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Parametric Optimization of Archimedes Screw Turbine by Response Surface Methodology and Artificial Neural Networks

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ABSTRACT

This study investigates the performance optimization of the Archimedes Screw Turbine (AST) to enhance power output, focusing on the key parameters of flow rate and inclination angle. Utilizing response surface methodology (RSM) through a central composite design (CCD) and artificial neural networks (ANN), the research explores the predictive accuracy of these methods for optimal power generation. The experimental work was carried out with two parameters: flow rate (5-15 lps) and inclination angle (15°-40°). The optimized power output predicted by the RSM and ANN models was 204.16 watts at flow rate of 14.58 lps and inclination angle 36.23°, while the ANN predicted 187.24 watts at a flow rate of 13.82 lps and inclination angle 34.15°, respectively. The correlation coefficients (R^2) for the ANN and RSM models were 0.9842 and 0.9718, respectively, revealing a significant quadratic regression for both models. Comparative analysis indicates that ANN offers better predictive accuracy than RSM, suggesting a more reliable approach for optimizing AST performance.

Index-words: *Archimedes screw turbine, Renewable energy, Micro hydropower, Ultra-low head, Response surface methodology, Artificial neural networks.*

Nomenclature:

Symbol	Definition with unit	Dimensionless parameter	Definition
De	External diameter (mm)	N	Number of blades
Di	Inner diameter (mm)	**Greek Symbol**	
p	Pitch length (mm)	β	Inclination angle
H	Head (m)	θ	Blade slope angle
Q	Flow rate (lps or m^3/s)	**Subscripts**	
g	Gravitational acceleration(m/sec^2)	in	Input
ω	Rotational velocity(rad/sec)	out	Output
F	Force(N)	**Abbreviation**	
L	Length of turbine (mm)	RSM	Response surface methodology
n	Turbine speed (rpm)	ANN	Artificial neural networks
P_{in}	Inlet power(watts)	SDG	Sustainable Development Goal
P_{out}	Outlet power(watts)	AST	Archimedes Screw Turbines
r	Radius of pulley(m)	UN	United Nation

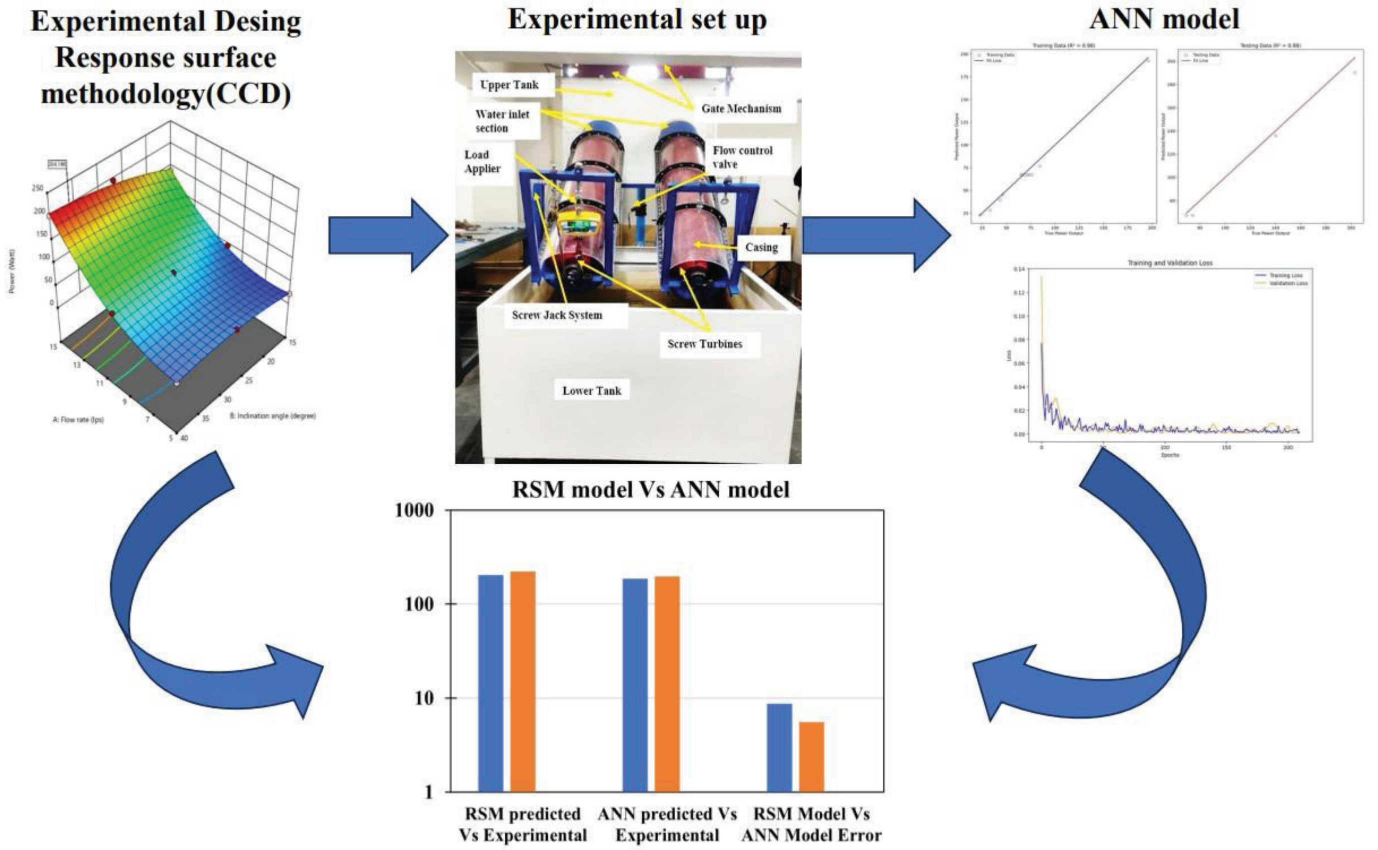


Fig. 1. Graphical abstract

I. INTRODUCTION

The global shift towards renewable energy has garnered significant attention due to its potential to reduce greenhouse gas emissions, foster sustainable development, and address energy security concerns. Many nations, particularly developed ones, have actively integrated renewable energy technologies into their energy portfolios as a strategic move to diversify energy sources and decrease dependence on conventional fossil fuels. Global renewable generation capacity reached 3371.76 Gigawatts (GW), which is 40% of global installed power capacity by the end of 2022 [1]. As of 2023, renewable energy sources accounted for approximately 29% of the world's total energy production, with a growing emphasis on increasing this share in the coming years [2]. UN SDG 7 targets cleaner energy and efficiency by 2030 [3]. The transition to renewable sources including geothermal, hydro, solar, and wind power—not only benefits the environment by lowering carbon emissions, but also stimulates economic growth by creating new avenues for innovation and efficiency. Numerous studies have demonstrated that incorporating renewable energy can improve overall energy efficiency and create novel economic opportunities, alongside contributing to long-term environmental sustainability [4]. Within the realm of renewable energy, hydropower plays a crucial role, standing as one of the most established and widely utilized technologies [5]. Large-scale hydropower plants dominate this sector, while small and micro-hydropower systems, such as Archimedes Screw Turbines, are increasingly recognized for their ability to harness energy from low-head and ultra-low-head water sources, thus extending the applicability of hydropower to previously untapped environments [6], [7].

Micro-hydropower plants are sustainable development technologies to generate electricity for both developing and developed countries [8]. A crucial element of micro-hydropower is the turbine, which converts water kinetic and potential energy into mechanical energy [9]. Various types of turbines can be used to generate micro-hydropower, with Archimedes screw turbines being one of the most popular types of renewable energy generation [10], [11].

Archimedes screw turbine a screw-like structure rotates inside a channel or pipe to capture the energy of flowing water and transform it into power [12], [13]. The first of these devices was launched in the UK in 2004/2005 after being installed across Europe in 1994. Brada introduced the Archimedes screw as an electrical turbine in 1999, which was a major addition to the area [14]. Fundamentally, ASTs operate in a different way than most other kinds of micro hydro power turbines. The primary force behind an AST is the static pressure differentials that arise between the screw surfaces as a result of varying water levels within the inclined screw [15], [16]. In essence, the open water volumes between the screw blades provide quasi-static water pressure, which powers the AST. Compared to Pelton or Turgo impulse turbines, or Kaplan or Francis reaction-type turbines, this energy transfer method is essentially different [17]. One advantage of the Archimedes screw turbine is that it may be used in low-head situations. These sites usually have a head of water between 1-10 meters and discharge range 0.01m^3/s-15m^3/s; therefore, this makes it a great option for such settings [18], [19]. These characteristics spread the use of clean energy sources by allowing Archimedes screw turbines to be installed in a variety of environments, such as irrigation channels, river flows, and small hydropower plants [20], [21], [22]. The most affecting parameters of the Archimedes screw turbine are inclination angle, flow rate, no of blades, diameter ratio, pitch, blade angle, and rotation of the turbine [23], [24]. According to Nagel's theoretical research, the ideal ratio of shaft tube diameter to screw external diameter should be between 0.45 and 0.55 [25]. Shahverdi et al. [7] suggest the Di/Do range 0.43-0.56, P/D range 1-1.2, and the number of blades 2-4. The torque and efficiency start to decrease as the diameter ratio increases above 0.55 [26]. 3-4 blade screw is a good choice for small scale AST. The inclination angle varies according to the head availability and length of the turbine. Abdullah et al. 2021 [27] suggest that the inclination angle ranges between 25°-35°. Pitch ratio(P/Do) range 1-1.5 is suggested by Shahverdi et al. 2020 [20]. Screw turbines can operate with good efficiency at partial fill levels, although they perform best when they are nearly full but not overflowing [28].

Despite significant research on conducting testing and performance analysis of AST, most studies focus on design specification and only using experimental and numerical approaches and leaving a gap in the optimization of AST by using computational technologies for ultra-low-head applications. Limited research has been done on the full-scale performance of AST under varying flow rates and inclination angles, especially using advanced predictive tools like artificial neural networks (ANN). This highlights the need for more comprehensive experimental investigations and optimization techniques for small-scale hydropower systems.

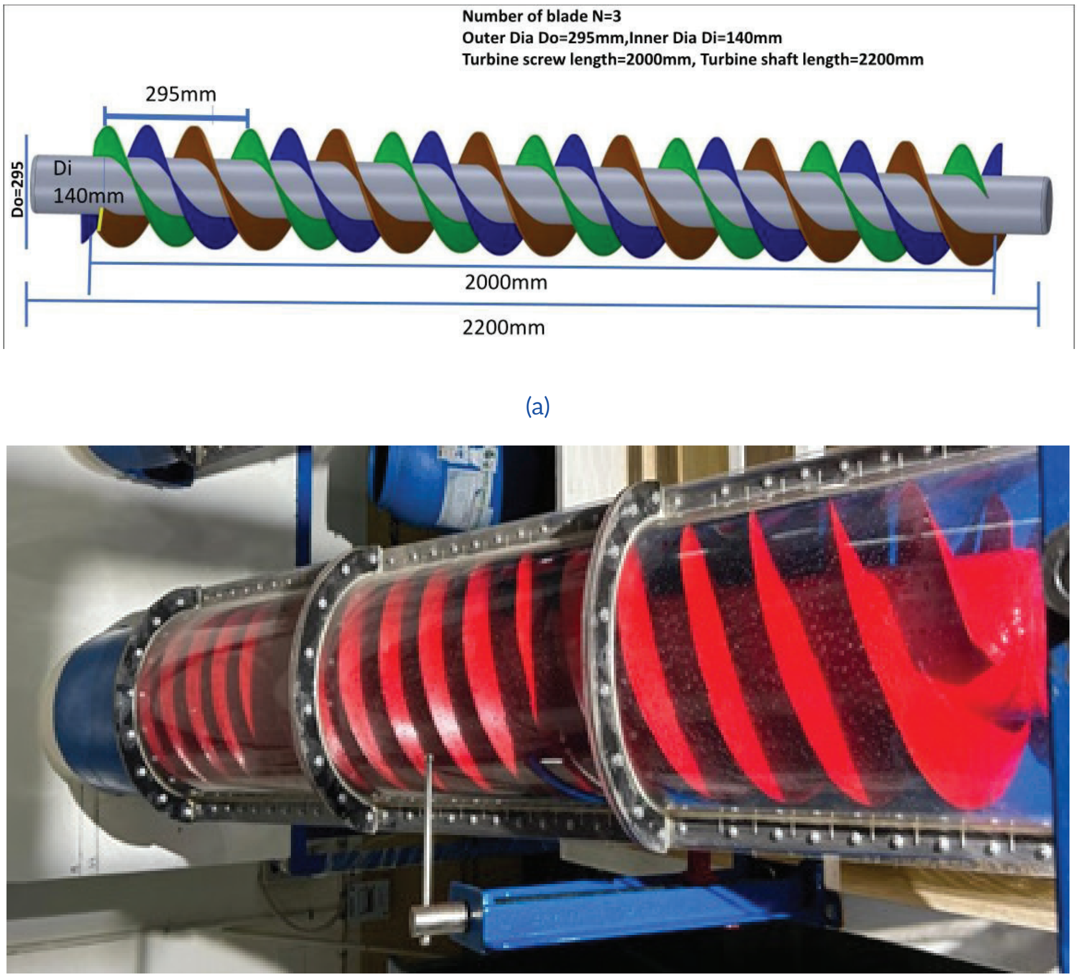
The objective of this study is to conduct a full-scale experimental investigation of the effects of varying flow rates and inclination angles on the power output of an Archimedes Screw Turbine for ultra-low-head(1-2m) applications. The novelty of this research lies in the combined use of RSM and ANN to optimize these parameters, providing a comprehensive comparison of their predictive capabilities, which has not been extensively explored in previous studies. This dual approach offers new insights into optimizing small-scale hydropower systems for real-world applications.

II. METHODS AND MATERIALS

This section outlines the experimental setup, design, and analytical approaches used to optimize the performance of the AST. It details the turbine configuration, experimental procedures, and the application of RSM and ANN for parametric optimization.

A. *Archimedes Screw Turbine Setup*

Archimedes screw turbines represent a remarkable convergence of historical ingenuity and modern sustainable technology. Water enters the mechanism at the upper segment, where its weight propels helical flights, initiating their rotation as water descends to lower levels [13], [29]. It is made up of helical blades with a pitch of p, internal diameter of Di, and external diameter of De, attached to a cylindrical shaft of length L. Figures 2(a) and 2(b) show the turbine used for this study and the specifications of the turbine are shown in Table I.



(a)

(b)

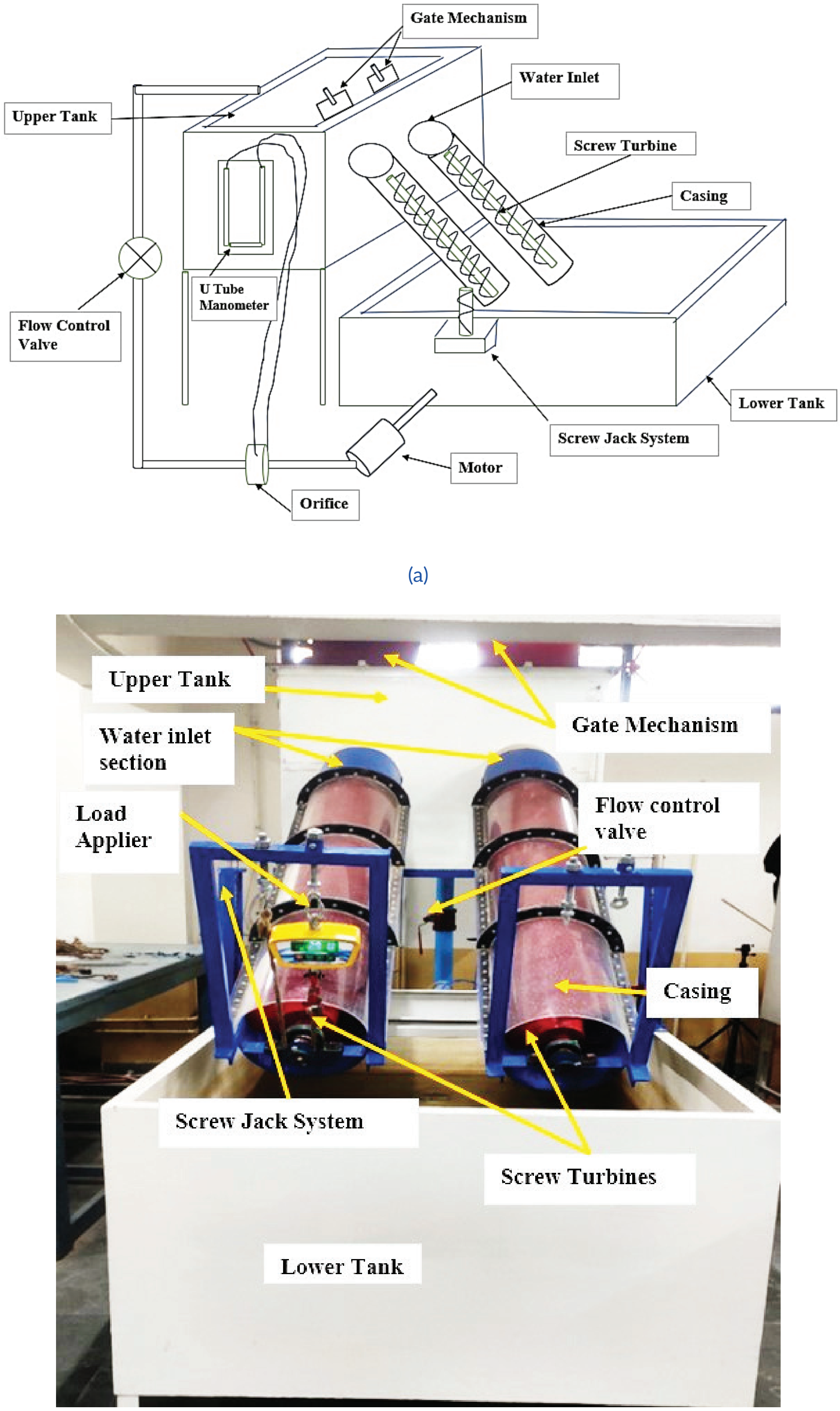
Fig. 2. (a). 3D drawing of AST (b). Actual screw turbine after manufacturing

TABLE I
AST SPECIFICATIONS USED FOR THIS STUDY.

Parameters	Symbol	Value
External diameter	*De*	295mm
Internal diameter	*Di*	140mm
Pitch	*S*	295mm
Number of blades	*N*	3
Length of shaft	*L*	2000mm
Length of trough	L_t	2200mm

B. *Experimental Setup*

The experimental data for this study were obtained using the Universal Testing Setup of an Archimedes screw turbine located at the Multiphase Flows Laboratory, University of Petroleum and Energy Studies (UPES). Figures 3 (a) and 3 (b) illustrate the schematic diagram and the experimental setup, respectively. The Universal Testing Setup comprises two reservoir tanks: A lower reservoir tank with a capacity of 2000 liters, which collects water discharged from the turbine, and an upper reservoir tank with a capacity of 1200 liters, providing the necessary hydraulic head for turbine operation. The system includes two water inlets, each with a diameter of 300 mm, facilitating the water enter into the turbine. The water flow is controlled by a gate system. Two screw jack mechanisms allow the turbine inclination angle to be adjusted within a range of 15° to 40°. Torque measurement is achieved through a rope brake dynamometer system equipped with an 80 mm diameter pulley located near the turbine outflow. Additionally, two pressure gauges are employed to monitor water movement between the lower and upper reservoirs. A 3.5-horsepower pumps water from the lower to the upper reservoir, enabling continuous operation of the system.



(a)

(b)

Fig. 3. (a). Schematic Diagram of Setup (b). Universal testing setup of Archimedes screw turbine at Multiphase flows laboratory UPES

C. *Data Recording*

The load and turbine revolutions are recorded using a load sensor, with a maximum load capacity of 200 kgs, and a tachometer. The torque on the turbine is determined using a rope brake dynamometer. Velocity data is recorded using a pygmy type water current meter, which has a measuring range of 0.1m/s to 3.5 m/s. Data generated during the experiments are continuously recorded for 5 minutes in each trial.

D. *Data Analysis*

A total of 18 trials are conducted as per the central composite design of response surface method, with each trial lasting 5 minutes. The data are processed in MATLAB, producing desired outputs such as efficiency, power available, and shaft power generated for variables such as load, water velocity, and RPM. The power output of the turbine is calculated by using the equation (1), equation (2) and equation (3).

The inlet power is calculated by:

$$P_{in} = \rho g Q H \tag{1}$$

Output power is calculated by:

$$P_{out} = \omega \times T_{screw} \tag{2}$$

$$\omega = \frac{2 * \pi * n}{60}$$

$$T_{screw} = F * r$$

The efficiency of the turbine is calculated by:

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \tag{3}$$

III. EXPERIMENTAL DESIGN

A. *Response Surface Methodology*

Design Expert 13 software was utilized to create the trials by applying Response Surface Methodology (RSM). A total of 18 experiments were conducted. An analysis of the literature reveals that factors including diameter ratio, flow rate, inclination angle, number of blades, and blade angle affect the power of AST. To determine how these characteristics affect power production, previous research has mostly concentrated on laboratory-scale analyses of these variables. Full-scale testing was carried out in this study for AST applications with ultra-low heads. For this study, two significant variables were selected in order to evaluate their effects on AST power production.: flow rate (A, expressed in liters per second) and inclination angle (B, expressed in degrees). Table II provides the lower and upper limits of these factors, which have a major impact on power production, based on existing literature. For the chosen parameters, these values served as the experimental range. The response pattern, namely the power output, was predicted using the selected parameters and their ranges, and an optimization model was created. Three primary steps made up the analysis: response surface charting, regression analysis, and analysis of variance (ANOVA).

TABLE II
PARAMETERS AFFECTING THE POWER OUTPUT.

Parameters	Unit	Lower limit	Upper limit
Flow rate	lps (liters per second)	5	15
Inclination angle	Degree	15	40

According to Central Composite Experimental Design (CCD), 18 trials are conducted. The trials are conducted in three flow conditions: 5 liters per second(lps), 10 liters per second(lps) and 15 liters per second(lps) and three inclination angles: 15°, 27.5°, and 40°, respectively. The experimental trials are shown in Table III.

TABLE III
DESIGN OF EXPERIMENT USING RSM.

Run	Flow rate	Inclination angle
1	10	27.5
2	10	27.5
3	10	27.5
4	10	27.5
5	15	27.5
6	15	40
7	10	27.5
8	5	40
9	15	15
10	10	27.5
11	10	27.5
12	10	27.5
13	5	27.5

14	10	27.5
15	10	40
16	10	27.5
17	10	15
18	5	15

B. Artificial Neural Networks

In this study, the process factors were optimized using the ANN approach. The information processing mechanism of the human brain serves as the basis for the artificial neural network (ANN). The three phases that it is mostly gathered from are the input layer, the output layer, and a few hidden layers. Each layer has a specific quantity of little individuals known as neurons that are almost entirely focused on processing constituents [30]. The ANN model of the Google Colab Python 3 was used. The correlation coefficients (R^2) and mean square error (MSE) can be used to quantify the effectiveness of the ANN process.

IV. RESULTS AND DISCUSSION

Discussion on experimental findings and the performance optimization of the AST, focusing on the effects of varying flow rates and inclination angles on power output have been conducted in this section. The results obtained from both RSM and ANN are compared to assess the accuracy and predictive capabilities of these models. The implications of the findings are discussed in the optimization of small-scale hydropower systems for ultra-low-head applications.

A. Power Output

According to the CCD, a total of eighteen runs were conducted to determine the ideal combination and impact of two parameters (flow rate and inclination angle) on power output, and the results are given in Table IV. An RSM model for power output as a function of two chosen process parameters within the given range has been created based on the results of the 18 trials. The prediction model is designated by equation (4).

$$\begin{aligned} Pout = 51.5774 - 24.8502 * F + 3.71418 * I \\ + 0.20888 * F * I + 1.68993 * F^2 \\ - 0.0784107 * I^2 \end{aligned} \tag{4}$$

Where P_{out} is the actual power generated for AST, F and I are the flow rate and inclination angle, respectively.

TABLE IV
EXPERIMENTAL VALUE AND PREDICTED VALUE OF VARIABLE (RSM).

Run	Flow rate (m/s)	Inclination angle (°)	Power (Watt) experimental value	Power (Watt) predicted value	RSM Error (%)
1	10	27.5	69.24	72.35	-4.4916
2	10	27.5	74.23	72.35	2.5327
3	10	27.5	70.21	72.35	-3.0480
4	10	27.5	73.2	72.35	1.1612
5	15	27.5	196.23	188.06	4.1635
6	15	40	203.23	207.5	-2.1011
7	10	27.5	74.23	72.35	2.5327
8	5	40	33.23	34.46	-3.7015
9	15	15	140.23	144.13	-2.7811
10	10	27.5	76.24	72.35	5.1023
11	10	27.5	68.23	72.35	-6.0384
12	10	27.5	66.23	72.35	-9.2405
13	5	27.5	43.23	41.14	4.8346
14	10	27.5	65.23	72.35	-10.9152
15	10	40	84.23	78.73	6.5297
16	10	27.5	76.23	72.35	5.0899
17	10	15	46.23	41.47	10.2963
18	5	15	22.45	23.31	-3.8307

B. ANOVA

The most effective way to assess how accurate the experiments and models are is to use the analysis of variance method (ANOVA). Table V shows the ANOVA results of the RSM for the Archimedes screw turbine. The probability of obtaining results as severe as those reported, assuming that the null hypothesis is true, is indicated by the p-value in statistical hypothesis testing. A significant model is one with a p-value of less than 0.05. The model in Table V has a p-value of less than 0.05, indicating that the model is significant and good for prediction and optimization. Conversely, a lack of fit p-value greater than 0.05 is considered non-significant, meaning there is no evidence that the model does not fit the data well. According to a study, a model is well-fitting if its R^2 value is at least 0.80 [31]. In the current study, the RSM model yielded an R^2 value of 0.9718, indicating a strong fit.

TABLE V
ANOVA OF THE RSM MODEL OF THE POWER OUTPUT OF AST.

Source	p-value
Model	< 0.0001
A-Flow rate	< 0.0001
B-Inclination angle	< 0.0001
AB	< 0.0001
A^2	< 0.0001
B^2	0.0014
Lack of Fit	0.0639

C. Parameters Effect on the Power Output of the AST

The experimental work has clearly shown that flow rate and inclination angle affect the power production of the AST. Figure 4 shows that the system power production is very small at low inclination degrees and flow rates. The power production rises in direct proportion to the increase in the inclination angle and flow rate, suggesting a correlation between these variables and the turbine performance. However, further increases in the inclination angle cause the power output to decrease after a certain point. This reduction is attributed to overfilling and leakage losses, which become more pronounced at higher inclination angles [32], [33].

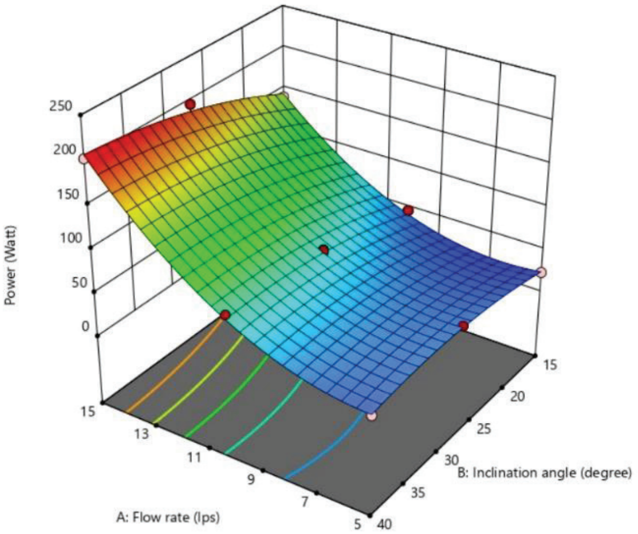


Fig. 4. Power output (watt) Vs flow rate and inclination angle

From Figure 5 it is found that the optimum value of power output is 204.16 watts. The power output increases with both flow rate and inclination angle, with the optimum performance observed at inclination angles between 35° and 40°, and flow rates between 13 liters per second (lps) and 15 lps. This result was supported by Yulistiyanto et al. [34] and Abdullah et al. [35]. The optimum criteria of parameters and power output are also shown in Table VII.

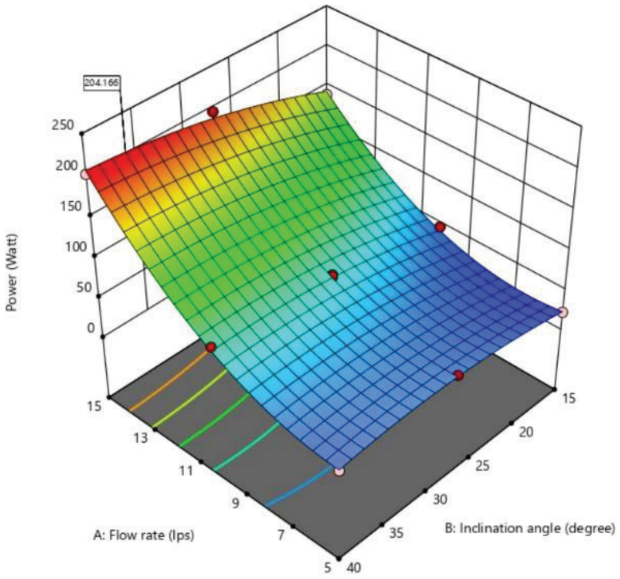


Fig. 5. Power optimum Vs flow rate and inclination angle

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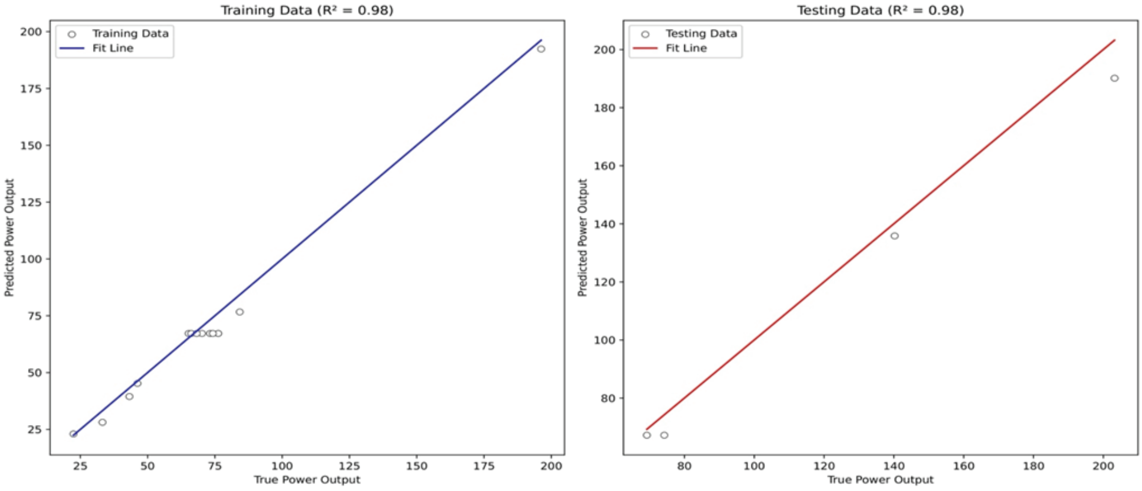
D. *Power Output Modeling Using ANN Model*

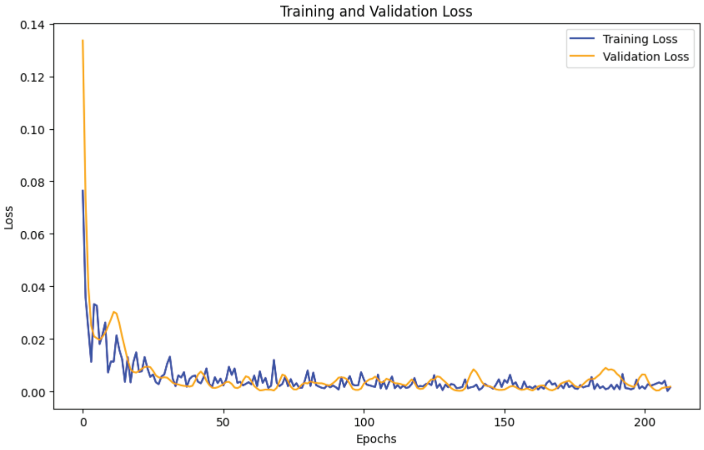
In the following experimental work, an optimized ANN model is developed that can predict power output based on flow rate and inclination angle. Initially, the data were normalized within the interval of 0 to 1, ensuring that each attribute contributed consistently. The researchers combined the normalized flow rate and inclination angle into a feature matrix, adding polynomial terms up to the second degree to capture potential nonlinear relationships between these features. In the subsequent step, the dataset was split into an 80:20 division for training and validation data. The ANN model was designed with several fully connected layers with ReLU activation and L2 regularization to avoid overfitting, while adding dropout layers to make the models more robust. To mitigate overfitting, the model was trained with early stopping, utilizing the Adam optimizer. Specifically, training was halted when the validation loss plateaued, indicating that further training would not result in significant improvements in model performance. The performance evaluation of the model was then done using the R^2 score on the validation set. Finally, the visualization is based on the actual versus predicted power output values and plotted the training and validation loss curves, which gave an insight into the model learning and generalization. The configuration of the ANN model is shown in Table VI.

TABLE VI
CONFIGURATION PARAMETERS OF ANN MODEL.

Parameter	Value/Description
Data Normalization Range	[0, 1]
Polynomial Feature Degree	2
Train-Validation Split Ratio	80-20
ANN Model Architecture	- Dense (256 units, ReLU, L2 regularization)
	- Dropout (0.3)
	- Dense (128 units, ReLU, L2 regularization)
	- Dropout (0.3)
	- Dense (64 units, ReLU, L2 regularization)
	- Dense (32 units, ReLU, L2 regularization)
	- Dense (1unit, Linear activation)
Regularization (L2)	0.001
Dropout Rate	0.3
Optimizer	Adam (learning rate = 0.0001)
Loss Function	Mean Squared Error (MSE)
Metrics	Mean Absolute Error (MAE)
Epochs	210
Batch Size	10
Early Stopping Patience	20 epochs
Validation Metric Monitored	Validation Loss
Evaluation Metrics	Root Mean Square Error (RMS error)
	R^2 Score



(a)



(b)

Fig. 6. (a). Training and Testing diagram (b). Training and validation Loss

From Figure 6 (a) the high R^2 values suggest that the model accurately predicts the power output, as the predicted values are closely aligned with the true values. R^2 value obtained through the ANN Model is 0.984921 with optimized RMS Error 0.0371. Figure 6 (b) indicates that the model has trained successfully, with both training and validation losses decreasing and stabilizing at low values, suggesting strong performance and good generalization.

E. Comparison of Experimental and Predictable Results

The experimental and predicted results were compared from both models. The R^2 value obtained from the RSM model was 0.9718, while the ANN model yielded an R^2 value of 0.9849, indicating a higher predictive accuracy for the ANN model.

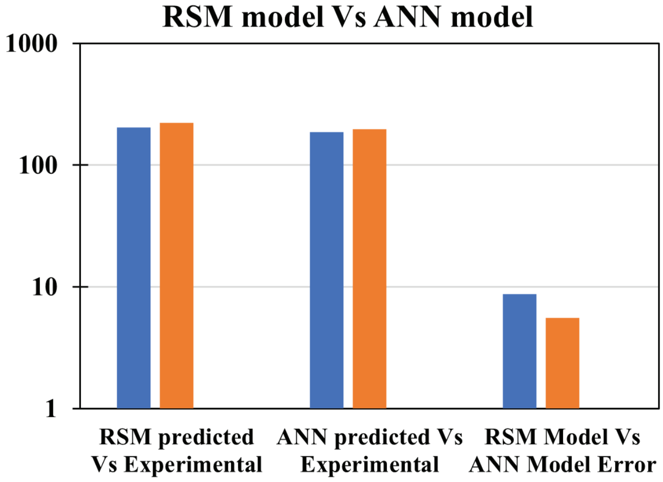


Fig. 7. Comparison between RSM and ANN Models

Table VII presents the optimized power output value for both models. The optimum power output value predicted by the RSM model was 204.16 watts, and the ANN model was 187.24 watts. According to the results, the RSM model has a higher optimized power output value than the ANN model. The experimental value of maximum power at optimum criteria suggested by the RSM model was 223.74 watts and the ANN model was 198.34 watts. The error from the RSM and ANN models is 8.75% and 5.59%, respectively. In comparison to the RSM model, the ANN model exhibits a lower error rate shown in Figure 7. Consequently, compared to the RSM mode, the ANN model shows more precision.

TABLE VII
OPTIMIZED VALUE OF THE TURBINE FOR POWER OUTPUT.

Parameters	Goal	Optimum value RSM predicted	Experimental Value	Error	Optimum value ANN predicted	Experimental Value	Error
Flow rate	range	14.58	14.58	-	13.82	13.82	-
Inclination angle	range	36.23	36.23	-	34.15	34.15	-
Power output	maximize	204.16	223.74	8.75	187.24	198.34	5.59

V. CONCLUSION

The impact of flow rate and inclination angle on the Archimedes screw turbine power production is examined in this work. RSM and ANN technologies were utilized for power output performance and analysis. The R^2 for both models (ANN and RSM) were 0.9849 and 0.9718, respectively, suggesting that the ANN model had a higher prediction accuracy. The RSM model predicted an optimized power output of 204.16 watts, achieved at a flow rate of 14.58 lps and an inclination angle of 36.23°. In contrast, the ANN model predicted an optimized power output of 187.24 watts, attained at a flow rate of 13.82 lps and an inclination angle of 34.15°. The research findings indicate that the ANN model has good predictive capability compared to the RSM model.

Future research could explore the optimization of additional factors, such as blade pitch number of blades, diameter ratio, blade angle, h/L ratio, immersion of blade to further enhance the performance of AST, by integrating real-time monitoring and control systems with advanced machine learning techniques that could improve the adaptability and efficiency of ASTs in diverse environmental conditions.

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Disclosure Statement

The authors declare that they have no known competing personal relationships that could have appeared to influence the work reported in this paper.

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