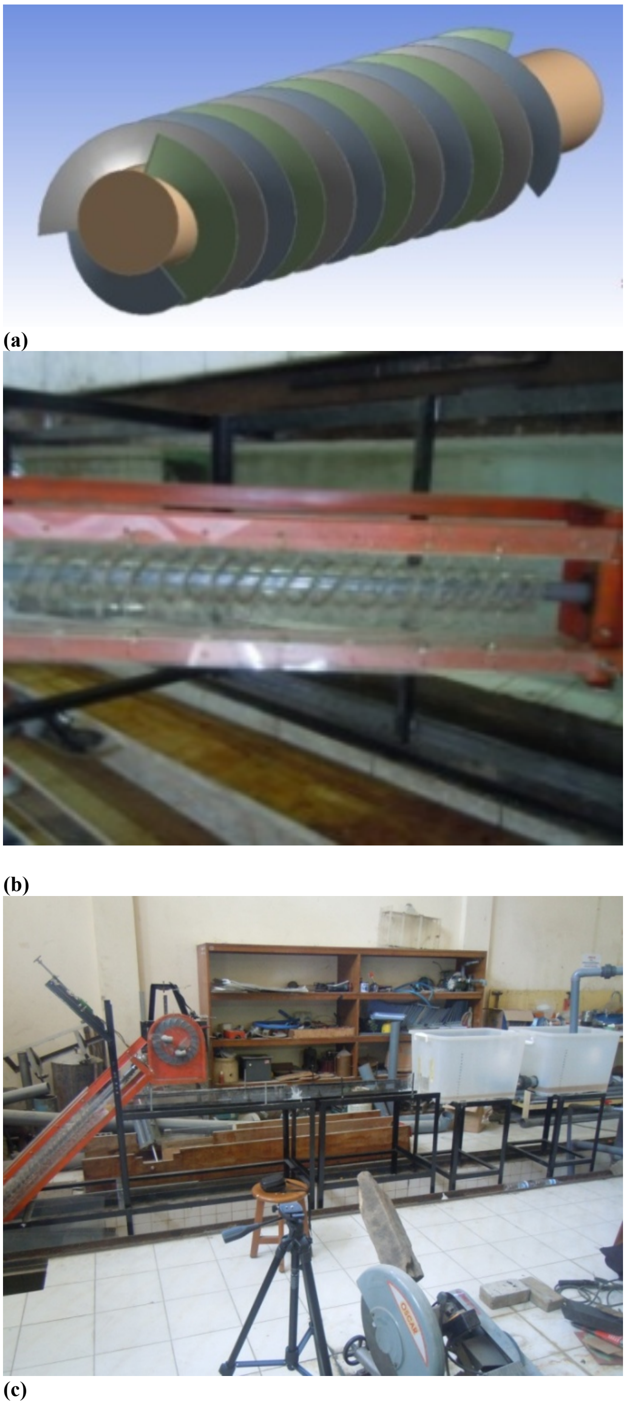

Fig. 3. Three bladed Archimedes screw, the model, b) experimental photo, (c) experimental setup

Furthermore, the water is filled into the special water tank through a connection pipe to prepare the water to be in a steady flow condition. The water flow speed inflow from the tank is then controlled by a special gate by monitoring and controlling the water height in the tank. The characteristic length (y) should be controlled by the water gate and should be measured at the turbine inlet end. The water flow, then goes into the turbine and would rotate the screw blades and the water goes to the reservoir tank would be pumped back to the upper water tank. From this cycle procedure the data taken could be start by adjusting the turbine shaft tilt position (α), set the characteristic length (y) inlet flow by controlling the water gate opening and the water level in the tank in a steady state condition. The data taken are the turbine rotation (n) using a tachometer, flow visualization using a digital camera, and turbine torque using a load braking device (spring scale). The spring scale is perpendicular with turbine's shaft which is connected with pulley and belt.

The measurements of flow rate were taken from volume of screw helix (V_u) that equal with rotation ($n/60$). The data measurements were taken respectively on a characteristic length variation (y) $1R_o$, $2/3R_o$, $1/2R_o$ with a flow velocity variation of 0.3 m/s, 0.4 m/s, 0.5 m/s on any axis tilt variation (α) of 25°, 35°and 45°. The data taken was repeated three times for each variable. Finally, the average value of this measurement was taken.

4. Results and Discussion

The fluid flow in the Archimedes screw turbine is the river water flow or irrigation channels as a source of kinetic energy and potential energy which is then converted into mechanical energy in the Archimedes screw turbine. It is generally assumed that the water density at the blade is moving screw rotation [11]. The screw blades will receive the water hydrostatic pressure [4]. The fluid flow form in the Archimedes screw turbine is a flow that is not fully filled with water, there is a free surface between the fluid water and the atmospheric air. Besides the screw geometric form, the screw turbine free surface allows a flow phenomenon that is important to be analyzed on the screw turbine power generation process. The main driving force of the Archimedes screw turbine is the weight of the fluid-gravity, which is affected by the characteristic length, the inflow water velocity and the turbine shaft slope. The dimensionless parameter, Froude number (Fr), is the ratio between the inertia and gravity which is used to analyze the flow with a free surface in this screw turbine, because the fluid weight factor flowing and hitting the turbine blade so that the turbine rotates and produces a shaft torque. The physical interpretation of the Froude number (Fr) is something that is measured, or something that is indicated by the relative importance of the inertial forces acting on the particles of the fluid toward the weight of the particles [10]. The relative inertia force measured is the fluid flow axial transport velocity (V_{ax}) obtained from the turbine torsion (n) proportional to the turbine screw pith (S). The axial transport speed value measured is $V_{ax} = S.(n/60)$. Surely the turbine rotation (n) is set based on apron brake through a weighing spring scale, while the characteristic length is obtained from the fluid flow depth (y). The fluid flow axial transport velocity (V_{ax}) is depending on the ratio between the water flow rate (Q) and the bucket cross-sectional area (πR_o^2) which is filled by the water flow [6]. Therefore, embodiment of Froude number in this study was $Fr = V_{ax}/\sqrt{g.y}$.

For a fluid flow with the free surface, the pressure distribution in the fluid is hydrostatic. The Archimedes screw turbine power generation is caused by the hydrostatic force F_{hyd} toward the blade screw on the two sides in opposite directions. The water linear momentum is a hydrostatic force that causes a turbine tangential force reaction that causes the turbine rotation produces a turbine torque. Hydrostatic force is strongly influenced by the weight of the fluid-gravity and the characteristic length. The behavior of the characteristic length, inflow velocity and the turbine shaft slope is used to identify the flow phenomena that occur between the turbine screw blades. This flow phenomenon is associated with the effects of the screw turbine efficiency Froude number (Fr). The relations between the Froude number (Fr) and screw turbine efficiency is the fluid flow axial transport velocity value (V_{ax}) obtained from the turbine rotation (n) associated with the torque value (T) and power generated by the screw turbine (P).

On the same Froude number position, $Fr = 0.12$, the slope of each turbine a different flow phenomenon occurs. It is seen on the flow visualization occur a vortex phenomenon accompanied with bubbles with different sizes at every turbine shaft slope position. The turbine shaft position automatically determines turbine head (H) and the characteristic length difference between the turbine and blades (Δy), thus affecting the hydrostatic force resultant on the screw turbine. As a result of the hydrostatic force resultant the turbine shaft will produce a different maximum rotation on each turbine slope. The highest turbine shaft rotation occurs at a turbine shaft inclination of 45° of 395 rpm. A high turbine shaft slope would produce a huge vortex between the blades, which finally would decline the turbine efficiency. From the flow visualization, the same turbine rotation of the fluid flow axial transport velocity $V_{ax} = 0.11$ m/s at each axis turbine slope is shown in Figure 4 to Figure 7, it appears that a small vortex occurs on 25° axis slope. From the experimental the axis slope $\alpha = 25$ ° would result a 89% turbine efficiency, which occurred at the characteristic length $y = 1.R_o$ with the Froude number $Fr = 0.12$. When compared with the axis slope of 35° and 45° at a same Froude number, the screw turbine efficiency would reach 84% and 81%.

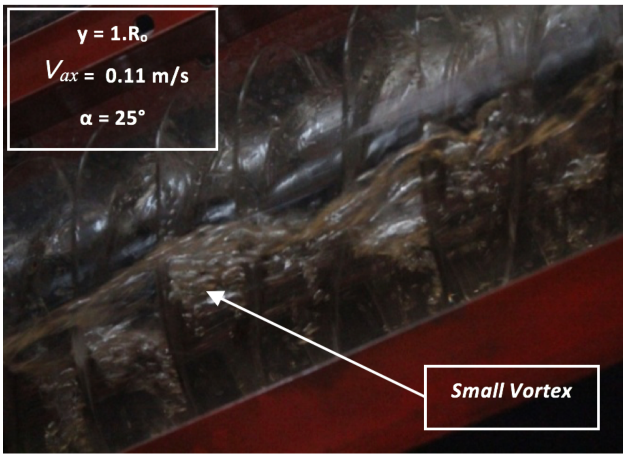

Fig. 4. Flow visualization at $y = 1.R_o$ and $V_{ax} = 0.11$ m/s, shaft slope 25°

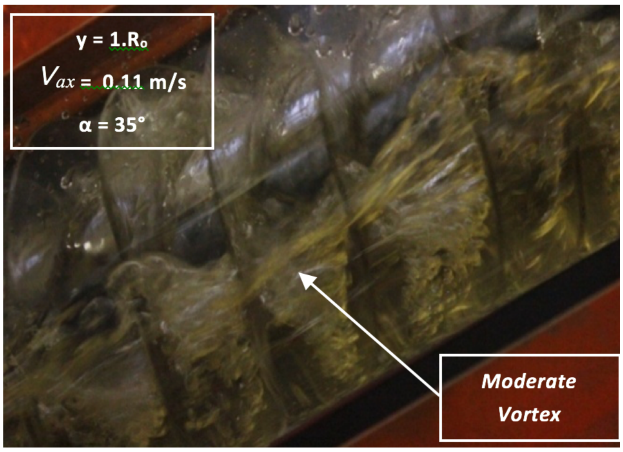

Fig. 5. Flow visualization at $y = 1.R_o$ and $V_{ax} = 0.11$ m/s, shaft slope 35°

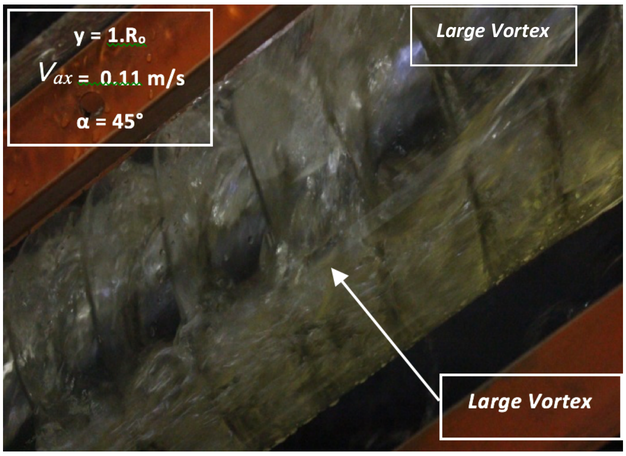

Fig. 6. Flow visualization at $y = 1.R_o$ and $V_{ax} = 0.11$ m/s, shaft slope 45°

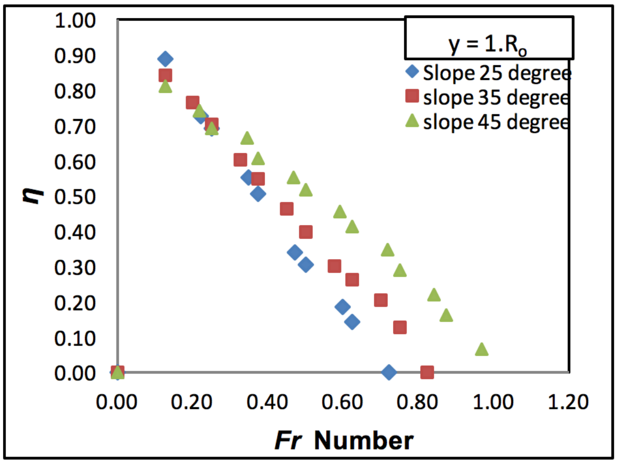

Fig. 7. Shaft slope effect toward Fr and efficiency at $y = 1.\ R_o$

Fig. 8. Flow visualization at $y = 2/3.R_o$ and $V_{ax} = 0.11$ m/s, shaft slope 25°

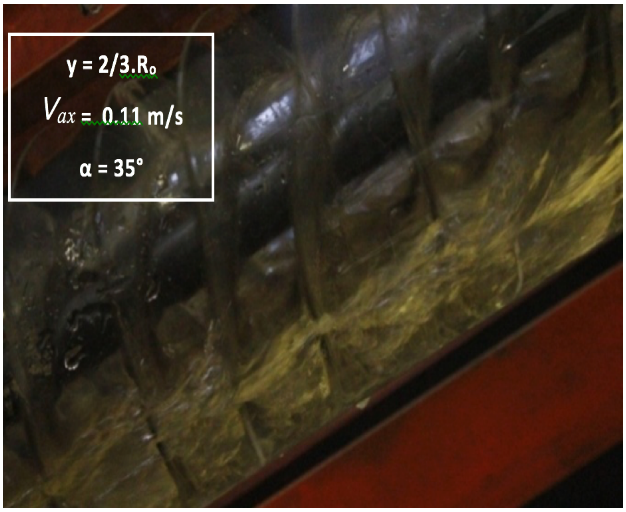

Fig. 9. Flow visualization at $y = 2/3.R_o$ and $V_{ax} = 0.11$ m/s, shaft slope 35°

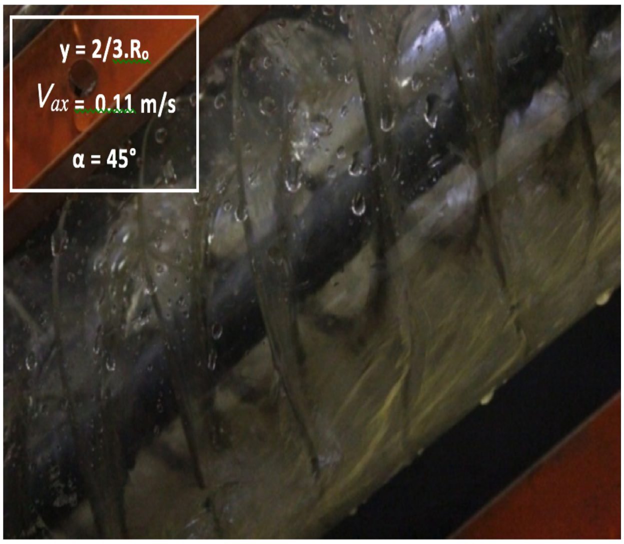

Fig. 10. Flow visualization at $y = 2/3.R_o$ and $V_{ax} = 0.11$ m/s, shaft slope 45°

Figure 8 to Figure 12 shows the influence of the characteristic length (y) at a Froude number on an inflow depth of $y = 2/3.\mathrm{R_o}$, the flow phenomenon is seen as uniform flow wave between the blades of the turbine. The flow stream would push the blades to rotate the turbine shaft, causing the hydrostatic force on both sides of the screw blade. The inflow variable depth $y = 2/3.R_o$ and $y = 1/2.R_o$ shows the same trend, but produces a lower efficiency of $y = 1.R_o$. These results prove that the hydrostatic force plays an important role in screw turbine power generation, because the characteristic length (y) in equation 1 affect the blade linear momentum and affects the turbine power.

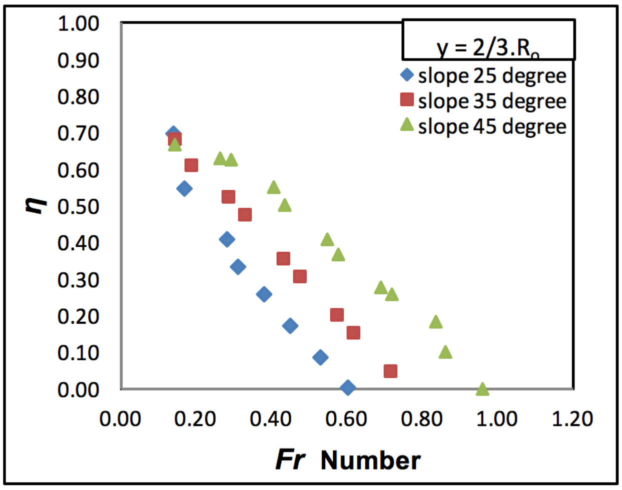

Fig. 11. Shaft slope effect toward *Fr* and efficiency at $y = 2/3.R_o$

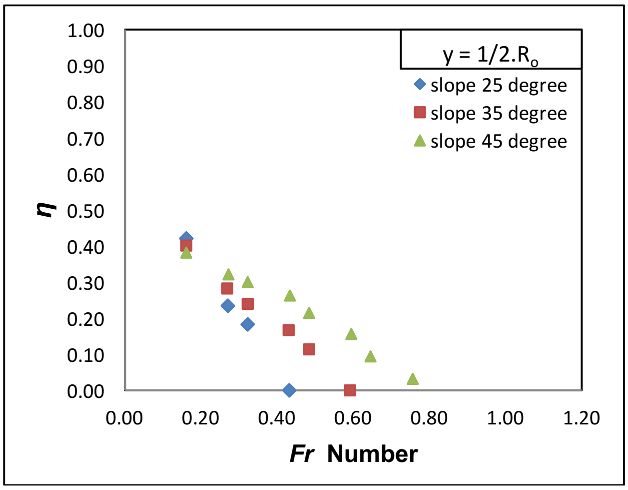

Fig.12. Shaft slope effect toward *Fr* and efficiency at $y = 1/2.R_o$

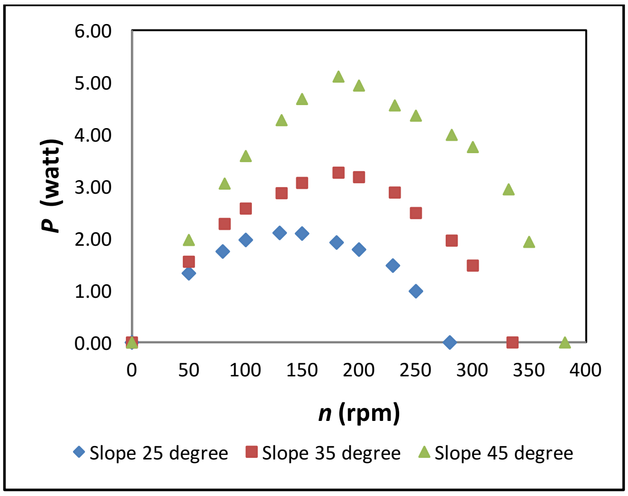

Fig.13. Rotation vs output power of screw turbine at $y = 1R_o$ and $c_o = 0{,}5$ m/s

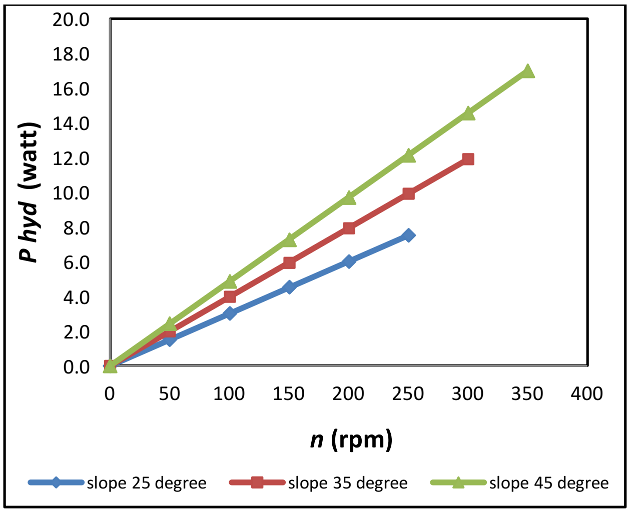

Fig.14. Rotation vs hydraulic power at $y = 1R_o$ and $c_o = 0{,}5$ m/s

Fig.13 shows that highest the shaft slope, the highest rotation of turbine, thus it will rise the power. Otherwise, shaft rotation affects torque according to equation (5).

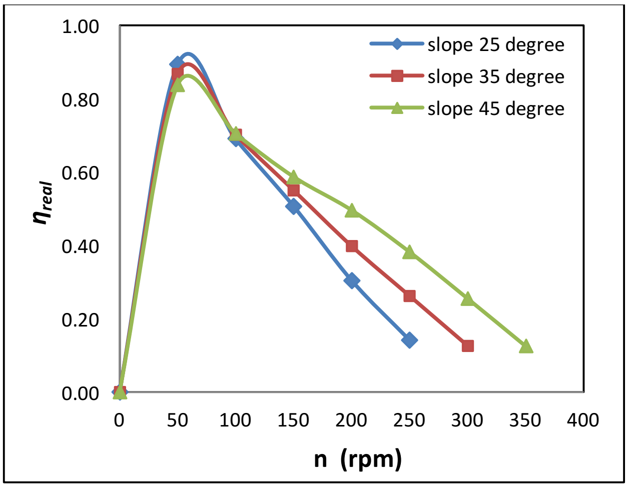

Fig.15. The effect of turbine shaft slope toward the turbine efficiency and turbine rotation.

At 50 rpm at shaft slope of 45°, the power of turbine is 1.97 watt. In the same rotation but shaft slope of 35°, the power of turbine is 1.55 watt. And at shaft slope of 25°, the power of turbine is 1.39 watt. Fig.14 shows the rotation versus hydraulic power of a three-bladed Archimedes screw turbine at characteristic length variable $y = 1R_o$ and inlet flow velocity $c_o = 0.5$ m/s. The highest hydraulic power occurs at shaft slope of 45^0 and rotation of 350 rpm is 16.97 watt. It seems that the hydraulic power increase if the achieved rotation also increases. This is due to the concept of hydraulic power in equation (9) and (8) that the flow rate factor (Q) is influenced by rotation of the screw turbine, where the volume of each bucket screw directly proportional to the turbine rotation.

By using the equation (5), equation (9) and equation (11) yields relationship between efficiency and turbine rotation as shown in Fig. 15. The magnitude of the output power (P) does not mean turbine efficiency will also great, because the turbine efficiency also depends on the hydraulic power (P_{hyd}). While shaft slope is 45^0, the efficiency is 81%. Furthermore, if the shaft slope is 25^0, the efficiency is 89 %.

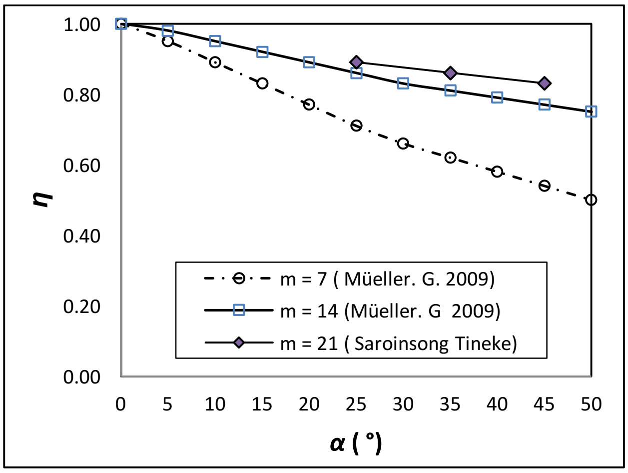

Fig. 15. The experimental results and the results of [4]

Hydraulic power is the power that needed by screw turbine through specific weight, head and flow rate. The slope of the turbine shaft is defined as a head factor in power-generating Archimedes screw turbine. High head of screw turbine will also result the high hydraulic power, but it will not be high in its efficiency. Because of gravitation and high slope of the shaft will cause the whirling flow between blades. Effect of Froude Number in this study is vortex phenomenon, this will affect losses in power-generating.

The experimental results the maximum screw turbine performance at a low axis slope, and automatically operates at a low head would be better. These results show the same trend as the study [4] in Figure 15. The lower the turbine axis slope (α) the higher the turbine efficiency would be. Through flow phenomena observation and analysis of with a Froude number associated with the turbine efficiency, proving that the screw turbine is suitable for low head.

5. Conclusion

The three blades screw turbine Archimedes experimental studies on a laboratory scale discovered the phenomenon of a wave vortex flow or vortex and bubble between the blades of the screw due to the momentum of the linear form of the hydrostatic force toward the blade screw occurs in two opposite directions and the effect of the angular momentum of the turbine shaft. The vortex would affect the screw turbine power generation process because most of the kinetic energy that goes into the turbine screw sucked into the vortex between the blades of the screw, but this phenomenon can be reduced if the turbine shaft slope is reduced.

High turbine output (*P*) does not mean high efficiency as well. This is because the turbine efficiency also depends on the hydraulic power (P_{hyd}). High head produces the maximum efficiency, due to gravity and shaft slope of turbine that affect turbulent flow between the blades.

The highest efficiency of 89 % occurred in the axis slope of 25° and a flow rate of 0.5 m/s, axial transport velocity of 0.11 m/s and characteristic length of $1R_o$ with a Froude number ofx 0.12. The Froude number (*Fr)* effect on the turbine efficiency proves that the factor of gravity on the turbine shaft slope (α) and the characteristic length (y) affecting the screw turbine power generatio

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