Effect of Froude Number on Three-Bladed Archimedes Screw Turbine Efficiency

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Abstract- Energy crisis which is globally occured around the world attract researchers to study renewable energy. Experimental study of Archimedes screw turbine that had been applied as microhydro power plant for low head, they are focused on fluid flow. Fluid flow on Archimedes screw turbine is a flow with a free surface. Froude Number is utilized for this free surface flow. Efficiency of screw turbine is influenced by geometric and flow losses. The aim of this experimental study is to recognize flow phenomenon among blades of screw turbine, which have connected to the effect of the Froude Number to efficiency. Observed parameters are varied in inlet flow as a characteristic length (y), inflow velocity (c_0), and the turbine shaft declivity (α). The model of screw turbine is made in laboratory scale with acrylic. The geometric shape of three-bladed have seven screws, number of helix turns are 21, thread angle of 30^0, the radius ratio of 0.54 with a pitch of $2.4R_0$. The Froude Number (*Fr*) is the ratio index of inertia fluid force (water) in an element by gravitation force. Relative value of measured inertia force is an axial tranport velocity of fluid flow (V_{ax}). The result of this study is if the Froude Number increase then the vortex is formed among the blades, therefore efficiency decrease. The highest efficiency is 89 %, it occurs in 25^0 of turbine shaft declivity and 0.15 of Froude Numbers, respectively..

Keywords- Screw turbines, Froude Number, vortex, efficiency.

1. Introduction

The screw turbine is able to apply for micro-hydro power plant. They usually use in rivers, irrigation channels as renewable energy resources. The screw turbine is adopted from Archimedes screw theory, it is initially used as a pump. The implementation of an Archimedes screw pump into the new turbine is a breakthrough and has the possibility for a wider application [1]. The benefit of this screw turbine is that it can operate at low head (H<10 m), no penstock, easy installation, easy maintenance, and fish-friendly [2]. Archimedes screw turbine also could be applied on sea and tidal current for electric power generation [3]. The kinetic and potential energy of water flow is converted into mechanical energy to rotate the turbine shaft, and finally it is converted into electrical energy via transmission to the generator. The water density on the blades that affect the screw to be rotated, assuming that there are no losses of all potential energy in the flow and could generate a maximum efficiency of 100 % [4].

Recently, the research of screw turbine has been developed in terms of both theoretical and experimental designs related to its efficiency. The numerical optimization of its geometric shapes [5] with a pitch ratio (R_1/R_0) of 0.54 in optimum pitch ratio. The efficiency of screw turbine is influenced by geometrical shape and flow losses [4]. Furthermore [6] introduced an analytical model of inlet flow in a screw turbine to consider the possibility of leakage flow in the gap between the screw and casing, and also the excess water in the center of the pipe. A MATLAB screw turbine simulation for hydroelectric power plant on the lower head has already carried out [7]. The modeling and theoretical result of Mueller [4], Nuernbergk [6], and Raza Ali [7] was then compared with the first [8] and second [9] experiment of Brada. The experimental study of screw turbine still must develop to get a real information in order to apply optimally screw turbine. The screw turbine is applied in the river and irrigation channel, that they are in open surface condition. The fluid which flows through Archimedes screw turbine is not fully charged, there are free surface between water and air. Generally, it is assumed that specific weight of water in the blade make the screw to rotate [11]. The blades will receive hydrostatic force by water [4]. In addition to the geometry of the screw, the free surface of the screw turbine allows the flow phenomena, it is important to analyze the process of power generation. The character of the open flow could be recognized by dimensionless parameter, it is known as Froude Number (Fr). The focus of this research is about study of fluid flow among screw's blades due to characteristic length or Froude Number (Fr), in this case are inlet flow as a characteristic length (y), inflow velocity (c_0), and the turbine shaft declivity (α).

Phenomena of water flow among screw turbine are an important thing in generating power, therefore the water flow is a source of kinetic and potential energy which is used to generate power. The screw turbine was made in laboratory scale, of acrylic. The aim of this study is to recognize the efficiency of screw turbine that is observed from Froud Number effect and its flow phenomena.

2. Principle of Screw Turbine Power Generation

The main force of Archimedes screw turbine is weight of fluid and gravitation force which is influenced of inlet flow as a characteristic length (y), inflow velocity (c_o), and turbine the shaft declivity (α). Gravitation force due to turbine shaft declivity becomes an important variable because it basically affects the screw turbine power generation. Physical interpretation of the Froude Number (Fr) is something that is measured, or something that could be shown by the relative important value of inertia force that occupied on fluid particles to weight particle. The measured relative value of inertia force is the axial transport velocity of fluid flow (V_{ax}) that gaining from turbine rotation (n), it is equal with pitch (s). The measured value of axial transport velocity is $V_{ax} = S.(n/60)$. In equation (1), variable of characteristic length (y) is inflow depth, and characteristic velocity is axial transport velocity (V_{ax}). Then, the Froude number (Fr) is

$$Fr = \frac{V_{ax}}{\sqrt{g.y}} \qquad \frac{inertia\ force}{gravitation\ force} \tag{1}$$

The important thing in generating screw turbine power is a force of the blade, because torsion which is resulted by turbine comes from a force of the blade. The force of screw turbine is a two-way hydrostatic force that opposite with screw blade. Hydrostatic force (F_{hyd}) occurred among screw blade in two-way due to flow that hit blades is reflected by further blade to initial blade as shown in Figure 1. Hydrostatic force (F_{hyd}) depends on the characteristic length (y), the Froude Number (Fr), and water density (γ). Theoretical efficiency (η_{th}) of the screw turbine is from the ratio between power (power per blade that is multiplied by the number of helix turn) and hydraulic power. İn other hand, real efficiency (η) is from the ratio between output power (torsion is multiplied by angular velocity) and input power (hydraulic power). Power generation of the screw turbine with parameter of inflow velocity (c_o), the Froude Number (Fr), and the turbine shaft declivity (α) will affect the performance of three-bladed Archimedes screw turbine.

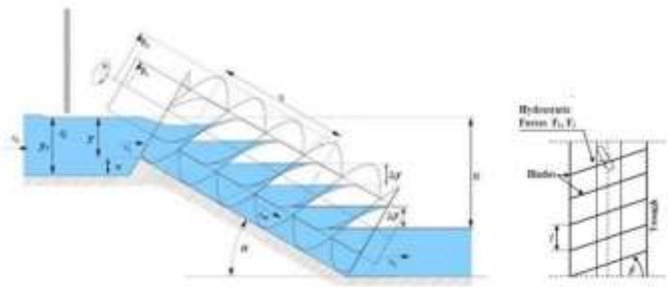


Figure 1. Flow and hydrostatic force model in Archimedes screw turbine blades [6]

3. Experimental Method

3.1 Test Instalation

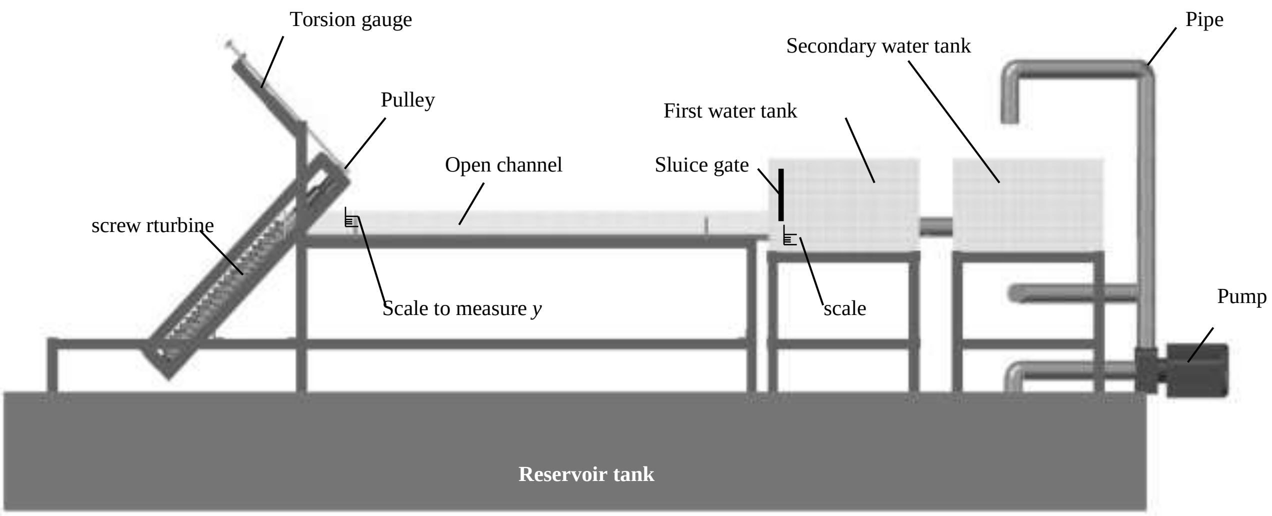
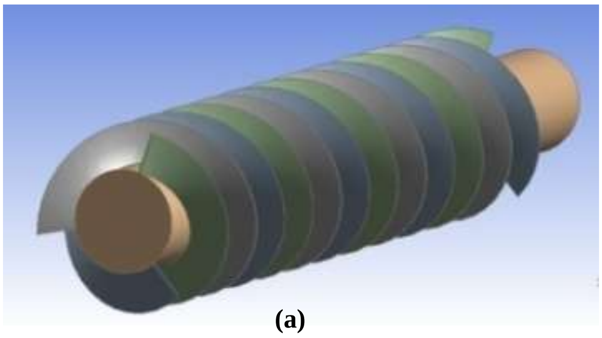


Figure 2. The screw turbine Installation [12], [13]

Parameters of screw turbine model :

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°	Thread angel
λv	0.059	Normalized volume/turn
α	25°, 35°, 45°	Turbine shaft declivity
y	$1/2R_o$, $2/3R_o$, $1R_o$	Characteristic length
c_o	(0.3, 0.4, 0.5) m/s	Inflow velocity



(a)

(b)

Figure. 3. Three bladed Archimedes screw, a) the model, b) experimental photo

3.2 The Testing Procedure

In this experiment, 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 screws 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°. Before the data taken, first is set the installation with the appropriate 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.

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 to the turbine's shaft which is connected with pulley and belt.

The measurements of flow rate were taken from a 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.

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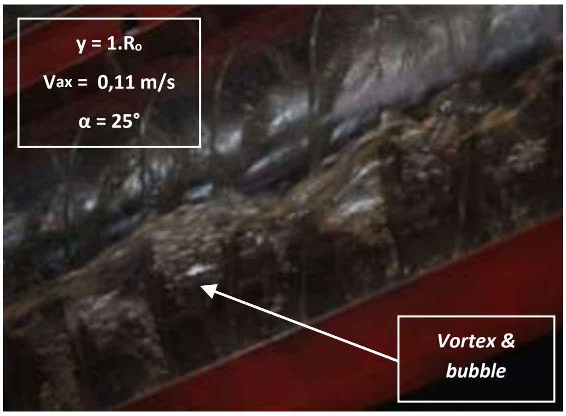
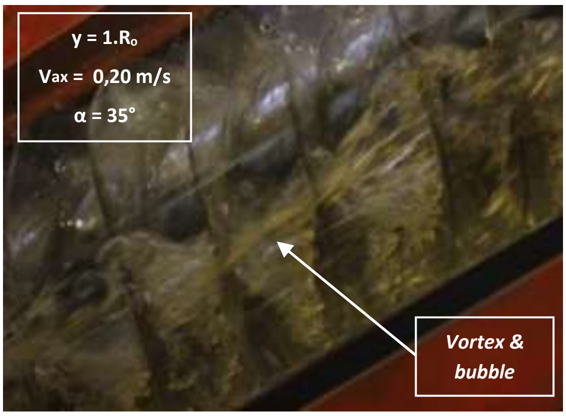
4. Results and Discussion

Fluid flow in an Archimedes screw turbine is river flow or irrigation channel flow as a source of kinetic and potential energy, thus they are converted to mechanical energy in the Archimedes screw turbine. İn general, it assumes that the water density in the blade due to the screw is rotated [11]. Screw blades will receive hydrostatic pressure from water [4]. The pattern of fluid flow in the Archimedes screw turbine is not fully flow, there are free surface between water and atmosphere. In addition to the geometry of the screw, the free surface of the screw turbine allows the flow phenomena that are important to analyze in the process of power generation.



(a)



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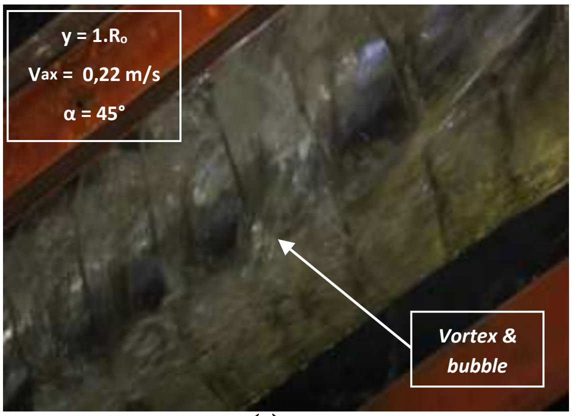
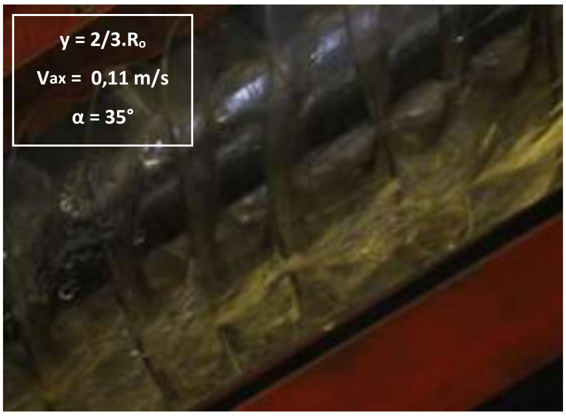


(c)

Figure 4. Flow visualization at $y = 1.R_o$
(a) shaft declivity 25°, (b) shaft declivity 35°, (c) shaft declivity 45°.

The flow phenomena that occur between the blades of the screw are shown in Figure 4 and Figure 5. It seems in flow visualization on the characteristic length y = 1Ro, in Figure 4 occurs vortex phenomenon which is accompanied bubbles with different sizes on each slope position of the turbine shaft. The role of the tilt shaft automatically determines the head (H) turbines and the difference between the blade head (Δy), thus affecting the resultant hydrostatic force on a screw turbine. As a result of the resultant hydrostatic force, then the turbine shaft will produce a maximum rotation, different on each slope of the turbine shaft. In Figure 4a vortex shape looks small compared to Figure 4b and Figure 4c, this is due to the high shaft rotation resulted in turmoil flow between the blades. Shaft rotation affects the axial transport speed (V_{ax}), thus affecting the Froude number. The higher the rotation shaft, the greater the Froude number. The slope of the high turbine shaft will affect a large vortex between the blades due to gravity, thus affecting the efficiency of the turbine.

(a)



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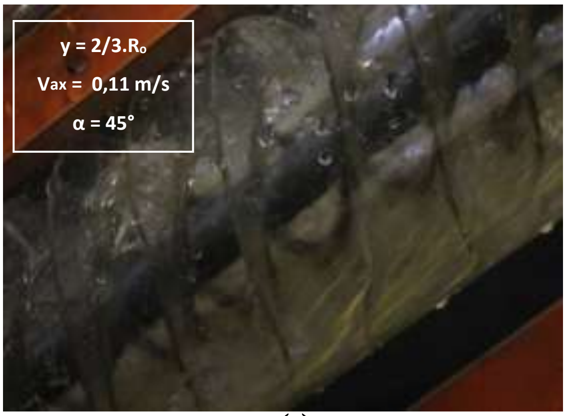

(c)

Figure 5. Flow visualization at $y = 2/3.R_o$ and $n = 50$ rpm, (a) shaft declivity 25°, (b) shaft declivity 35°, (c) shaft declivity 45°

Figure 5 shows the flow phenomena at the characteristic length variable y = 2/3Ro. It seems almost the same wave flow on the slope of shaft 25, 35 and 45 degrees. The Froude Number decreases due to lower of the characteristic length. Froude number was also reduced due to the resulting turbine rotation is lower than the characteristic length y = 1Ro. This occurs because the characteristic length affects the momentum or hydrostatic force against the blade thereby affecting the turbine rotation.

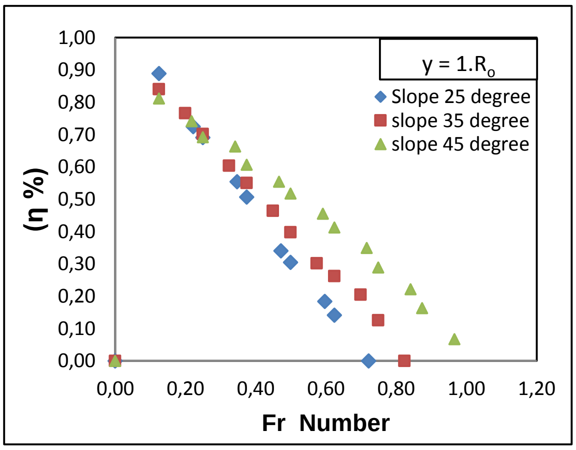

Figure 6. Shaft declivity effect toward *Fr* and efficiency at $y = 1. R_o$

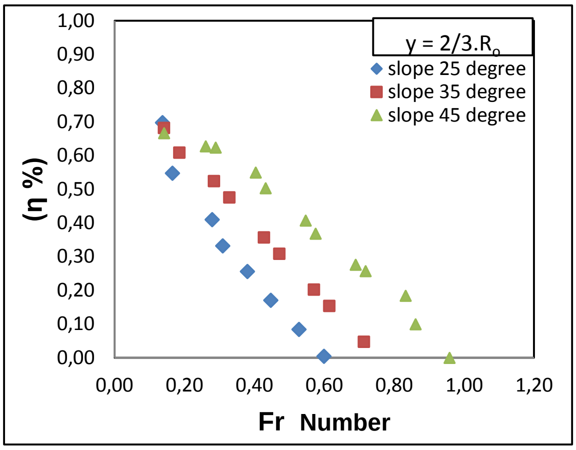

Figure 7. Shaft declivity effect toward *Fr* and efficiency at $y = 2/3.R_o$

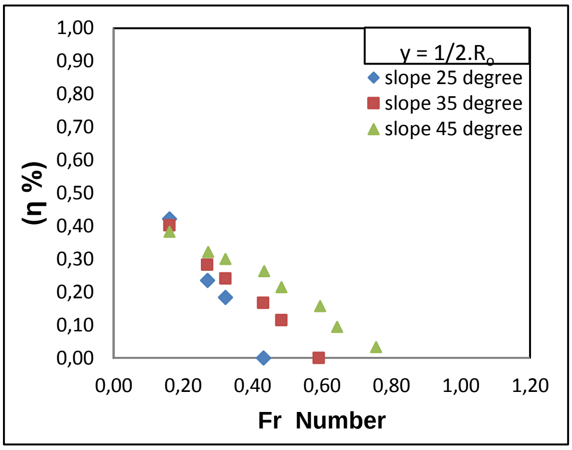

Figure 8. Shaft declivity effect toward *Fr* and efficiency at $y = 1/2.R_o$

Figure 6 to Figure 8 shows the effect of the Froude number of the Archimedes screw turbine efficiency. In the characteristic length variable y = 1Ro produce the highest efficiency of 89% that occurred at an inclined shaft 25 degrees. While the tilt shaft 35 and 45 degrees produce an efficiency of 84% and 81%. The lower the slope of the shaft, the higher the efficiency of the screw turbine. It is influenced by gravity on the Froude number. The higher the Froude number, the lower the efficiency of the turbine. The highest Froude number was 0,97 occur at α = 45 ° resulted in an efficiency of 6.78%. The lowest Froude number of 0.15 occurs at α = 25 °, α = 35 ° and α = 45 ° resulted in an efficiency of 89%, 84% and 81%.

The effect of high Froude number results turmoil vortex flow between the blades of the turbine. Thus, partially the kinetic energy of the flow sucked into the vortex. A vortex can be reduced by lowering the slope of the turbine shaft. Flow phenomena and effects of the Froude number this suggests to use a screw turbine on the lower head, so that efficiency can be optimized.

In the characteristic length variable y = 2 / 3R_o produce an efficiency of 70% that occurred at an inclined shaft 25 degrees. And the tilt shaft 35 and 45 degrees produce efficiency of 68% and 67%. The same trend decline in the efficiency of the characteristic length y = ½R_o.

The slope of turbine shaft as head factor in the process of Archimedes screw turbine power generation. High Head will generate a large hydraulic power, but will not produce the maximum efficiency. Due to gravity and the slope of the turbine shaft to cause turbulent flow between the blade screw. The effects of of the Froude number in this study was the occurrence of the adverse vortex phenomenon in the process of screw turbine power generation. The slope of the turbine shaft is an important factor in the process of Archimedes screw turbine power generation.

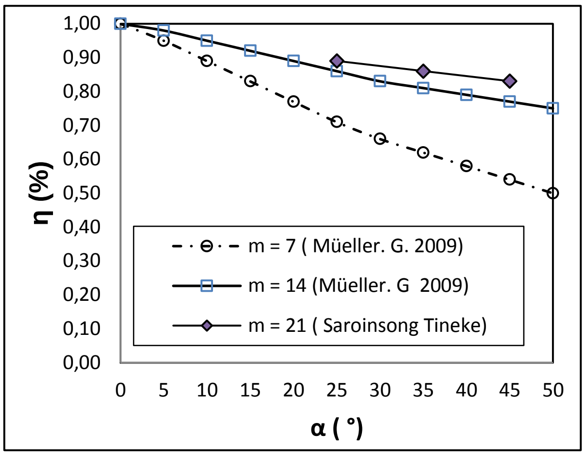

Figure 9. The experimental results and the results of [4]

The results of the experiment showed that the maximum screw turbine performance on the lower slope of the shaft, automatically operates at lower head to be better. These results show the same trend with the study (Mueller, G, 2009) in Figure 9. The lower the slope of the shaft the higher efficiency of the turbine. Through observation and analysis of flow phenomena with of the Froude number effects associated with turbine efficiency, proving that the screw turbine is suitable for low head.

5. Conclusion

The conclusion of this study is the phenomenon of the flow between the blades of the three-bladed Archimedes screw turbine occurs wave whirlpool or vortex flow and bubble. The effect of the Froude number on the efficiency of the turbine is greater Fr screw the lower the efficiency of the turbine. The highest Fr of 0.97 occurs at α = 45 ° resulted in an efficiency of 6.78%. The lowest of Fr of 0.15 occurs at α = 25 °, α = 35 ° and α = 45 ° resulted in an efficiency of 89%, 84% and 81%. The difference results turbine efficiency at the same Fr due to gravity on the slope of the turbine shaft (α). The best performance is in the shaft declivity (α) of 25° than 35° and also 45° respectively. The highest eficiency is 89 % that occur in the shaft declivity of 25° and flow velocity (c_o) of 0,5 m/s and characteristic length (y) of 1R_o, and also Froude number (Fr) of 0.15. Froude number effect on efficiency of turbine prove that gravitation factor in the shaft (α), Flow velocity (c_o) and characteristic (y) affect power and efficiency of three-bladed screw turbine.

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