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Enhancing Performance Evaluation of Archimedes Screw Turbines under Optimal Conditions: A Focus on Flow Rate Analysis, Empirical Equations, and Comparative Scaling Methods

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A B S T R A C T

Due to the necessity of utilizing renewable energies, the Archimedes screw turbine can be used as a power generation converter for the use of hydropower energy from river flows. A laboratory-scale model of this turbine with a scale of 1:6 has been designed and constructed. In the experimental tests, the performance characteristics of the turbine were investigated based on variations in the flow rate and electrical resistance. The optimal flow rate for the turbine was determined with the aim of achieving maximum efficiency. The performance characteistics of the turbine at this flow rate were evaluated using empirical equations derived from the experimental tests for various parameters. These equations indicated higher values for these parameters at this flow rate. Furthermore, for the scaling of the Archimedes screw turbine, dimensionless numbers such as Froude number and flow rates ratio were introduced. The experimental results were extrapolated to the prototype scale at the optimal flow rate of 2.6 (lit/s), where the maximum turbine efficiency occurs. The results showed that the use of Froude scaling led to approximately 25% higher values for the performance characteristics of the turbine compared to scaling based on flow rates ratio.

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NOMENCLATURE

D_i	Inner diameter (m)	p	Pitch (m)
D_o	Outer diameter (m)	Q	Flow rate (lit/s)
h	Head of turbine (m)	T	Torque (N.m)
I	Electric current (A)	V	Voltage (V)
N	Number of blade	**Greek Symbols**	
n	Rotational speed (rpm)	η	Efficiency
P	Output power (W)	β	Instaliation angle (degree)
$P_{available}$	Available power (W)	ω	Angular velocity (rad/s)

INTRODUCTION

Nowadays, due to the increasing need for energy in countries and the shortage of fossil fuels, as well as the problems they create, such as greenhouse gas emissions [1], the use of renewable energy sources has become very important [2]. Governments also encourage people to use renewable energy sources [3]. Also, due to the importance of this issue, in some cases, renewable energy converters are used in combination [4]. Renewable energies are derived from natural resources that renew themselves in less than a human lifespan without losing resources. These resources are practically inexhaustible and, more importantly, they cause little damage to the climate and the environment [5]. Hydropower is one of the most important and accessible renewable energy sources.

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According to statistical analysis conducted by PB in 2020, hydropower accounted for approximately 15.6% of global electricity production in 2019, ranking third after coal and natural gas [6].

The Archimedes screw turbine (AST) can be used as a hydroelectric plant for the use of hydropower. These turbines are classified as parallel flow reaction turbines [7]. This turbine consists of a cylindrical shaft connected to a series of helical blades. When water enters the turbine, it flows through the space between the blades and travels along the length of the screw, causing the turbine to rotate and generate power [8]. Due to the rotational speed of these turbines and the space between their blades, fish and rubbish can easily pass through without causing any problems [9]. Figure 1 shows different models of Archimedes screw turbines, including inclined axis turbines, horizontal axis turbines, and submersible turbines. The inclined axis model has the ability to produce more power than other models because the output power of the turbine is created through two components, namely the water flow velocity and hydrostatic force (due to the difference in water level between the turbine inlet and outlet). On the other hand, this model creates less restriction in using different gearbox and generator configurations for power generation compared to other models. Therefore, the inclined axis model of Archimedes screw turbine is more commonly used than other models [10].


(a)


(b)


(c)

Figure 1. Different models of Archimedes screw turbines: a) inclined axis turbine, b) horizontal axis turbine, and c) submersible turbine [10]

The most famous Archimedes screw turbine power plants in the world are Windsor Castle and Linton Lock Archimedes screw turbine power plants. Both of these power plants are in the United Kingdom and have a power generation capacity of 300 and 270 KWh, respectively. Figure 2 (a) and (b) shows these power plants. According to this figure, it can be seen that the Winsor Castle power plant consists of two Archimedes screw turbines weighing about 40 tons. Linton Lock power plant also has an Archimedes screw turbine with a diameter of 5 meters. Since these turbines are derived from the Archimedes hydrodynamic screw, many scientists and researchers have conducted numerous studies on this hydrodynamic screw and its various applications, including its use as a


(a)


(b)

Figure 2. a) Windsor Castle and b) Linton Lock AST hydro power plant

turbine, from the past to the present. In 2000, Rorres [11] presented an optimal dimensionless ratio for optimal turbine geometry design with the aim of maximizing the water volume in each bucket. In 2013, Nuernbergk and Rorres [12] presented a model to investigate the effects of flow parameters on the performance of an AST. The model examined the impact of upstream water level and flow disturbances on the turbine's performance. The results indicated that the presence of flow disturbances at the turbine inlet led to incomplete filling of buckets and reduced turbine efficiency. In 2015, Charisiadis [13] conducted an experimental and numerical study on the Archimedes screw turbine. He observed that the values related to the rotational speed of the turbine decrease as the turbine diameter increases. He also theoretically investigated the leaks associated with the Archimedes screw turbine and provided analytical equations for these parameters based on the turbine geometry. In 2015, Lee et al. [14] used a 3D printer and plastic materials to build turbine with the aim of reducing the cost of construction and increasing accuracy. In 2017, Kozyn and Lubitez [15] presented a model to investigate the power loss of the Archimedes screw turbine. They used the flow rates ratio method to scale the turbine. In 2018 Dellinger et al. [16] investigated the performance of the turbine with experimental and numerical methods and evaluated the energy losses created in different parts of the turbine geometry. By validating the experimental results and numerical simulations, they predicted the performance of the turbine to achieve high efficiency. In 2019, Maulana et al. [17] experimentally studied an AST and found that the turbine efficiency has a nonlinear trend with increasing flow rate, and the maximum efficiency of the turbine occurs at an intermediate flow rate. In 2021, Bustomi et al. [18] conducted an experimental investigation of a inclined axis turbine. They used a gearbox with a conversion ratio of 1:2.5. In this study, the turbine torque was examined mechanically and its output power was examined electrically. In 2021, Lee and San Lee [19] studied an Archimedes screw turbine and found that increasing the input flow rate to the turbine increases the rotational speed and torque of the turbine. They then extrapolated the results of this laboratory model to the prototype turbine. In 2021 Sari et al. [20] investigated the issue of overflow leakage in the turbine. They stated that overflow leakage could affect the turbine rotational speed and, as a result, its performance. They suggested that by changing the installation angle of the turbine, this leakage could be reduced. In 2022, Thakur et al. [21], with an experimental study of the Archimedes screw turbine, showed that this turbine has a good performance with a relatively high efficiency under the conditions of low head, lower installation angle (20-25 degrees) and under load. In 2022, Darmono and Pranoto [22] used numerical methods to investigate the effect of increasing the number of blades on the performance of the turbine. In this study, they did not consider the limitations of building turbines with different numbers of blades. In 2022, Ortiz Osornio [23] studied the possibility of using the Archimedes screw turbine in prototype scale in rural areas with suitable river flows. He stated that, considering the amount of power produced and the consumption of the area, it is possible to generate income by selling the excess power produced by using this turbine. In 2023, Zamani et al. [24] experimentally studied a laboratory model of the AST and then extrapolated the results to the prototype scale turbine using Froude scaling. Also, in 2023, Zamani et al. [25] according to the results of experimental tests, calculated the optimal flow rate for the Archimedes screw turbine with the genetic algorithm method. They further investigated the performance of the turbine at the optimum flow rate numerically. In 2023, Kusumanto and Nugraha [26] investigated the applications of the AST as a portable mini hydropower plant. After determining the characteristics of the river water flow, they extracted the power and other geometric characteristics of the turbine. In 2023, Davirov et al. [27] by making a change in the geometry of the turbine, they presented a two-turbine laboratory model of the AST and determined the performance characteristics of this two-turbine model. In 2023, Indarto et al. [28] investigated the use of gearboxes with different conversion ratios for use in an Archimedes screw turbine generator. They concluded that with an increase in the conversion factor, the values of rotational speed, voltage, current and power of the turbine increased. It is also possible to check different generators to convert the rotational movement of the turbine into electricity. Usually, DC generators are used for this turbine in various studies. In 2023, Mousavi et al. [29] investigated VSG generators. These generators can be used as suitable generators for Archimedes screw turbine due to their various advantages, including more accuracy and better controllability.

Based on the studies conducted on the Archimedes screw turbine, the optimal performance of the turbine and various methods of scaling the Archimedes screw turbine have received less attention. For this purpose, an AST is designed and manufactured in laboratory scale and then tested in the experimental site related to at the Sea-Based research group. The results of the experimental tests are taken into consideration. After examining the performance characterisicts of the turbine in various experimental test conditions, the results of these tests are optimized to achieve maximum efficiency and the optimal flow rate at which the turbine has the maximum efficiency is determined. The optimal flow rate at which the maximum efficiency of the turbine occurs is determined using the genetic algorithm method. Finally, the performance of the turbine at the optimal flow rate are determined using output equations from the experimental test data. Furthermore, after determining the performance characteristics of the turbine at the optimum flow rate, various scaling methods are used to extend the results of the laboratory-scale experimental tests to the full-scale prototype that is six times larger than the laboratory-scale model. Non-dimensional numbers such as Froude and flow rates ratio are used for scaling and the performance results of the turbine were compared using these non-dimensional numbers in the full-scale prototype. And finally, these different scaling methods for this turbine were compared.

EXPERIMENTAL STUDY

After introducing the AST as a river flow power plant and reviewing the available resources on the subject, this section discusses the various stages related to the experimental study of this type of turbine.

Design of turbine

The design of the Archimedes screw turbine is carried out using non-dimensional ratios defined by Rorres [11]. Table 1 shows the optimal non-dimensional parameters for Archimedes screw turbines based on the number of blades. To design the turbine, certain dimensions and specifications need to be determined as input parameters. These parameters can include the outer diameter, turbine length, and number of blades. The outer diameter and turbine length are determined based on the experimental test site. For the number of blades, due to the limitations in manufacturing turbines with a large number of blades, a four-bladed turbine is chosen for design. Then, by examining the different parameters including the radius ratio, pitch ratio, and volume ratio according to Table 1, and also by examining the available equations for determining the appropriate installation angle for the turbine [11], the designed turbine have the specifications listed in Table 2.

The physics of the problem

Figure 3 shown the site used for simulating river flow, where the experimental tests of the AST are carried out [24]. To measure the output power of the turbine, the electrical circuit shown in Figure 4, which is connected to the turbine output generator, is utilized. The power of the turbine is calculated by Equation (1). This equation calculates the output power of the turbine using the electrical method [30].

$$P = V.I \tag{1}$$

Turbine efficiency is also determined using Equation (2) which is the ratio of output power to total available power [31].

$$\eta = \frac{P}{P_{available}} \tag{2}$$

The total available power is also calculated according to Equation (3). This equation is the same for all hydro turbines according to the site related to their use [25].

$$P_{available} = \rho.g.Q.h \tag{3}$$

Also, according to the existing relationships for turbine power by mechanical method, turbine torque can be calculated according to Equation (4) [30].

$$T = \frac{P}{2\pi n} \tag{4}$$

Design of experiment

The important parameters for measurement in these experiments for the designed Archimedes screw turbine include the output power and rotational speed of the turbine. To calculate the output power based on the generator connected to the turbine, which is responsible for converting the rotational motion of the turbine into electrical current, an electrical circuit is used according to Figure 4, and the output power is measured electrically through it. To calculate this output power, the measurement of electerical current and voltage at the time when a consumer is present in the circuit is necessary. Rheostat is used as a consumer in the circuit, a voltmeter and ammeter are also used to measure voltage (V) and electerical current (I). Additionally, a tachometer is used to measure the rotational speed of the turbine.

Table 1. Optimal non-dimensional parameters based on the number of blades for Archimedes screw turbines presented by Rorres [11]

N	ρ^*	λ^*	$\lambda^*\nu(N,\rho,\lambda)$	$\nu(N,\rho^*,\lambda^*)$
1	0.5358	0.1285	0.0361	0.2811
2	0.5369	0.1863	0.0512	0.2747
3	0.5357	0.2217	0.0598	0.2697
4	**0.5353**	**0.2456**	**0.0655**	**0.2667**
5	0.5352	0.2630	0.0696	0.2647
6	0.5353	0.2763	0.0727	0.2631
7	0.5354	0.2869	0.0752	0.2619
8	0.5354	0.2957	0.0711	0.2609
9	0.5356	0.3029	0.0788	0.2601
10	0.5356	0.3029	0.0802	0.2592

Table 2. Geometrical characteristics of the designed turbine

D_o (m)	0.1
D_i(m)	0.05
L (m)	0.17
β (degree)	25
N	4
P (m)	0.17
H (m)	0.0718

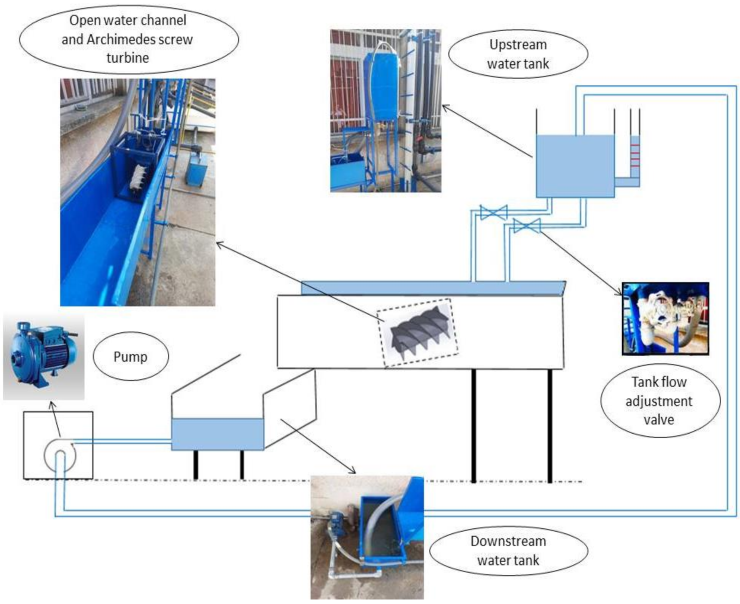


Figure 3. Archimedes screw turbine experimental tests site [24]

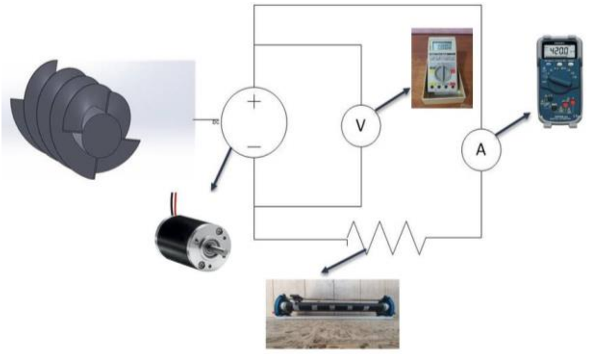


Figure 4. Electric circuit related to experimental tests

Considering that the site for conducting experimental tests has the ability to change the input flow rate to the turbine, and on the other hand, the output power is calculated using the electrical circuit connected to the generator, the effect of changing the input flow rate and the electrical resistance of rheostat (consumer load) can be examined on the performance characteristics of the turbine. Based on the measurements performed, 15 different experimental test cases were examined with 3 input flow rates of 1.2, 2.4, and 3.6 (lit/s) at 5 electrical resistances of 10, 20, 30, 40, and 50 Ohms. According to the equations related to uncertainty analysis, suitable uncertainty for experimental tests is obtained by repeating each test 5 times [24], [32], [33].

Scaling

After examining the performance characteristics of the turbine on a laboratory scale, and considering the various limitations in obtaining the prototype turbine model directly for examining its performance characteristics, it is possible to use the scaling of the laboratory model to the prototype model for investigating the performance characteristics of the turbine on this scale. In this section, various scaling methods are used to investigate the turbine on a prototype scale, which is six times larger than the laboratory model.

Froude scaling

For scaling open channel flows, such as those found in open water channels and rivers, half-submerged propeller turbines such as Archimedes screw turbines are tested using the Froude scaling. The dimensionless Froude expressed according to Equation (5) [34].

$$Fr = \frac{V}{\sqrt{gL_c}} \tag{5}$$

By applying the Froude number in both prototype and laboratory scale conditions, results obtained from laboratory tests can be extrapolated to prototype. Scaling can be achieved using the dimensionless Froude number, taking into account the ratio of the size of the prototype

Table 3. Froude scaling equations [18]

Parameter	Coefficient
Q (lit/s)	$\lambda^{2.5}$
n (rpm)	$\lambda^{-0.5}$
R (Ohm)	λ^{-1}
P (W)	$\lambda^{3.5}$
T (N.m)	λ^{4}

model to the laboratory sample, and calculating various parameters for the prototype model according to Table 3 [35].

$$\lambda = \frac{(L_c)a}{(L_c)s} \tag{6}$$

Scaling by using flow rates ratio

Another method used for scaling Archimedes screw turbines is the use of the dimensionless flow rate ratio. Based on Equation (3), the power of the turbine is a function of the flow rate, angular velocity, and head of the turbine [15].

$$P = f(Q, \omega, h, p) \tag{7}$$

Based on the effective parameters mentioned, the dimensionless flow rate ratio can be obtained by non-dimensionalizing these parameters. This ratio, is a function of flow rate (Q), turbine angular velocity (ω), screw pitch (p), as well as internal (D_i) and external (D_o) diameters for various scales. By applying this dimensionless ratio to the turbine in both prototype and laboratory scales, the performance of the turbine can be examined at the prototype scale. Equation (8) shows the ratio of flow rate for scaling Archimedes screw turbines [15].

$$Q_r = \frac{\omega p}{2\pi Q}(D_0^2 - D_i^2) \tag{8}$$

RESULTS

In this section, the results of experimental studies on Archimedes screw turbines are examined based on the aforementioned equations. Initially, performance characteristics of the turbine, including rotational speed, torque, output power, and efficiency, are investigated in the form of three-dimensional contours based on variations in input flow rates and electrical resistance. Next, considering the nonlinear trend of the efficiency curve, this parameter optimized and the optimal flow rate for the turbine is determined. The performance of the turbine at the optimal flow rate is then determined using equations related to the three-dimensional contour fitting curve obtained from experimental tests. Finally, the results about turbine at the optimal flow rate are extrapolated to the prototype model using the aforementioned scaling methods, and the results of the turbine scaling using these two methods were compared.

Turbine performance specifications

Figure 5 shows the three-dimensional contour of the variations in rotational speed of the turbine with changes in input flow rate and electrical resistance. Based on these contours, the values of the rotational speed always increase with an increase in the flow rate and decrease with an increase in electrical resistance. The upward trend

Table 4. The constants of the turbine rotational speed equation

A_0	25.65
A_1	129.9
A_2	-0.1218
A_3	-18.39
A_4	-0.05422
A_5	-2.193e^{-17}

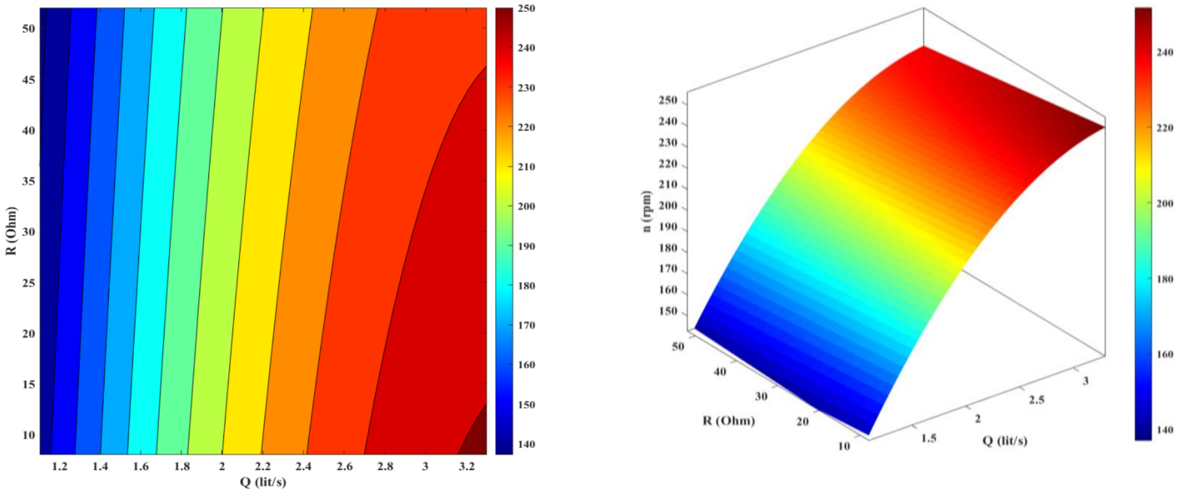


Figure 5. Three-dimensional contour of rotational speed

of the rotational speed of the turbine with an increase in flow rate occurs due to the increase in the momentum of the fluid flow. Also, with the increase of electrical resistance according to the DC motor speed relationship, with the increase of electrical resistance, the rotating speed of the turbine always decreases. Since this figure is extracted by inputting the results obtained from experimental tests into the CFTool section of the MATLAB software, the equation related to the fitting curve can be obtained according to Equation (9).

$$n(Q,R) = A_0 + A_1Q + A_2R + A_3Q^2 + A_4QR + A_5R^2 \tag{9}$$

Table 4 shows the constants of Equation (9).

In the following, using Figure 6, the changes in turbine torque are investigated. This figure shows the three-dimensional contour of the variations in the torque of the turbine with changes in input flow rate and electrical resistance. Similar to the variations in rotational speed, the changes in the torque parameter are observed to be directly proportional to the input flow rate and inversely proportional to the electrical resistance within the range of experimental tests. The process of changing the torque parameter is analyzed according to the changes in the rotational speed and output power of the turbine, as well as the available analytical equations for calculating the mechanical torque of the turbine [24]. Equation (10) represents the fitting curve equation for the contour shown in Figure 6.

$$T(Q,R) = B_0 + B_1Q + B_2R + B_3Q^2 + B_4QR + B_5R^2 + B_6Q^2R + B_7QR^2 + B_8R^3 \tag{10}$$

Table 5 shows the constants of Equation (10).

In addition, Figure 7 presents the three-dimensional contour depicting the fluctuations in the power of the turbine in response to alterations in both the input flow rate and electrical resistance. In line with other performance characteristics, such as rotational speed and torque, it can be observed that the output power exhibits a positive correlation with the input flow rate, while displaying a negative correlation with electrical resistance. The experimental testing yielded a maximum power output of 1.59 watts when the flow rate was measured at 3.6 liters per second. Equation (11) denotes the mathematical expression that describes the curve of best fit for the contour depicted in Figure 7.

Table 5. The constants of the turbine torque equation

B_0	-0.03822
B_1	0.0626
B_2	0.000306
B_3	-0.009506
B_4	-0.0002748
B_5	-1.98e^{-6}
B_6	4..477e^{-5}
B_7	-3.962e^{-8}
B_8	1.944e^{-8}

Table 6. The constants of the turbine output powr equation

C_0	-1.159
C_1	1.562
C_2	0.001636
C_3	-0.2063
C	-0.002255
C_5	2.902e^{-6}

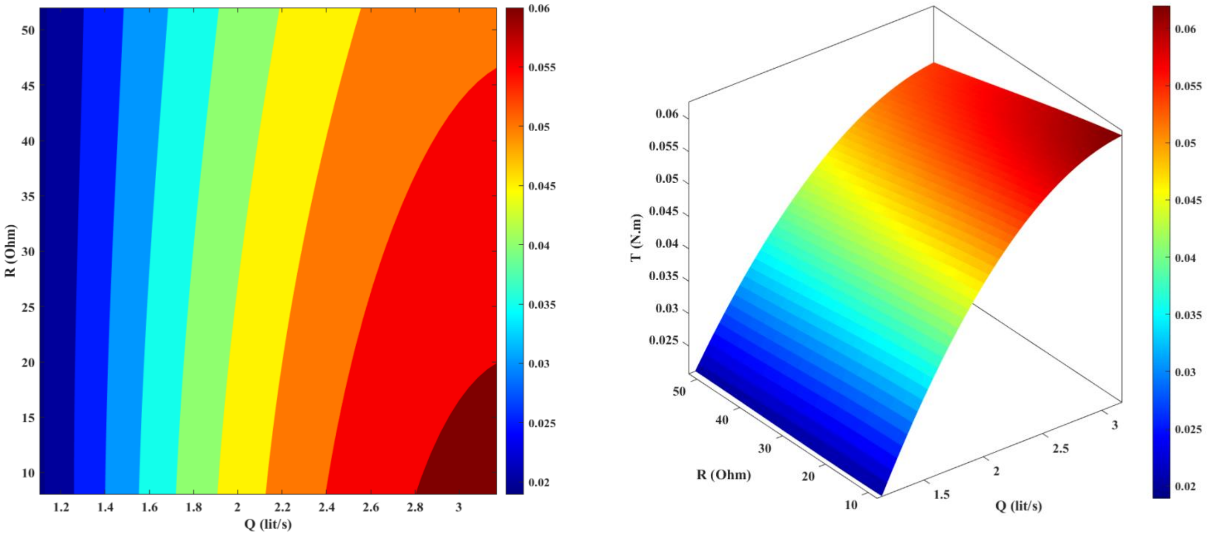


Figure 6. Three-dimensional contour of torque

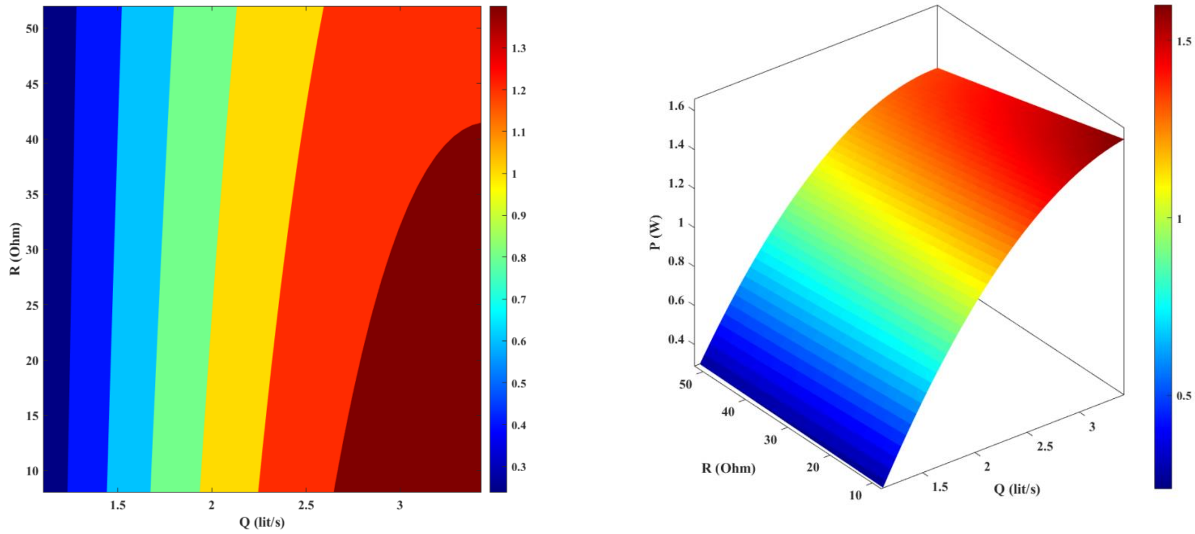


Figure 7. Three-dimensional contour of output power

$$P(Q,R) = C_0 + C_1 Q + C_2 R + C_3 Q^2 + C_4 QR + C_5 R^2 \tag{11}$$

Table 6 shows the constants of Equation (11).

Figure 8 also shows the three-dimensional contour of the efficiency of the turbine with changes in input flow rate and electrical resistance. Similar to the previous parameters, the efficiency decreases with the increase in electrical resistance. However, with an increase in input flow rate, the efficiency show a nonlinear behavior and reaches its maximum value (77.2%) at an intermediate flow rate (2.4 (lit/s)). Equation (12) represents the fitting curve equation for the contour shown in Figure 8.

$$\eta(Q,R) = D_0 + D_1 Q + D_2 R + D_3 Q^2 + D_4 QR + D_5 R^2 + D_6 Q^2 R + D_7 QR^2 + D_8 R^3 \tag{12}$$

Table 7 shows the constants of Equation (12).

Turbine performance in optimal condition

Based on the analysis performed on the results obtained from experimental tests, can optimized the efficiency results using Equation (12) to achieve maximum turbine efficiency at an optimal flow rate. For a more detailed investigation of the efficiency curve, can refered to Figure 9, which shows that the efficiency of the turbine increases for a period after the flow rate of 2.4 (lit/s). To achieve the optimum flow rate at which the Archimedes screw turbine operates with maximum efficiency, can use Equation (12) and use the genetic algorithm optimization method [32] to obtain the optimum flow rate of 2.6 (lit/s). MATLAB software is used for this purpose. This software is one of the most comprehensive and practical numerical calculations software. Also, it is one of the most important programming languages. For optimization by genetic algorithm method in this software, according to the models ready for optimization, by placing the equation related to efficiency changes and determining the specific range of optimization for the flow rate parameter and determining other settings, this optimal flow rate can be achieved.

To investigate the performance characteristics of the turbine at the optimal flow rate, the values of various parameters can be examined at the optimal flow rate by using Equations (9) to (12) and considering different electrical resistances. Figure 10 compares the results of the turbine performance at the optimal flow rate with the results obtained at a flow rate of 2.4 (the flow rate with the maximum efficiency in experimental tests). Based on this figure, various parameters have higher values at the optimal flow rate. According to the contents stated about the changes in rotational speed and torque of the turbine, it can be seen that the values of this parameter will be higher in the optimal flow rate. Also, due to the maximum

Table 7. The constants of the turbine torque equation

D_0	-0.4143
D_1	0.0931
D_2	0.002982
D_3	-0.1764
D_4	-0.004583
D_5	1.124e^{-5}
D_6	0.0008971
D_7	6.161e^{-6}
D_8	1.677e^{-8}

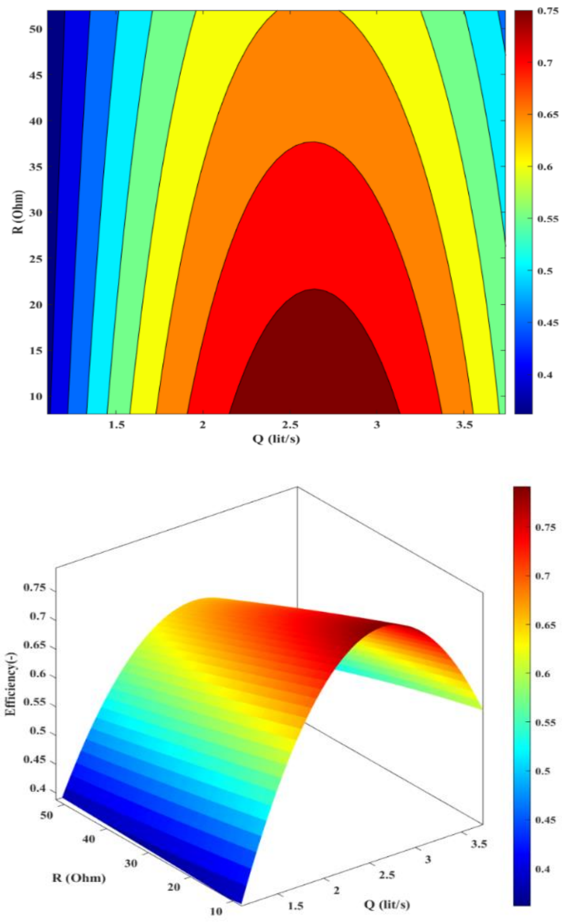


Figure 8. Three-dimensional contour of efficiency

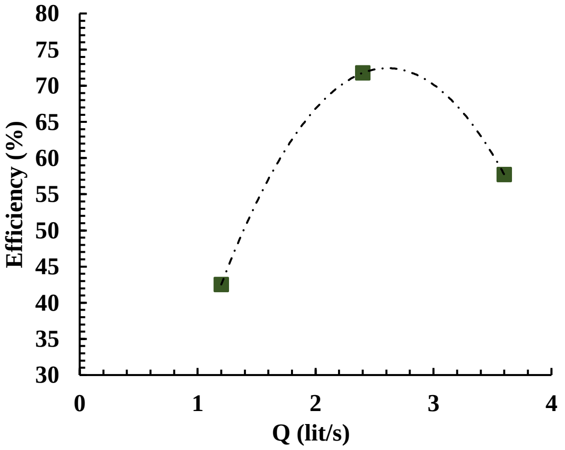
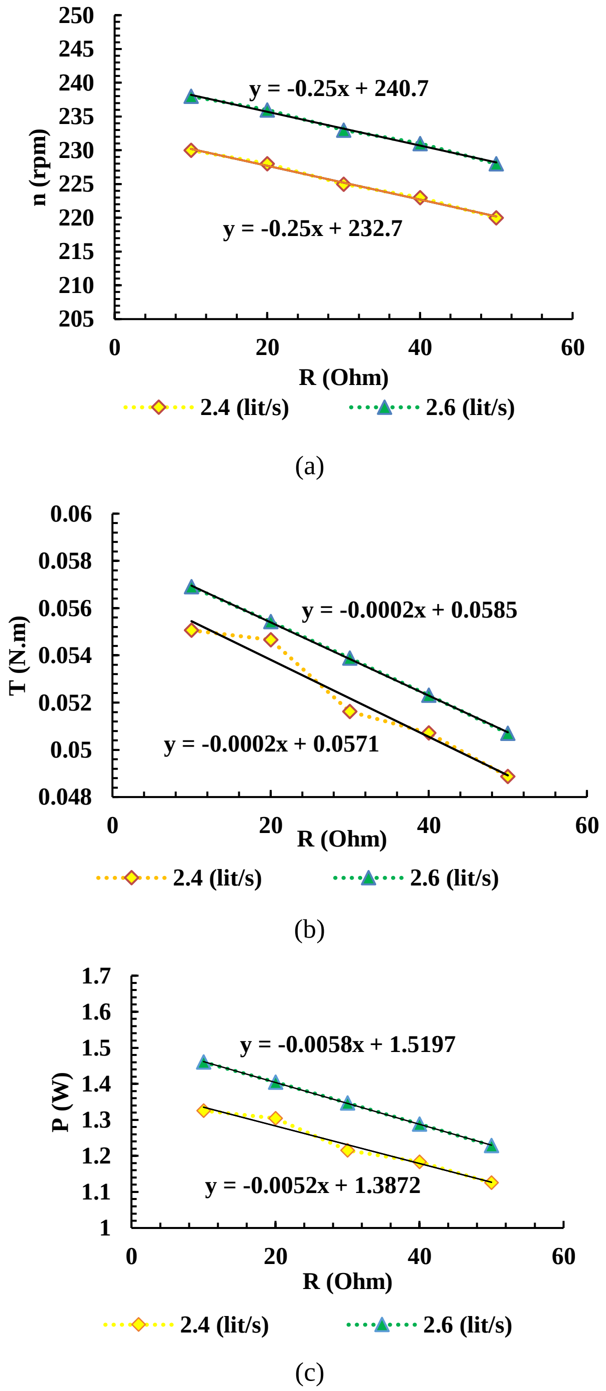


Figure 9. Efficiency of turbine according to flow rate

efficiency values in this flow rate, it can be seen that the output power of the turbine will also have higher values (according to the turbine efficiency equation).

Turbine scaling results

As mentioned in the previous section, the maximum efficiency of the turbine occurs at the optimal flow rate of 2.6 (lit/s). In this section, the results obtained for this flow rate, based on experimental tests, are extrapolated for the prototype model using the previously specified.

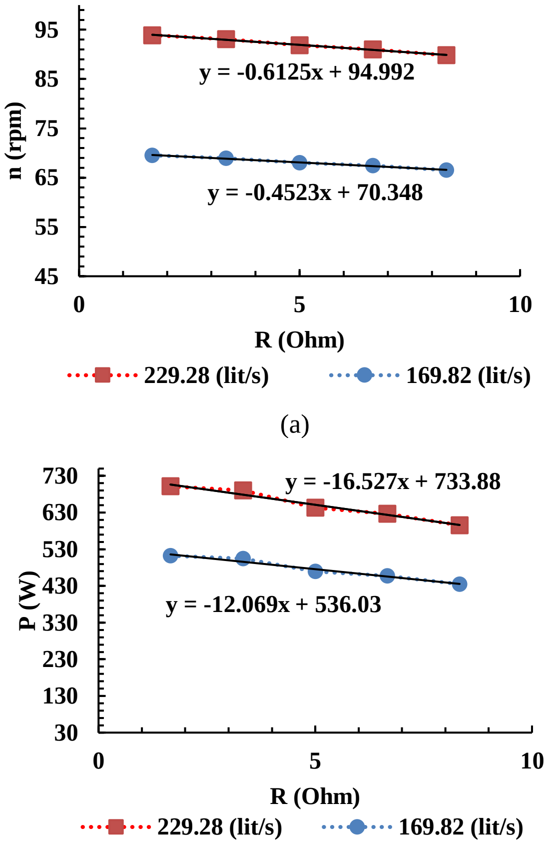


(a)

(b)

(c)

Figure 10. a) Rotational speed, b) torque and c) output power of turbine at optimal flow rate



(a)

(b)

Figure 11. Comparison of different scaling methods

CONCLUSION

In this paper, after designing the turbine and determining the experimental testing stages, the performance characteristics of the turbine were initially examined in laboratory scale. Subsequently, after determining the optimal flow rate for this turbine, the results of the experimental tests at this flow rate were extrapolated using scaling by dimensionless numbers of Froude and flow rate ratio for the prototype model, which was 6 times larger than the laboratory sample. The general results obtained from this paper are as follows:

- As the flow rate increases, the rotational speed, torque, and power values increase continuously, and the efficiency follows a nonlinear trend.
- Increasing the electrical resistance results in a continuous decrease in the rotational speed, torque, power, and efficiency.
- The optimal flow rate for the turbine, where the efficiency is maximum, is 2.6 liters per second.
- Dimensionless numbers such as Froude number and flow rates ratio can be used for scaling the Archimedes screw turbine.
- The analysis of the turbine's performance characteristics at the prototype scale, as determined by scaling with Froude number, indicates an estimated increase of 25% compared to the scaling based on flow rates ratio.

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Persian Abstract

چکیده

با توجه به ضرورت استفاده از انرژی‌های تجدیدپذیر، توربین پیچ ارشمیدس می‌تواند به عنوان مبدل تولید برق برای استفاده از انرژی آبی حاصل از جریان رودخانه‌ها مورد استفاده قرار گیرد. برای این منظور مدلی در مقیاس آزمایشگاهی از این توربین با مقیاس ۱:۶ طراحی و ساخته شد. در آزمایش‌های تجربی، مشخصات عملکرد توربین بر اساس تغییرات در دبی و مقاومت الکتریکی مورد بررسی قرار گرفت و دبی بهینه برای توربین با هدف دستیابی به حداکثر بازدهی تعیین شد. مشخصات عملکرد توربین در این دبی با استفاده از معادلات تجربی به دست آمده از آزمون‌های تجربی برای پارامترهای مختلف مورد ارزیابی قرار گرفت. این معادلات مقادیر بالاتری را برای این پارامترها در دبی بهینه نشان دادند. علاوه بر این، برای مقیاس‌بندی توربین پیچ ارشمیدس، اعداد بدون بعد مانند عدد فرود و نسبت دبی‌ها معرفی شدند. نتایج تجربی به نمونه مقیاس اصلی در دبی بهینه ۲.۶ لیتربرثانیه (که در آن حداکثر بازدهی توربین رخ می‌دهد) تعمیم داده شد. نتایج نشان داد که استفاده از مقیاس بندی فرود، بالاتر بودن حدود ۲۵ درصدی مقادیر مربوط به مشخصات عملکرد توربین در مقایسه با مقیاس بندی نسبت دبی‌ها را به همراه دارد.