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Experimental Investigation on the Effect of Flow Rate and Load on the Hydrodynamic Behavior and Performance of an Archimedes Screw Turbine

M. Zamani, R. Shafaghat*, B. Alizadeh Kharkeshi

Sea-Based Energy Research group, Babol Noshirvani University, Babol, Iran

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ABSTRACT

One of the best solutions to overcome problems caused by fossil fuel consumption is using renewable energy. In this research, effect of flow rate and load on the performance of an Archimedes turbine was experimentally studied. At first, Archimedes turbine with optimal size was made using 3D printer technology. Then it was placed in the river simulation setup. After the calibration and uncertainty analysis, tests were performed for three flow rates and five electrical resistances. The results showed that increasing the flow rate leads to a rise in power, torque, and angular velocity of the turbine, but it leads to a non-linear behavior in efficiency. On the other hand, an increase in electrical load has also led to a decrease in converter performance for all conditions. In addition, by implementing π-Buckingham theory, the converter's hydrodynamic behavior was studied by using Reynolds numbers, dimensionless flow, and power coefficiency. The results showed that an increase in Reynolds number leads to a decrease in power coefficiency. However, an increase in dimensionless flow increases the power coefficiency first and then decreases (nonlinear behavior). In addition, the Archimedes screw turbine was also studied from an economic point of view, and the results showed that increasing discount rate leads to an increase in discounted payback period, and in the worst case, the payback period is 3.09 years, and in the best case, it is 1.6 years. Also, the construction of the Archimedean screw turbine in Iran can save currency for $1439.5.

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1. INTRODUCTION

Fossil fuels can cause many problems and have side effects including global warming [1], increased pollutants [2] and greenhouse gases [3]. Also, the usable sources of these fuels are limited. Therefore, renewable energies such as geothermal, solar, wind, biomass, wave energy, and hydropower are solutions to tackle the fossil fuel’s problems and help to preserve the resources of fossil fuels [4].

Archimedes hydro screw turbine can generate power from the river currents. This turbine consists of a cylindrical shaft along with some spiral surfaces called blades and is a screw-like structure. The water flow enters the turbine from the top and moves along the screw between the blades, and this movement of the water flow causes the shaft to rotate and generate power. These turbines have high efficiency in the low head and flow rates. Archimedes screw turbines can be installed and operated in rivers, channels, sloping places, dams, and places with variable currents [5].

Due to the ancient history of Archimedes screw turbine, many studies have been done on these turbines. The studies carried out in the field of Archimedes screw turbines are divided into two parts: studies related to changes in flow parameters and studies related to turbine geometric parameters. Nagel [6] presented an analytical and experimental equation for the rotational speed and the leakage width to avoid the decrease in efficiency due to the flow turbulence. Rorres [7] maximized the volume of water in each bucket in the Archimedes screw turbine. He has theoretically presented optimal dimensionless ratios for turbine radius, pitch, and water volume in the form of a table. Muller and Senior [8] compared the

*Corresponding Author Institutional Email: *rshafaghat@NIT.ac.ir*
(R. Shafaghat)

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experimental results and the theoretical model of the Archimedes screw turbine to determine the effective parameters of turbine efficiency. The results showed that by increasing the turbine's rotational speed, decreasing the horizon angle and increasing the input flow rate, the efficiency of the turbine rises. Raza et al. [9] simulated this turbine in MATLAB with the help of mathematical equations. The simulation results showed that with an increase in the input flow rate to the turbine, the turbine's rotational speed and output power rise. Rohmer et al. [10] experimentally and numerically studied an Archimedes screw turbine model using the model presented by Rorres [7]. He has found that efficiency is a function of flow rate and torque. Hizhar et al. [11] studied the effect of flow rate and installation angle on the output power for an Archimedes screw turbine experimentally. Power increases with the growth of the flow rate, and also, at low flow rates, the efficiency declines with an increase in the turbine angle. Mulana et al. [12] conducted an experimental study on the maximum power and torque of Archimedes screw turbine and showed that maximum efficiency occurs at an average flow rate. Krystyadi et al. [13] used a governor to set the turbine's rotational speed in an optimal range to maximize efficiency. Abdullah et al. [14] experimentally and numerically studied the effect of changing the flow rate and installation angle on turbine performance. The results showed that with an increase in the input flow rate, the rotational speed and the output power always increase, but efficiency shows a non-linear behavior. Bustomi et al. [15] exprimentally studied the mechanical and electrical characteristics of different inlet flow rates. The results showed that the rotational speed, torque and output power of the turbine increases with the rise in flow rate but an increase in electrical resistance leads to a decrease in the mentioned characteristics. Cahyono et al. [16] conducted an experimental study with the aim of determining the effect of changing the angle of Archimedes turbine on the rotational speed and output power of the turbine. The power shows a non-linear trend by slope. In 2022, Darmono and Pranoto [17] carried out a numerical simulation of the Archimedes screw turbine to find the effect of the number of blades on the torque and output power of the turbine. Three turbine models with nine, six and four blades were simulated, and the results showed that increasing the number of blades rises the torque and output power of the turbine, but the technical and economic limitations regarding increasing the number of blades should be considered.

Based on past studies, suitable analytical and experimental equations for the optimal design of Archimedes screw turbine have been presented. However, past studies have mainly relied on studying the performance characteristics of the turbine, such as rotational speed, torque and power. The study of turbine performance according to dimensionless numbers is not presented. In this regard, dimensionless numbers affecting the performances of the turbine were extracted using the π-Buckingham theory, and the effect of dimensionless variables on the power coefficient was studied. For this purpose, an optimal Archimedes screw turbine was designed and built with the help of 3D printer technology. Also, to carry out the tests, a laboratory facility was designed and built to simulate the conditions of the river in the sea-based energy research group of Babol Noshirvani University of Technology. The effect of flow rate and electrical resistance on turbine performance characteristics such as rotational speed, torque, power, efficiency, blade tip speed ratio and power coefficient were studied. Then, by using Froude scaling method, the laboratory study results were scaled to the prototype model. Finally, the economic analysis for the payback period was performed.

2. EXPERIMENTAL STUDY

2. 1. Turbine Design

This research aims to design an Archimedes screw turbine that can produce electricity for low-power applications. For the optimal design of the turbine, the model presented by Rorres [7] has been used.

$$0 \leq R_i \leq R_o \tag{1}$$

$$0 \leq R_i \leq \frac{2\pi R_o}{k} \tag{2}$$

$$p = \frac{R_i}{R_o} \tag{3}$$

$$\lambda = \frac{KP}{2\pi R_o} \tag{4}$$

The screw geometry is determined according to two types of parameters. The input parameters include the inner radius (Ri), pitch (p), and the number of blades (N) and the output parameters include radius ratio (ρ), pitch ratio (λ), and volume ratio (ν) [18].

The input parameters of the turbine have a maximum outer diameter of 10 cm, a maximum length of 17 cm, and 4 blades. This optimal design for maximizing water volume in one screw cycle is calculated using Equation (5).

$$V_{tmax} = \pi {R_o}^2 p \tag{5}$$

And the volume of each duct is equal to:

$$V_c = \frac{\pi(R_o^2 - R_i^2)l}{N} \tag{6}$$

The volume of each bucket will be calculated by Equation (7).

$$V_b = \frac{V_t}{N} \tag{7}$$

The values of R_o and N are available as fixed values. Now it is necessary to maximize the value of V_t by finding suitable values for Ri and p. For this purpose, the dimensionless parameters provided by Rorres [7] are used. In order to simplify the design process, three dimensionless parameters have been considered according to the number of blades used in the turbine design, whose value is between 0 and 1. They are radius ratio and volume ratio, which are obtained according to Equations (3) and (4), respectively and volume ratio which is calculated using Equation (8).

$$\mathrm{v} = \frac{V_t}{\pi R_o^2} \tag{8}$$

Table 1 summarized the geometrical characteristics of designed Archimedes screw turbine in this article.

2. 2. Turbine Construction with 3D Technology

There are many ways to build an Archimedes screw turbine. Due to the complex geometry of this turbine, making it in the traditional way and using cutting and turning to create separate metal blades and welding the blades to the central hollow metal cylinder reduces the accuracy of the construction due to environmental and operator errors [19], [14],[20]. And it may affect the performance of the turbine. Also, the construction of turbine blades by machining aluminum sheets and sticking them to PVC pipes as the central cylinder can make the turbine lighter and reduce losses and friction [21]. But still, there will be errors in the correct construction of the design and it affects the performance of the turbine. For this reason, in this article, the 3D printer of the Sea Based Energy Research Group of Noshirvani University of Technology, Babol is used to make the Archimedes screw turbine. Figure 1 and Table 2 show the used 3D printer and its specifications, respectively.

A 3D printer is a device that can turn a file designed in design software into a tangible object by successively adding materials on top of each other [22]. For this purpose, first Archimedes screw turbine is designed in SolidWorks software and is imported as input to the printer. In order to make the turbine lighter and reduce the losses and friction related to its rotation, the turbine is made of ABS Filament and hollow. This model made by 3D printer has all the details in the design of the turbine and helps the turbine to work better according to its optimal design. Figure 2 shows Archimedes screw turbine made using 3D technology.

2. 3. System Description

2. 3. 1. Experimental Tests Site

Figure 3 shows the device for conducting experimental tests of Archimedes screw turbine, designed and built in the sea-based energy research group. This site includes two water tanks and an open water channel. Water flows from the upstream water tank is transferred to the downstream water tank through an open water channel in which the Archimedes screw turbine is located. When the water flow passes through this channel, it passes through the

TABLE 1. Geometrical characteristics of designed Archimedes screw turbine

Turbine installation angle (degrees)	Screw turbine length (m)	Number of blades	Inner diameter (m)	Outer diameter (m)	Turbine pitch (m)	Turbine head (m)
25	0.17	4	0.05	0.1	0.17	0.0718

Figure 1. 3D printer used to make Archimedes screw turbine

TABLE 2. Printer specifications

Printer model	FDM
Printer dimensions	300*300*300 (mm)
Print speed	1800(mm/min)
Print accuracy	100 (μm)
Print material	ABS Filament

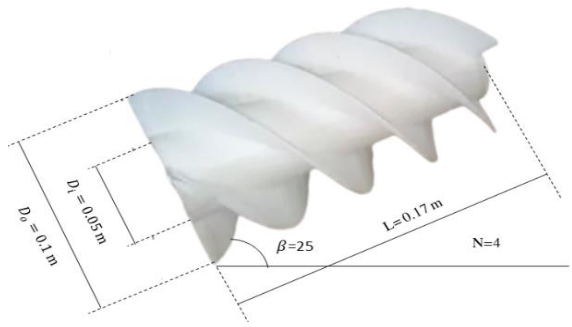


Figure 2. Archimedes screw turbine with 4 blades made with 3D printer technology and its geometrical characteristics

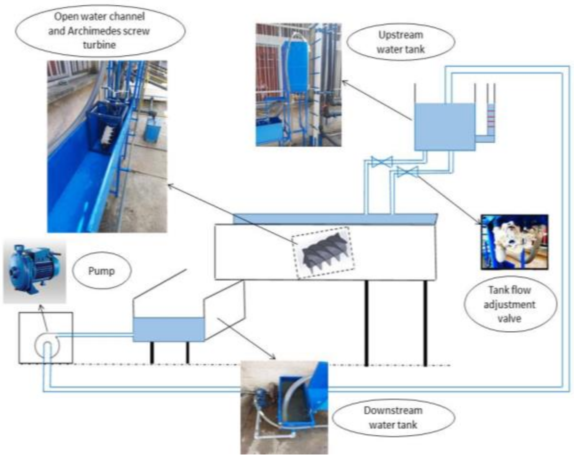


Figure 3. Schematic view of placement and exprimental installation Archimedes screw turbine in the labratory

turbine and causes the turbine to rotate and finally generate electricity through the generator connected to the turbine. A pump is also used to pump water to the upper tank and also a drain pipe has also been installed to prevent the tank from filling up and overflowing.

2. 3. 2. Archimedes Screw Turbine Performance Study Turbine power equation is as follows.

$$P_{in} = \rho g Q H \tag{9}$$

where ρ is the water density, g is the gravitational acceleration, Q is the flow rate and H is the head of the turbine. Also, Equations (10) and (11) are used to calculate efficiency.

$$\eta = \frac{P_{out}}{P_{in}} \tag{10}$$

$$P_{out} = \eta P_{in} \tag{11}$$

The output power of the turbine is also calculated mechanically or electrically in the experimental tests accordinding to Equations (12) and (13) [23].

$$P_{out\ mec} = T\omega = 2\pi n T \tag{12}$$

$$P_{out\ elc} = V.I \tag{13}$$

Also, the experimental equation presented by Nagel [6] for the rotational speed limit of Archimedes screw turbine, in order to prevent flow turbulence, is in the form of Equation (14).

$$\mathrm{n} = \frac{0.85}{D_0^{\frac{2}{3}}} \tag{14}$$

The blade tip speed ratio (TSR) is another parameter evaluated in Archimedes screw turbine performance study. This ratio is the blade tip's linear velocity to the flow's speed entering the turbine and is expressed in the form of Equation (15).

$$TSR = \frac{r\omega}{V} \tag{15}$$

The angular velocity of the turbine is determined by Equation (16).

$$\omega = 2\pi f \tag{16}$$

2. 3. 3. Dimensionless Governing Equations Dimensionless numbers are essential to create a dynamic similarity between the model and the prototype.

In the study of the performance of semi-submerged propellers, including Archimedes screw turbine, the dimensionless power coefficient is used to evaluate the performance. The power of an Archimedes screw turbine is a function several parsmeters given by Equation (17) [24].

$$P = f(Q, D_o, n, \rho, \mu) \tag{17}$$

According to the π-Buckingham theory [25], based on number of variables in Equation (17), three dimensionless groups can be made in the form of the following equations.

$$\pi_1 = \frac{P}{\rho n^3 D_o^5} \tag{18}$$

$$\pi_2 = \frac{Q}{n D_o^3} \tag{19}$$

$$\pi_3 = \frac{\rho V D_o}{\mu} \tag{20}$$

That respectively represents the dimensionless numbers of power coefficient, flow and Reynolds number for Archimedes screw turbine. Finally, the power coefficient of Archimedes screw turbine is calculated according to Equation (21).

$$C_p = \frac{P}{\rho n^3 D_o^5} = f\left(\frac{Q}{n D_o^3}, \frac{\rho V D_o}{\mu}\right) \tag{21}$$

2. 3. 4. Froude Scaling For the scaling of semi-submerged propellers, including the Archimedes screw turbine, the dimensionless Froude number is used. This dimensionless number is defined as the ratio of inertial force to gravity force in the movement of a fluid and is expressed according to Equation (22) [26].

$$Fr = \frac{V}{\sqrt{g L_c}} \tag{22}$$

In this equation, V is the flow velocity and Lc is the characteristic length. For Archimedes screw turbine, Lc will be equal to the outer diameter of the turbine. Table 3 shows Froude scaling coefficient [27].

$$\lambda = \frac{(L_c)a}{(L_c)s} \tag{23}$$

2. 3. 5. Economic Study of Archimedes Screw Turbine The cost of building micro hydropower

TABLE 3. Different parameters for the prototype scale

Parameters	Q	ω	R	P	T
coefficient	$\lambda^{2.5}$	$\lambda^{-0.5}$	λ^{-1}	$\lambda^{3.5}$	λ^{4}

plants in Iran is $300 /kW and the income is $0.025 /kWh. The Discounted Payback Period is the time required to offset investment costs with incoming cash flow. The payback period equation is as follows [28]:

$$DPP=\frac{-Ln\left(1-\frac{Inv*Disc}{CF}\right)}{Ln(1+Disc)} \quad (24)$$

In this equation DPP is discounted payback period, Inv is the investment cost, Disc is the discount rate and CF is cash flow in one year. Another critical point in the economic analysis of the use of Archimedes screw turbine is the issue of currency savings.

2. 4. Design of Experiment

The most important parameters affecting Archimedes screw turbine are the flow rate and the turbine's rotational speed. For this purpose, the test device is designed in a way to change the flow rate for three different flow rates. On the other hand, studying the turbine's performance should be possible according to the consumption load. Therefore, the turbine performance was also studied for 5 electrical resistances. A total of 75 tests (considering uncertainty analysis and repeating each test 5 times) should be performed on the turbine's performance. Table 4 shows the design of the experiment.

2. 5. Laboratory Equipment in Experimental Tests

Essential parameters to measure in this study include rotational speed and output power. In order to calculate the power, the electrical current and voltage have been measured and also, a rheostat has been used to study the effect of electrical resistance on the performance of the turbine. Table 5 shows the equipment and measuring tools in experimental tests and their accuracy.

TABLE 4. Design of experiment

Flow rate (lit/s)	**Resistance (ohm)**	**Flow rate (lit/s)**	**Resistance (ohm)**
1.2	10	2.4	10
	20		20
	30		30
	40		40
	50		50
Flow rate (lit/s)	**Resistance (ohm)**		
3.6	10		
	20		
	30		
	40		
	50		

TABLE 5. Characteristics of measuring tools in experimental tests of Archimedes screw turbine

Device	**Model**	**Device work**	**Measurement accuracy**	**Image**
Tachometer	Dual Digital Tachometer DT-2268	Measuring the rotational speed of the turbine	0.1 rpm for values less than 1000 rpm	
Ammeter	HIOKI 3256-50	Measuring the current passing through the circuit	$\pm 1.5\%(rdg) \pm 4(dgt)$	
Voltmeter	HIOKI 3200	Measuring the voltage of both ends of the generator	$\pm 0.07\%(rdg) \pm 2(dgt)$	

Rheostat	–	Creating variable resistance in the circuit and changing the voltage and current of the circuit	1 ohm in the range of 1 to 55 ohms	
Chronometer	HS43	Measuring the duration of tank water discharge to calculate the flow rate	0.01 seconds	
Generator	127.P.02620 dunker motoren	Connecting to the output shaft of the turbine and generating electricity from the rotational movement of the turbine	–	

2. 6. Uncertainty Analysis Uncertainty is very important in experimental studies. First, the average of the parameters is obtained [29].

$$\bar{x} = \frac{\sum_{i=1}^{m} x_i}{m} \tag{25}$$

where x_i and $\bar{x}$ will be the parameter's value in each experiment and the average value of the parameter, respectively. In the continuation of the uncertainty analysis process, the standard deviation of the measured values and the standard deviation of the average of the measured values are determined according to Equations (26) and (27), respectively [25].

$$s = \sqrt{\frac{\sum_{i=1}^{m}(x_i-\bar{x})^2}{m-1}} \tag{26}$$

$$\sigma_m = \frac{s}{\sqrt{m}} \tag{27}$$

According to these equations, Equation (30) is valid for uncertainty.

$$u = \sqrt{\sigma_m} \tag{28}$$

In the following, the expanded uncertainty is calculated according to Equation (29).

$$U = k.u \tag{29}$$

Where k will be the overlap coefficient. Finally, the size range is calculated using Equation (30) [4].

$$x_f = \bar{x} \pm U \tag{30}$$

According to the measuring tools and the site of experimental tests of Archimedes screw turbine, experimental test parameters will include input flow rate, rotation speed, generator voltage, electric current and rheostat resistance, uncertainty analysis has been done in order to determine the number of tests required to achieve the acceptable result for each of these parameters. Uncertainty analysis for flow rate parameters, voltage and rotational speed are summarized in Table 6 (for instance) and the results show that each test should be repeated 5 times.

TABLE 6. Checking the uncertainty of different parameters

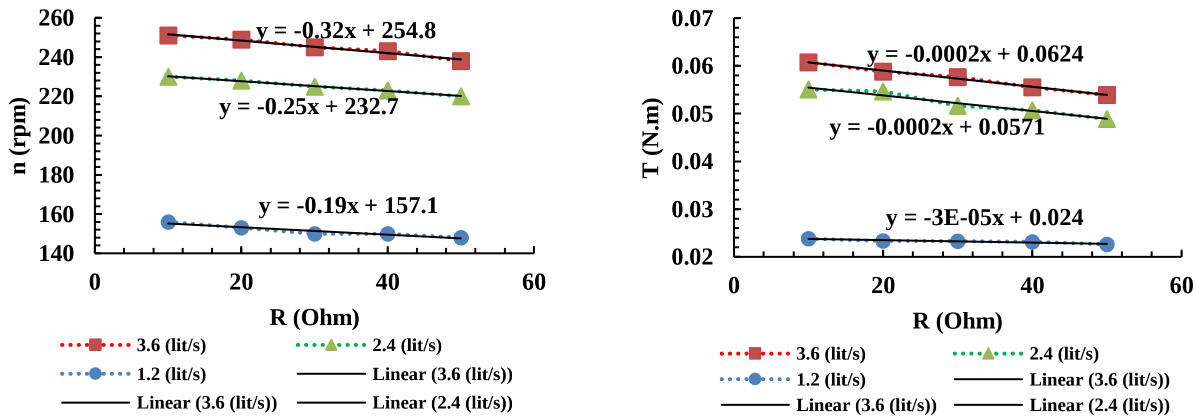
Value	1	2	3	4	5	Average value	Standard deviation	Average uncertainty	Uncertainty with overlap factor
circuit voltage at a flow rate of 3.6 (l/s) and resistance of 10 ohms (V)	1.20	1.19	1.23	1.22	1.21	1.21	0.01581	0.00707	0.01414
The rotational speed of the turbine at a flow rate of 3.6 (l/s) and a resistance of 10 ohms (rpm)	250	252	250	249	252	251	1.4142	0.6324	1.2648
Tank outlet valve flow rate (l/s)	1.19	1.19	1.22	1.22	1.18	1.2	0.01871	0.00836	0.01673

3. RESULTS

In this section, the results of the experimental tests are shown and related analyzes are performed. At first, the results of studying the performance characteristics of the Archimedes screw turbine are presented in the form of diagrams of variation in rotational speed, output power, torque and efficiency of the turbine according to different values of rheostat resistance for the inlet flow rates to the turbine. In the following, for a detailed investigation of the turbine efficiency diagram, the 3D diagram of efficiency is drawn and then, the diagrams of dimensionless power coefficient and blade tip speed ratio are studied according to the changes of flow and Reynolds numbers. Then, the results of the study of the performance of the turbine in the prototype scale are presented and the diagrams of the turbine in the prototype scale are shown. Finally, the results of the economic analysis were investigated.

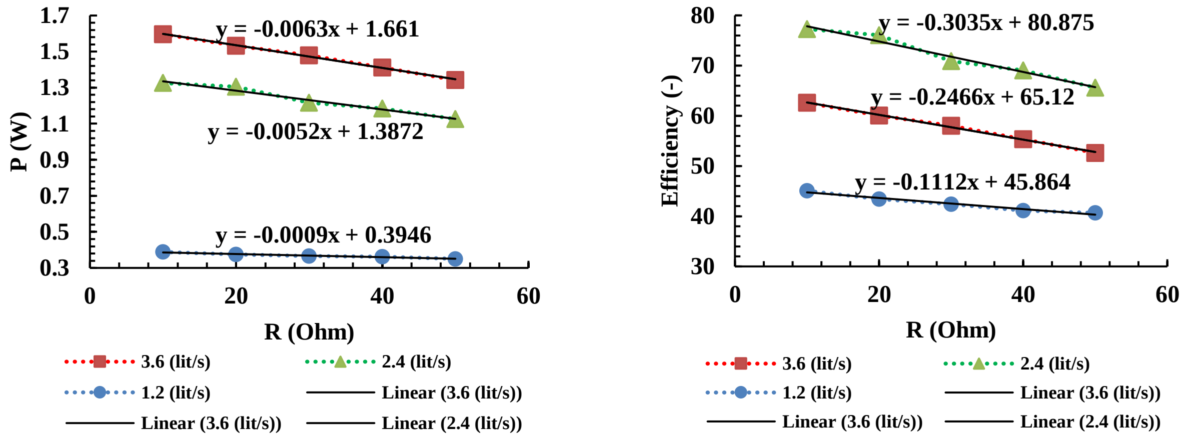
3. 1. Turbine Performance Figures 4(a) and 4(b) show the variations in turbine rotational speed and torque according to rheostat resistance for different flow rates. With an increase in the inlet flow rate of turbine, due to the rise in the momentum value, the rotational speed of the turbine always grows. Also, due to the fact that in the design and construction of Archimedes screw turbine, direct coupling of a DC motor was used as a generator to Archimedes screw turbine, the rheostat, which plays the role of a consumer in the electrical circuit output from the turbine, is used to create resistance in the circuit and variation the rotational speed of the turbine generator. According to the speed equation of the shunt electric motor [30], by increasing the resistance of the rheostat at a constant flow rate, the turbine's rotational speed will decrease. The gradient of this decrease in rotational speed increases with the rise in flow rate, so that the slope decrease in the highest flow rate is 68% more than the lowest flow rate. This shows that the system is more sensitive to the consumer load at high flow rates. Figure 4(b) also shows the change of turbine output torque according to different rheostat resistances for different flow rates. According to this figure, changing the torque output from the turbine is the same as changing the rotating speed and always increases with the rise of flow rate within the range of experimental tests. In constant flow, it also decreases with increasing rheostat resistance. The torque reduction rate is almost constant for two flow rates of 2.4 and 3.6 (l/s), but for the flow rate of 1.2 (l/s), the rate of reduction with increasing resistance is small, and it can be said that the torque at low flow rates has a behavior independent of the electrical resistance (consumer load).

Figures 5(a) and 5(b) show the power and efficiency variations with electrical resistance for different flow rates. By increasing the inlet flow rate to the turbine, the output power of the turbine rises. This trend of output power variations with increasing flow rate is always upward in the range of experimental tests, and the maximum output power in experimental tests was 1.59 (W) at a flow rate of 3.6 (l/s). Also, at a constant flow rate, the output power of the turbine decreases with an increase in the rheostat resistance. Considering that the output power of Archimedes screw turbine is measured electrically by using an electric circuit connected to the generator, by increasing the resistance of the rheostat, the resistance value of the circuit increases and more power is consumed. Therefore, the output power decreases. Also, with the rise of the rheostat resistance at a constant flow rate, the turbine's rotational speed decreases; therefore, according to turbine power equation [23], the output power of the turbine decreases. Figure 5(b) also shows the diagram of the variations in turbine efficiency. According to this figure, for a constant flow rate, the



(a) (b)

Figure 4. Diagram of a) rotational speed and b) output torque according to the value of rheostat electrical resistance for different conditions of the inlet flow rate to the turbine



(a) (b)

Figure 5. Diagram of a) output power and b) efficiency of turbine according to the value of rheostat electrical resistance for different conditions of the inlet flow rate to the turbine

efficiency value decreases with an increase in the rheostat resistance (reduction of the turbine's rotational speed). This reduction in efficiency is due to an decrease in the output power of the turbine with an increase in rheostat resistance. So, the output efficiency falls by reducing the output power according to turbine efficiency equation [23] for a constant flow rate. Also, in this figure, it is clear that the highest turbine efficiency will be at flow rate of 2.4 (l/s). As mentioned, with an increase in the flow rate, the turbine's rotational speed grows. According to rotational speed limit of Archimedes screw turbine equation [6], when the rotational speed exceeds this limit, the flow turbulence reduces the efficiency of the turbine. Since the rotational speeds measured in the experimental tests, in the flow rate of 3.6 (l/s), are higher than the speed limit provided by Nagel [6]. Consequently, the efficiency of the turbine has decreased in this flow rate.

By curve fitting the experimental data obtained for efficiency (by MATLAB CFTool), it is possible to draw the efficiency variations for different flow rates and resistances (Figure 6). According to Figure 6, the efficiency of the Archimedes screw turbine initially increases with an increase in the input flow rate and by reaching its maximum value and passing the rotational speed limit at the same time as the flow turbulence increases, it starts to drop. According to the experimental tests, the maximum efficiency of Archimedes screw turbine is 77.28%, which occurs at the input flow rate of 2.4 (l/s), which is 23.47% higher than the flow rate of 3.6 (l/s).

3. 2. Dimensionless Study of Performance

For analyzing of the power coefficient values for Archimedes screw turbine, diagram of power coefficient variations according to two dimensionless Reynolds and flow number is shown in Figure 7. According to this figure, with the increase of the Reynolds number, the power coefficient values always decrease due to the increase of

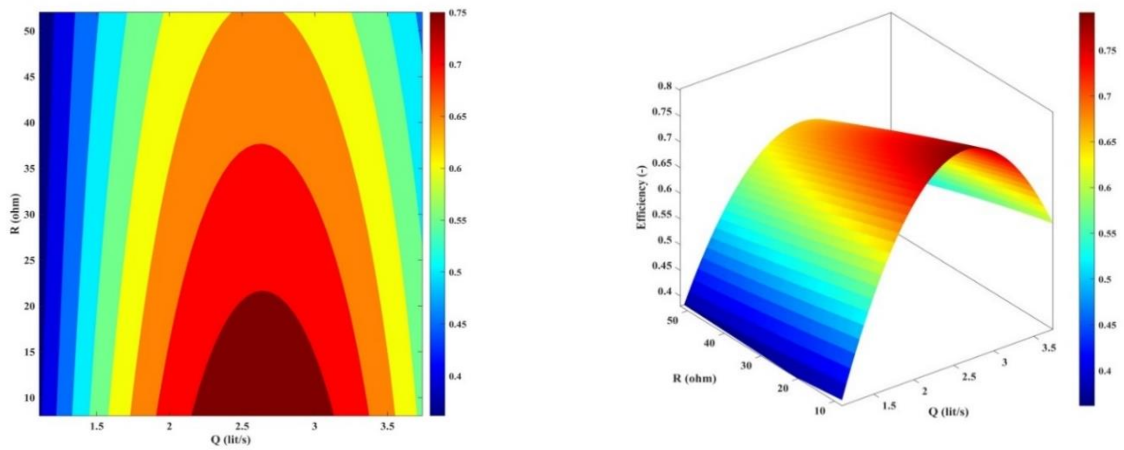


Figure 6. 3D diagram of turbine efficiency changes according to changes in inlet flow rate and resistance

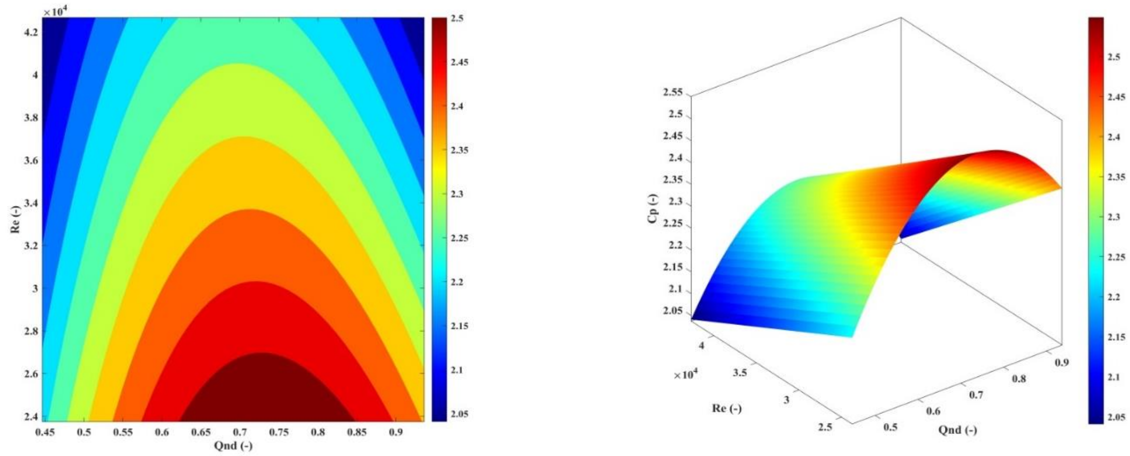


Figure 7. 3D diagram of power coefficient according to flow and Reynolds dimensionless numbers

the flow turbulence. Also, for constant Reynolds number, with an increase in the dimensionless number of flow, the power coefficient increases at the beginning like the changes in the turbine efficiency, and after reaching its maximum value, it begins to decrease.

Figure 8 shows the blade tip speed ratio variation according to flow and Reynolds numbers. According to this figure, with an increase in the Reynolds number, the value of the tip speed ratio rises. At a constant inlet flow rate, the turbine's rotational speed increases with the upturn of the Reynolds number and according to the Equation (15), the value of the blade tip speed ratio increases. Also, according to this figure, in a constant Reynolds number, the value of the blade tip speed ratio decreases with the rise in the dimensionless flow number. According to Equation (19), with this dimensionless number's rise, the turbine's flow rate increases or the turbine's rotational speed decreases. By growing this dimensionless number, the inlet flow rate of the turbine rises or the rotational speed of the turbine decreases, both of these factors reduce the value of the dimensionless number of the blade tip speed ratio.

3. 3. Prototype Performance The scaling has been considered 1:6, so it is possible to evaluate the performance of the Archimedes screw turbine in the prototype scale according to the results of the laboratory model performance and the equations in Table 3. Figure 9(a to c) shows the rotational speede, torque and power of prototype turbine to rheostat electrical resistance for different flow rates. Figure 9(a) shows the rotational speed of the Archimedes screw turbine in prototype scale. According to this figure, the behavior is similar to the diagram related to the laboratory model. Considering Archimedes screw turbine rotation speed limited equation [6] with an increase in the diameter of the Archimedes screw turbine, the rotational speed of the screw turbine decreases. In the diagram of Figure 9(a), this reduction in speed is evident in the prototype model compared to the laboratory model. The maximum

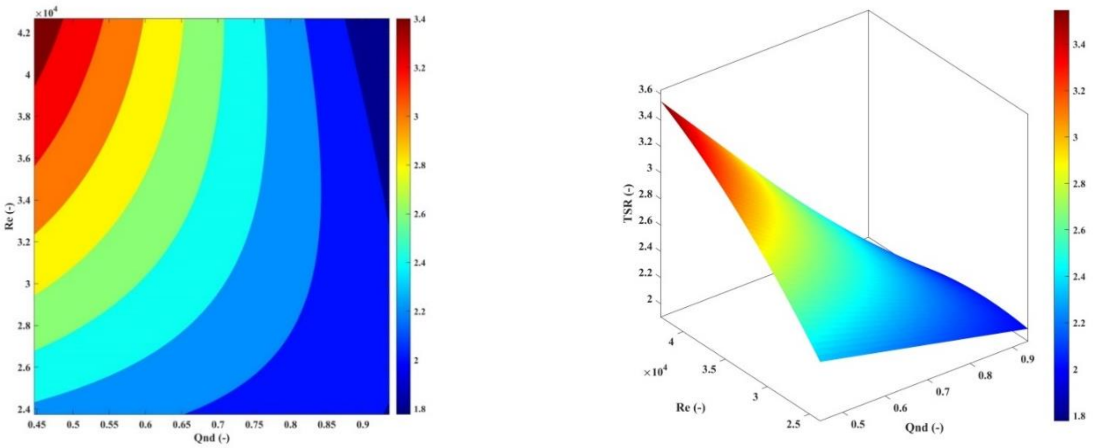


Figure 8. 3D diagram of blade tip speed ratio according to flow and Reynolds dimensionless numbers

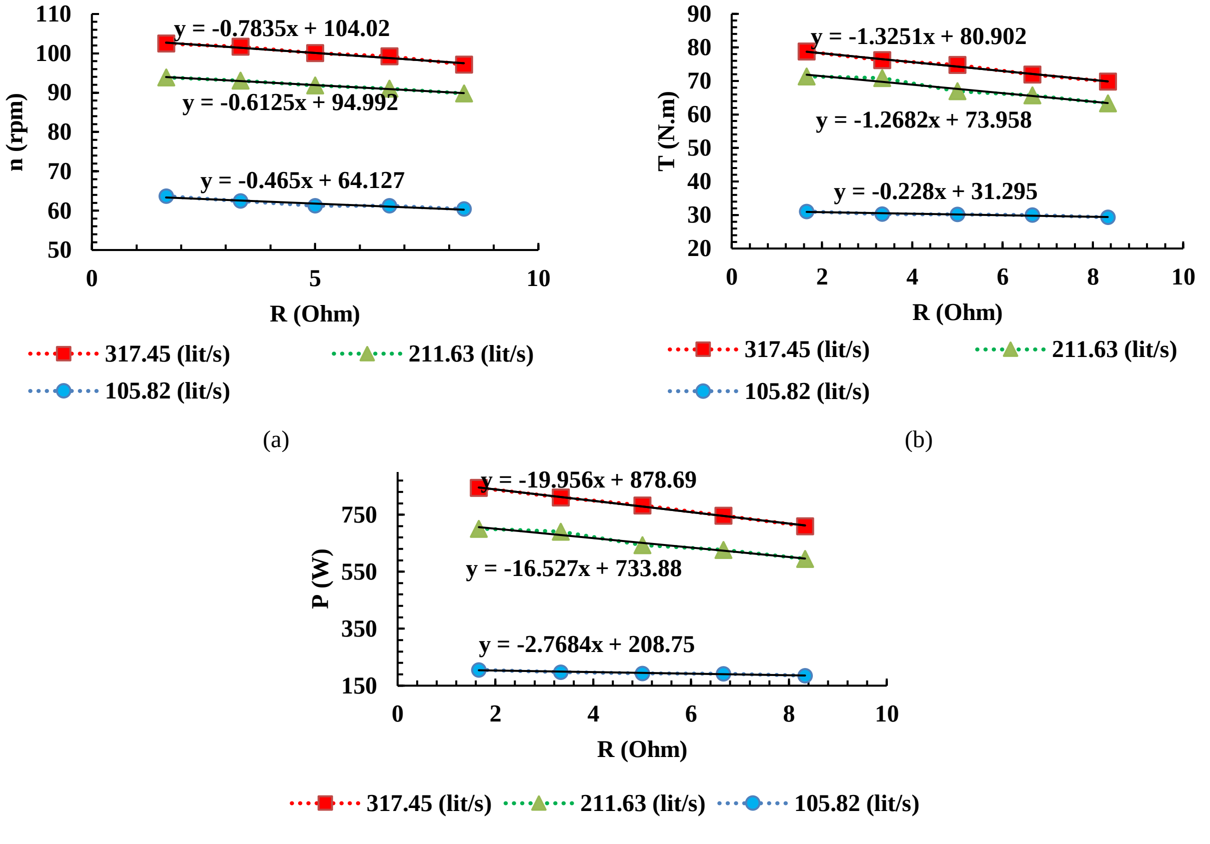


Figure 9. Protoype a) rotational speed, b) torque and c) power to rheostat electrical resistance for the different inlet flow rate to the turbine

rotational speed of the turbine will equal 102.47 (rpm) at flow rate of 317.45 (l/s). According to the gradient of the rotational speed variation diagram for laboratory and prototype model, the sensitivity of rotational speed to load changes in the prototype model has increased by about 145% compared to the laboratory model.

Figure 9(b) shows the torque variations of the Archimedes screw turbine on a prototype scale. According to the equations in Table 3 for prototype, the sensitivity of the torque variation to the electrical load has also increased significantly in prototype, according to the slope of the torque change diagrams for the laboratory model and prototype turbine. This rate is higher than the rate of changes in rotational speed and lower than the rate of variations in power.

Figure 9(c) also shows the diagram of power according to the changes in electrical resistance for different flow rates entering the turbine in the prototype scale. The behavior is just like the laboratory model. Due to an increase in the geometrical dimensions of the turbine in the prototype and the equations in Table 3 for different parameters, the head and flow rates of the input to the turbine have increased for the prototype. The maximum output power of the turbine in the prototype is equal to 844.63 W at a flow rate of 317.48 (l/s). This power is about 527 times the output power of the laboratory model. Also, according to the slope of the output power diagrams for laboratory and prototype models, the sensitivity of the power to changes in the consumption load in the prototype compared to the laboratory model significantly increased.

3. 4. Economic Study

Using the results of the Archimedes screw turbine in the prototype scale, the turbine's design, construction and operation can be economically studied for the inlet flow rates and output powers. Table 7 shows the amount of annual power production, costs and income related to the operation of the Archimedes screw turbine for different flow rates tested. In this table, the power plant's maintenance cost equals 4% of its construction cost [31].

Figure 10 shows the effect of the discount rate on the payback period for the different conditions of the inlet flow rate to the Archimedes screw turbine. This figure shows that the payback period is not much further according to the costs and income of the construction and operation of the power plants for different flow rates entering the Archimedes screw turbine. According to this

TABLE 7. Specifications of production power and its costs and income for Archimedes screw turbine in prototype scale

Flow rate (l/s)	Annual electricity production (kWh)	Power plant construction cost ($)	Power plant maintenance cost ($)	Total costs ($)	Annual income from selling electricity ($)
105.82	1800.61	62	2.5	64.5	45
211.63	6143.47	210	8.5	218.5	153
317.45	7398.95	254	10.5	264.5	185

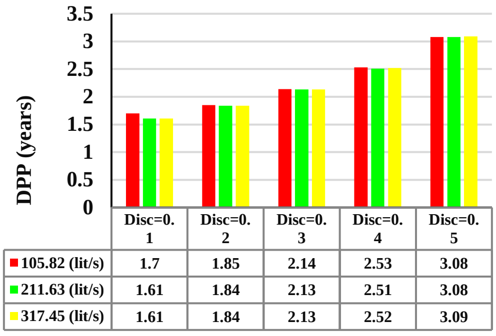


Figure 10. The effect of the discount rate on the payback period for different condition of inlet flow rate to the Archimedes screw turbine

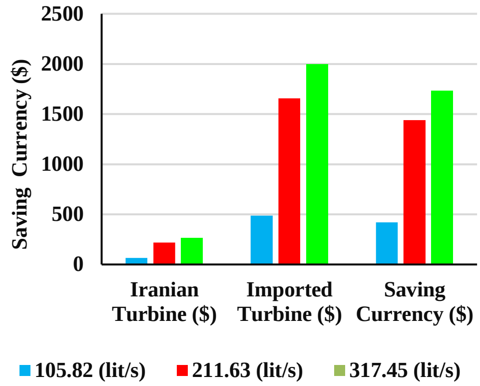


Figure 11. Amounts of costs related to the construction of the Archimedes screw turbine power plant in Iran and the foreign model and the amount of currency savings for different condition of inlet flow to the Archimedes screw turbine

diagram, the minimum payback period with a discount rate of 0.1 for the flow rates of 211.63 and 317.45 (l/s) is 1.7 years.

Figure 11 shows the amount of costs related to the construction of the Archimedes screw turbine power plant in Iran and the foreign model and the currency savings for different conditions of inlet flow rate to the Archimedes screw turbine. According to this figure, the values of Iranian and foreign model manufacturing cost and currency exchange for the flow rate of 317.45 (l/s) are more than the other flow rates of the Archimedes screw turineb.

And at the end of this paper, the performance results of the Archimedes screw turbine made with 3D printer technology in this paper are compared with the traditional turbine made by Yulistiyanto et al. [20]. The dimensions of these two turbines were different. For this reason, the results of Yulistitano et al's [20] turbine close to the results of this paper by using Froude scaling. Figure 12 shows the power changes according to flow rate for these two turbines. In this figure, it is clear that the turbine made with a 3D printer in this paper has higher power values (with the exception of the flow rate of 1.2 (l/s)) compared to the turbine made with the traditional method. This shows the improvement of the performance of the turbine made with 3D technology compared to the traditional method.

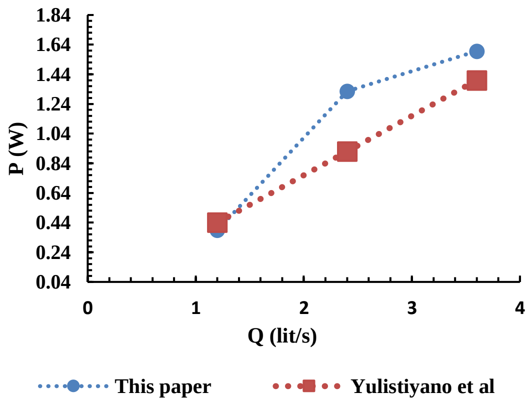


Figure 12. Comparing results

4. COCLUSIONS

In this article, the effects of changes in the inlet flow rate to the turbine and electrical resistance on the performance characteristics of the laboratory model of an Archimedes screw turbine, which include rotational speed, output power, output torque, and turbine efficiency, were discussed, and these results were scaled for the prototype by using Froude dimensionless number. Also, the effects of dimensionless flow and Reynolds numbers on power coefficient and blade tip speed ratio of the turbine were investigated. Finally, the design, construction and operation of the Archimedes screw turbine in the prototype scale were analyzed from an economic viewpoint. The main results obtained from this study are as follows:

- The performance of the turbine made with 3D technology has a better performance than the turbines made with traditional methods.
- By increasing the value of rheostat resistance, the rotational speed, output power, torque and efficiency always decrease in the laboratory and prototype scale.
- The maximum value of turbine efficiency is equal to 77.28, which occurs in the flow rate of 2.4 (l/s).
- The maximum value of output power of the turbine for the laboratory model will be equal to 1.59 (W) and for the prototype it will be equal to 844.63 (W).
- Reynolds number increase lead to rise in blade tip speed ratio and the power coefficient decreases.
- Increasing dimensionless flow number cause decreases in the blade tip speed ratio and the power coefficient increases at first and decreases after reaching a maximum value.
- The discounted payback period depends on the discount rate and can be considered between 1.6 and 3 years according to the discount rate. Also, it can sell $153 of electricity to the grid annually to achieve the best system efficiency.

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Persian Abstract

چکیده

یکی از بهترین راه‌حل‌ها برای غلبه بر مشکلات ناشی از مصرف سوخت‌های فسیلی استفاده از انرژی‌های تجدیدپذیر است. در این راستا، در این تحقیق تأثیر دبی و بار مصرفی بر عملکرد یک توربین پیچ ارشمیدس به صورت تجربی مورد بررسی قرار گرفت. در ابتدا توربین ارشمیدس با ابعاد بهینه با استفاده از فناوری چاپگر سه‌بعدی ساخته‌شد. سپس در سایت شبیه‌سازی رودخانه قرار گرفت. پس از کالیبراسیون و تجزیه‌وتحلیل عدم قطعیت، آزمایشات برای سه نرخ جریان و پنج مقاومت الکتریکی انجام شد. نتایج نشان داد که افزایش دبی منجر به افزایش توان، گشتاور و سرعت دورانی توربین می‌شود، اما باعث رفتار غیرخطی در راندمان می‌شود. از سوی دیگر، افزایش بار الکتریکی نیز منجر به کاهش عملکرد مبدل برای همه شرایط شده‌است. علاوه بر این، با استفاده از نظریه پی–باکینگهام، رفتار هیدرودینامیکی مبدل با استفاده از اعداد رینولدز، دبی بی‌بعد و ضریب توان مورد بررسی قرار گرفت. نتایج نشان داد که افزایش عدد رینولدز منجر به کاهش ضریب توان می‌شود. با این حال، افزایش دبی بدون بعد، ابتدا ضریب توان را افزایش و سپس کاهش می‌دهد (رفتار غیرخطی). علاوه بر این، توربین پیچی ارشمیدس از دیدگاه اقتصادی نیز مورد بررسی قرار گرفت و نتایج نشان داد که افزایش نرخ تورم منجر به افزایش دوره بازگشت سرمایه تنزیل‌شده می‌شود و در بدترین حالت، دوره بازپرداخت ۳/۰۹ سال و در بهترین حالت، ۱/٦ سال است. هم‌چنین ساخت توربین پیچ ارشمیدس در ایران می تواند ۱٤۳۹/۵ دلار صرفه جویی ارزی به همراه داشته‌باشد.