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# Numerical Investigation of Archimedes Screw Turbines under Low-Head Conditions

Muhammad Ilham Maulana[1,*], Ahmad Syuhada[1], Deendarlianto[2], Syafiie Syam[3], Fikri Fiqi Aulia[1]

[1] Department of Mechanical Engineering, Faculty of Engineering, Syiah Kuala University, Indonesia
[2] Department of Mechanical & Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, Jalan Grafika No.2 Yogyakarta, Indonesia
[3] Chemical and Materials Engineering Department, Faculty of Engineering Rabigh, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia

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**ABSTRACT**

The development of screw turbines for micro-hydro power generation has garnered heightened interest lately, attributed to their capability to perform efficiently despite low head and low discharge. The present numerical work aims to evaluate the prospect of low-head water energy widely available in the Aceh region. In this region, the Archimedes Screw turbine is the most commonly used. In the present numerical study, the characteristics of the Archimedes screw turbine were studied under the constant of the head of 1 meter and the inclination angle of 30°, with the flow rate served as the varying parameter. In the simulation, a three-dimensional numerical investigation of pressure characteristics, flow velocity, and kinetic energy turbulence due to the change in the flow rates was carried out using the Navier-Stokes equations. Next, the turbulence model of K-Epsilon was also implemented. The comparisons between the experimental and the simulation results were carried out to ensure the accuracy of the simulation model, and the results indicated that the changes in flow rates have a marked influence on pressure distribution, the flow velocity field, and turbulent kinetic energy. It was found that the performance of the Archimedes double screw turbine was improved by increasing the flow rate due to the uniform distribution of pressure, flow velocity, and turbulent kinetic energy. Moreover, the optimum condition was achieved in a turbine with 8 screws. Therefore, maintaining the inflow rate is crucial as it significantly impacts the efficiency of the Archimedes Screw Turbine.

## 1. Introduction

Renewable energy stands as a substitute for conventional fossil energy sources nowadays. Indonesia is home to significant renewable energy potential that remains underutilized to date. The current utilization of naturally generated power remains substantially below expectations. For instance, in hydropower, Indonesia has a resource potential of 94,476 MW, yet the country has tapped into only 5,976 MW of this, translating to a mere 6.4% usage [1,2].

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[*] *Corresponding author.*
*E-mail address: ilhammaulana@usk.ac.id*

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However, most existing water energy potential generally has a low head, such as irrigation and rivers [3,4]. An initiative to harness the significant potential of water as a renewable energy source involves choosing a turbine for a medium-scale power generation facility [5-7]. When dealing with low head and moderate flow conditions, an Archimedes screw turbine (AST), or Archimedes screw generator, is often a better choice than a traditional hydropower turbine. AST operates with low heads (0.1–10 m) and moderate flow rates (0.01–10 $m^3/s$) at 50% to 80% of river-to-wire efficiencies [8-12]. Some installations were reported to be more efficient [12].

Owing to their environmentally friendly (fish-friendly) design and straightforward maintenance, Archimedes turbines remain a focus for development aimed at achieving peak efficiency [13-15]. For example, Rorres [16] conducted an analysis to determine the optimal design specifications and dimensions for the Archimedes turbine [14]. In another study, Siswantara *et al.,* [17] analyzed the effect of inclination and pitch ratio on the Archimedes Screw turbine design. Furthermore, research conducted by Erinofiardi *et al.,* [18] and Lyons [19] examined the power production of Archimedes turbines in laboratory conditions, in contrast to Maulana *et al.,* [20], who performed their experimental work on small-scale turbines in an actual field environment.

Opting for numerical simulations is advantageous as they circumvent the extensive time and costs associated with experimental methods and provide clearer insights into the flow patterns characteristic of turbines. The research by Stergiopoulou and Kalkani [21] focused on enhancing the Archimedes Screw turbine, assessing the effect of axial tilt on its threads via simulations of complex three-dimensional phenomena to scrutinize the hydrodynamic behavior of such turbines. Alternatively, Dellinger *et al.,* [22] explored the characteristics of 3D turbulent flow and the resulting energy loss within turbine threads.

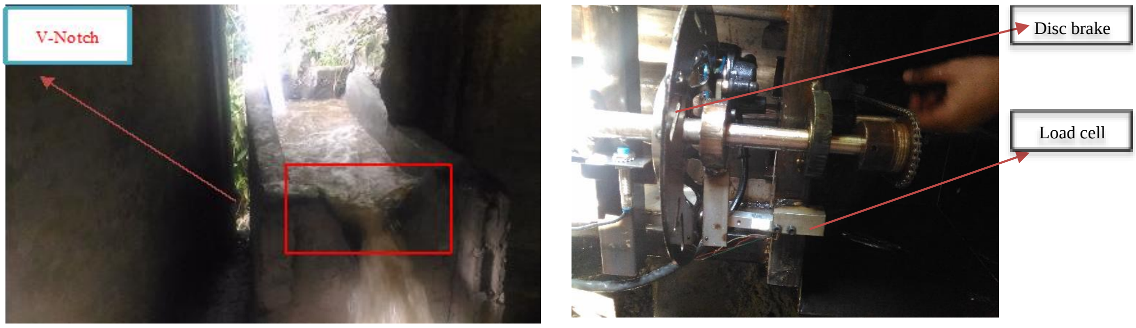
In addition, Dellinger *et al.,* [23] simulated the effects of three different blade counts (3, 4, and 5) on the AST with standard design parameters. The study revealed that screws with three blades performed optimally at lower tilt angles, while those with four and five blades reached peak efficiency when tilted between 20° and 24.5°. In comparison, Maulana *et al.,* [24] analyzed the relationship between the number of blades and the operational effectiveness of screw turbines, with an emphasis on the parameters of pressure distribution. The study highlighted the critical need to ascertain the precise measurements of the turbine, given that the quantity of blades substantially affects the pressure at the turbine's terminus. Shahverdi *et al.,* [25] investigated the performance of AST numerically using Computational Fluid Dynamics (CFD) due to different screw rotation speeds, volume flow rates, and tilt angles. This research enables us to visualize the pressure and velocity fields of the turbine. Recently, to provide valuable insights into low-head Archimedes turbines' dynamics, Maulana *et al.,* [26] characterized the two-dimensional flow performance of low-head Archimedes turbines with turbine heads of less than 1 meter. Most research points to heads exceeding 2 meters due to the effectiveness of turbines in such conditions. Although considerable potential exists for water flow at a 1-meter head, the suitable design to harness this condition has not been examined.

The present numerical study examines the influence of flow rate and blade quantity on the performance characteristics of Archimedes Double Screw Turbines with a head height of 1 meter, focusing on pressure distribution, flow velocity, and turbulent kinetic energy. The analysis was conducted based on the flow pattern characteristics in the turbine obtained using the computational fluid dynamic (CFD) commercial software of Ansys Fluent v16.0 [27]. A preliminary validation was conducted for the developed model by comparing the model's results against the torque of the experimental results taken by the Fluid Mechanics Laboratory, the Faculty of Engineering of Syiah Kuala University, in the location of Air Dingin, South Aceh [20]. Subsequently, a numerical simulation was utilized to depict the flow phenomena in Archimedes Screw Turbines, a result unattainable with experimental approaches.

## 2. Computational Model

### *2.1 Measurement of Flow Rate and Torque*

Figure 1 shows the experimental facility measuring the flow rate and torque. The actual flow rate in the field was ascertained by measuring the descent of the water level at the V-Notch tip, utilizing the established 90-degree V-notch weir discharge method illustrated in Figure 1(a). Moreover, the torque data was retrieved by the disc brake dynamometer method, which involves a load cell mounted directly on the turbine shaft, as depicted in Figure 1(b). The measurement technique was also documented by Mutasim *et al.,* [28].



(a) Standard 90-degree V-notch (b) Disc brake dynamometer

**Fig. 1.** The Method of both flow rate (a) and torque (b) measurements

### *2.2 Geometrical Parameters*

In the present study, the model geometry of the Archimedes turbines, shown in Figure 2, was created using SolidWorks software and is tabulated in Table 1. Next, the meshing process of the simulation model is carried out. The meshes partition the computational domain into minor components for computational iteration. In the present CFD simulation, the tetrahedral meshing in the turbine domain was used, as shown in Figure 3.

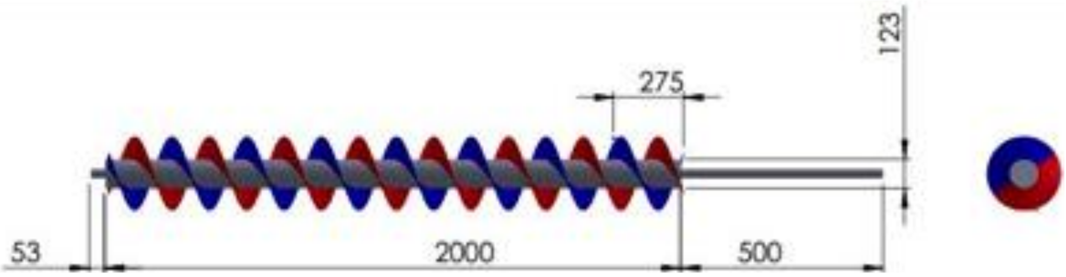


**Fig. 2.** Geometry of Archimedes double screw turbines

**Table 1**
The important geometrical dimensions

| Geometry | Size (mm) |
|---|---|
| Turbine length | 2000 |
| Pitch distance | 275 |
| Inner diameter | 123 |
| Outer diameter | 241 |

**Fig. 3.** Meshed model of turbine geometry

The procedure segments the volume of the object into small equilateral triangular units. The mesh size used has a minimum size of 0.2 mm, a maximum face size of 0.5 mm, and a maximum size of 0.8 mm.

### *2.3 Computational Setup*

In the present CFD simulation, the k-ε model is identified as the appropriate turbulence model to represent the turbulent flow defined by fluctuating velocity fields. The equation of k is formulated by Launder and Spalding [27] and Darmono and Pranoto [29]

$$\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\epsilon - Y_M \tag{1}$$

The equation ε is formulated by

$$\rho \frac{D\epsilon}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_i}\right] + C_{1\epsilon}\frac{\epsilon}{k}(G_k + C_{3\epsilon}P_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_\epsilon \tag{2}$$

In Eq. (1), $G_k$ describes the derivative of turbulent kinetic energy, which is influenced by the average velocity of the fluid, $G_b$ is the turbulent derivation of kinetic energy, which is affected by the buoyancy force of the fluid, YM shows compressible turbulent fluctuation. $C_{1\epsilon}$, $C_{2\epsilon}$ and $C_{3\epsilon}$ are constants; $\sigma_k$ and σϵ are Prandtl Numbers, as explained also by Cengel and Cimbala [30]. Furthermore, the value of constant variables used in the present CFD study is shown in Table 2.

The inlet was set as a velocity inlet, with constant velocity profiles of 0.65, 0.92, and 1.14 m/s, while the outlet was set as a pressure outlet. The velocity specification method uses a magnitude that is normal to the boundary. The Turbulence Specification Method chosen is the Intensity and Viscosity Ratio. Two boundary conditions of "wall and interior" are used as the turbine blanket wall boundary.

Data samples are gathered across the turbine to assess the impact of turbine modifications on water flow direction. Data was taken by dividing the length of the Archimedes screw turbine model into five parts, as shown in Figure 4. As shown in the figure, the location of the cut planes aims to display the value of pressure distribution, flow velocity, and turbulent kinetic energy in the turbine. The area under review is located on the inlet, about a quarter of the turbine's length, in the turbine's centre, and near the turbine outlet.

**Table 2**
Set up Values

| Variables | Specifications |
|---|---|
| Cmu | 0.09 |
| C1 – Epsilon | 1.44 |
| C2 – Epsilon | 1.92 |
| TKE Prandtl Number | 1 |
| TDE Prandtl Number | 1.2 |
| Turbulen Disipation | 1.3 |
| Fluida | Water - liquid |
| Density | 998.2 kg/m3 |
| Viscosity | 0.001003 kg/m.s |
| Solid | Stainless Steel |
| Velocity Magnitude (m/s) | 1.14, 0.92 and 0.65 m/s |
| Turbulent intensity | 5 % |
| Turbulence Viscosity Ratio | 10 |
| Gauge Pressure | 0 Pa |
| Hydraulic Diameter | 1 m |

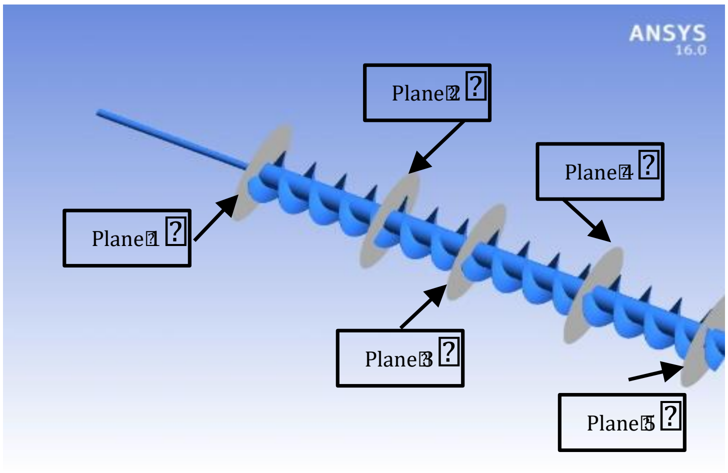


**Fig. 4.** Plane location on a turbine

## 3. Results and Discussion

Numerical simulation data reveals the interaction of pressure distribution, flow velocity, and turbulent kinetic energy within the turbine's operation. The simulation's visual results display how pressure distribution, flow velocity, and turbulent kinetic energy fluctuate when the turbine is subjected to three different flow rate changes akin to those in field situations. The pattern of changes along the turbine is characterized by changes in color degradation, as shown in the simulation results. The phenomenon that affects the turbine performance can be analyzed based on the pattern produced. Drawing on essential turbine concepts, this insight is instrumental in driving initiatives aimed at optimizing and elevating the functionality of the Archimedes Screw turbine to meet projected outcomes.

The most important thing in numerical simulations is verifying the assumptions of the governing equation models that involve the conservation of mass, momentum, and energy for a steady three-dimensional flow. This condition can be achieved by validating the built model with the real data obtained from the experiments. Furthermore, the three distribution patterns obtained from the simulation results are discussed in the following sections.

Based on the results of direct data collection from the experiment, the data were obtained at various flow rates under a constant head of 1 m. The flow discharge in field conditions was measured by measuring the height of falling water from the V-notch tip, which is set with valve openings. Then, using a 90-degree V-notch weir discharge table, the amount of flow discharge can be determined. As demonstrated in Table 3, widening the valve opening within the flow pipe approaching the V-Notch results in a rise in the water level discharged from the V-Notch and an enhanced flow towards the turbine. This condition will eventually result in increased torque produced by the turbine shaft. Furthermore, torque measurement was carried out using the disc brake dynamometer method, which uses a load cell. When the turbine spins, it places a load on the shaft, causing a friction force to act within the turbine, defined as the total of all the loads plus the force detected by the sensor.

**Table 3**
Actual Flow Rate and Torque

| Notation | Valve Opening | Flow Rate ($m^3/s$) | Torque (Nm) |
|---|---|---|---|
| Q1 | Full Open | 0.0250 | 3.33 |
| Q2 | Open 2/3 | 0.0125 | 2.05 |
| Q3 | Open 1/3 | 0.0044 | 1.16 |

After performing simulations under the same flow condition, a torque analysis from the simulation is compared with experimental results intended to serve as benchmark data for the simulation. Should the experimental values and the simulations show considerable variation and contrasting patterns, this would indicate that the simulation outcomes are not valid for reflecting actual flow scenarios. In other words, the built simulation model is not right, although it uses references from existing literature with similar conditions. Likewise, vice versa, if the values obtained are not much different, the model built to carry out numerical simulations is appropriate.

Figure 5 shows the comparison of torque between the simulation and the experiment. Close observation of the figure reveals that the torque values from the simulation and the experiment are almost the same. Both data show the same trend, whereas torque increases proportionally with the decrease in water flow rate. This condition proves that the simulation model can be used as a reference to obtain pressure characteristics, speed, and kinetic energy in the turbine.

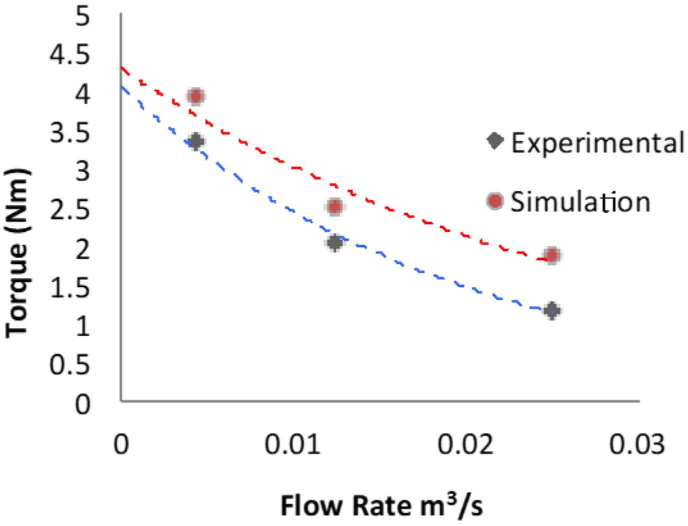


**Fig. 5.** Comparison of torque results of experiments with simulations

The calculated pressure along the screw turbine is shown in Figure 6 for different planes according to the location selection as described above. As depicted in the figure, there is a direct linear correlation between pressure and the length of the turbine trough. The change in momentum of the rotating energy of the shaft along the bucket causes the pressure reduction.

Careful examination of the diagram indicates that the pressure reduction pattern in the Archimedes double screw turbine is consistent with earlier research findings. It can be seen that the maximum flow rate (Q1) of Archimedes turbines works very optimally in comparison to that of Q2 and Q3. Q1 recorded the highest pressure at 4.88 kPa, outperforming Q2 and Q3, though it subsequently fell to 0.073 kPa on Plane 5.

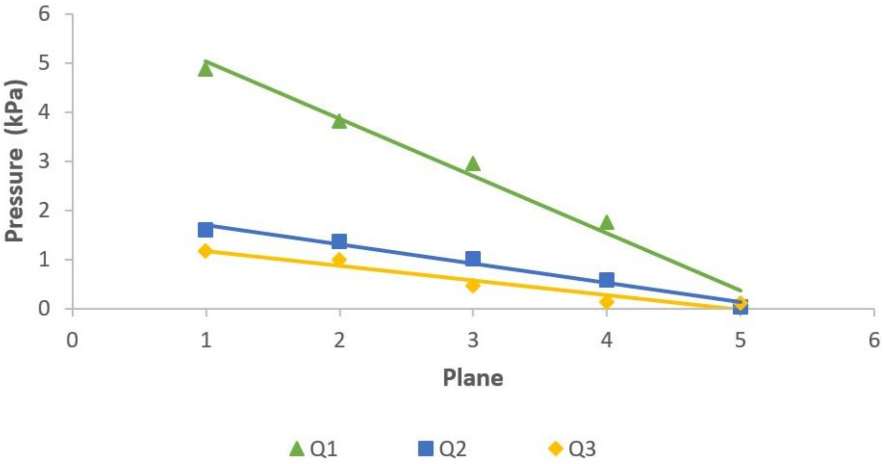


**Fig. 6.** Pressure distribution

It is essential to analyze the pressure in the screw trough, as it has a direct impact on the amount of torque the shaft yields from the turbine. To eliminate redundancy owing to the nearly identical findings across simulations, the discussion will focus on showcasing the pressure pattern for the flow velocity of 0.025 m³/s (Q1) in this part. It is postulated that the pressure in the turbine trough is mainly composed of the fluid's static pressure, as illustrated in Figure 7. In contrast, the pressure decreases along the middle of the screw trough (bottom of the domain). In the figure, the color gradation means that the turbine inlet has the greatest pressure because it is the first part hit by fluid flow and the occurrence of fluid separation to produce an initial moment to rotate the turbine [24]. The pressure will drop at the turbine's outlet due to momentum loss and flow discharge to ambient pressure.

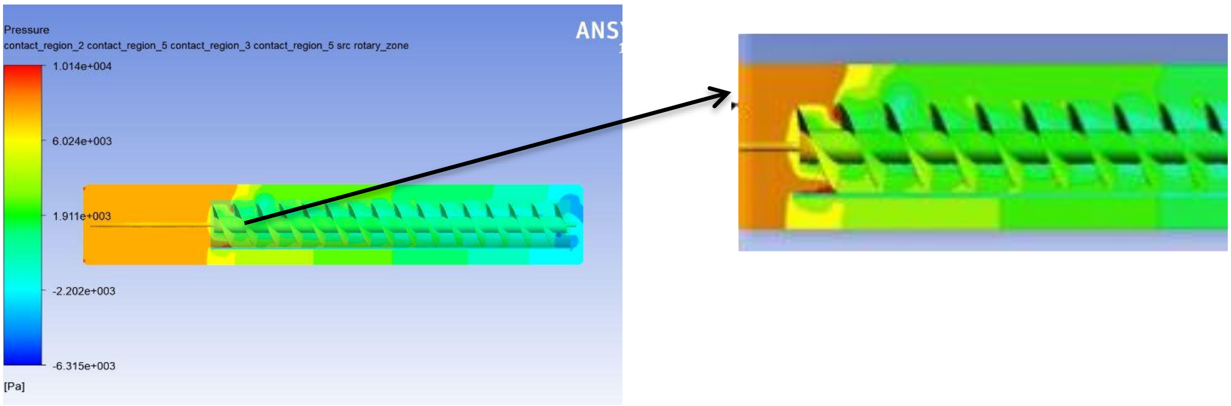


**Fig. 7.** Pressure pattern distribution in the turbines

Figure 8 shows the calculated velocity of a screw turbine under the different mass flow rates when it flows along the turbine trough from the inlet to the outlet. The velocity distribution inside the turbine shows that the increase in flow velocity along the turbine is a form of pressure change along the turbine. Under the flow discharge condition of $Q_1 = 0.05\ m^3/s$, the velocity experienced a sharp increase from 1.61 m/s at the inlet and distributed increased to 2.21 m/s in the outlet section. The increase in velocity occurs at a larger flow rate, indicating that the increase in kinetic energy is directly proportional to the initial velocity.

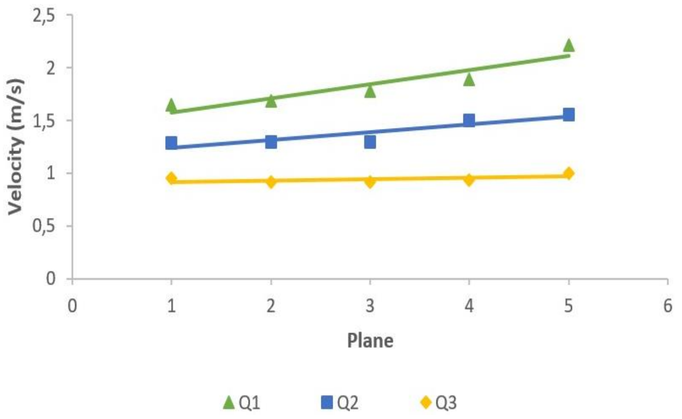


**Fig. 8.** Velocity distribution trends in the turbine

Figure 9 shows that the velocity contour experiences a gradation from dark blue at the inlet and turns red at the part leading to the turbine outlet side. The velocity will increase proportionally when the pressure is reduced, or vice versa. This phenomenon is consistent with Bernoulli's theorem, as it posits that an increase in velocity leads to a reduction in pressure, demonstrating that pressure is inversely proportional to velocity at the fluid's outlet. The effect of pressure loss has been discussed previously, namely the change in pressure into torque. The increase in velocity is partly due to the fact that, upon exiting the turbine, the fluid discharges unimpeded into the surroundings.

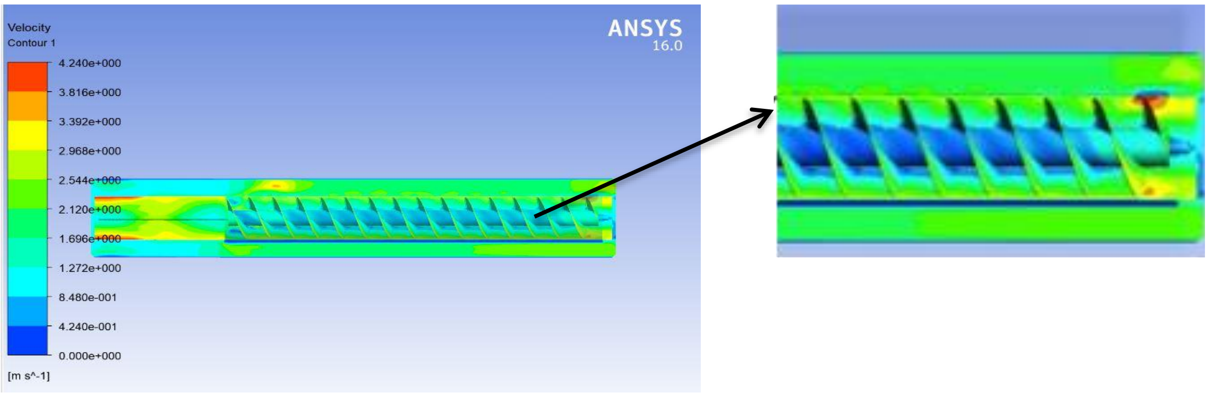


**Fig. 9.** Velocity distribution pattern in the turbine

Figure 10 shows the total turbulent kinetic energy (k) in the turbine bucket plotted on the plane along the turbine. With the increased rotational speed, turbulence within the bucket intensifies, and the kinetic energy also escalates. It is important to be noted that the kinetic energy is a function of any fluid movement in the screw's buckets in steady-state cases. As shown in the figure, if the increase in flow velocity is higher, then the turbulent kinetic energy is also higher. The higher the turbulent kinetic energy, the higher the generated power [31].

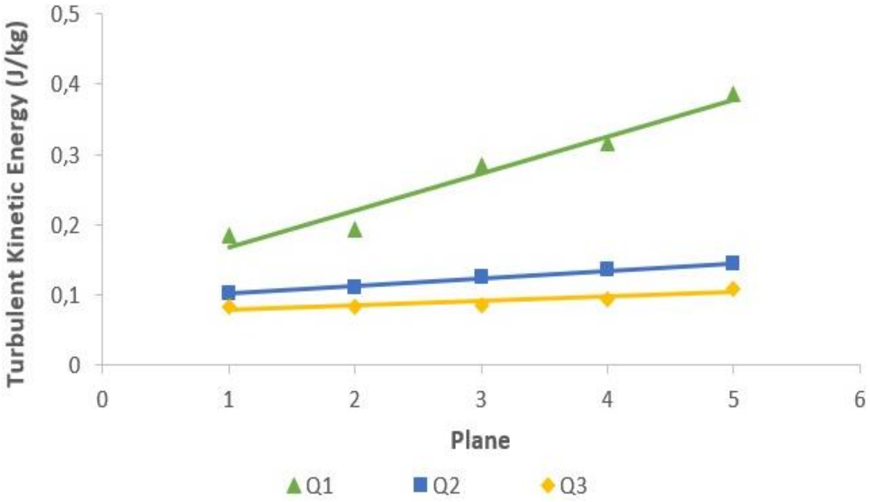


**Fig. 10.** Turbulent kinetic energy distribution trends in the turbine

A more detailed examination of the turbulent fluid kinetic energy in the bucket was achieved by sampling its distribution in the turbine's vertical plane, illustrated in Figure 11. The figure represents a distinct color gradation at each screw wall of the turbine, compared to other parts, suggesting that every thread of the turbine effectively converts flow velocity into turbulent kinetic energy.

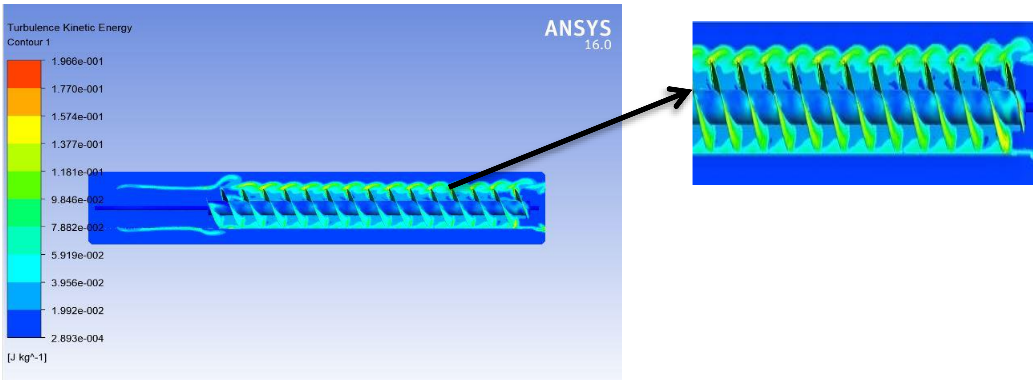


**Fig. 11.** Turbulent kinetic energy distribution pattern in the turbine

The same analysis was also carried out on the important parameters such as the pressure, speed, and turbulent kinetic energy for the turbine under the optimum conditions (maximum flow rate) to analyze the effect of the number of blades. Here, the blade number varied from 7 to 9 [20]. Figure 12 shows the pressure distribution on the Archimedes turbine under the variation of number of blades. In a turbine configured with 7 threads on its initial plane, a high pressure of 5.188 kPa is recorded, which then significantly diminishes in the next plane as a result of the screw being positioned too far, limiting the turbine blade's capacity to absorb the impact force optimally. However, the turbine, which has 9 threads, has a significant pressure drop due to the thread's distance being too close, so the initial pressure is largely absorbed in the area in the plane of part 1. The Archimedes turbine, featuring 8 threads, achieves an ideal blade count, ensuring pressure is more evenly spread across the turbine, unlike those with 7 or 9 blades where the decrease is marginal. The obtained result indicates the importance of precisely adjusting the number of turbine blades (distance between threads) because it has a very large effect on the pattern of pressure that occurs and, consequently, on the overall performance of the turbine.

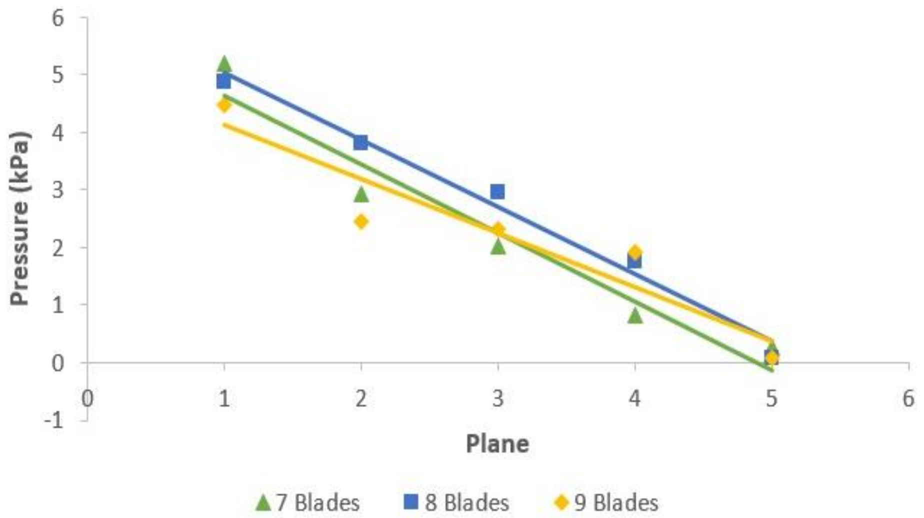


**Fig. 12.** The relationship between pressure and blade number

Figure 13 shows that the increase in the flow velocity is a form of energy transition from the pressure following the Bernoulli law, as discussed in the previous section. The highest increase point in flow velocity occurs in plane 5 (near the outlet) with a velocity value of 2.065 m/s for 7 blades, 2.212 m/s for 8 blades, and 2.17 m/s in turbines with 9 blades.

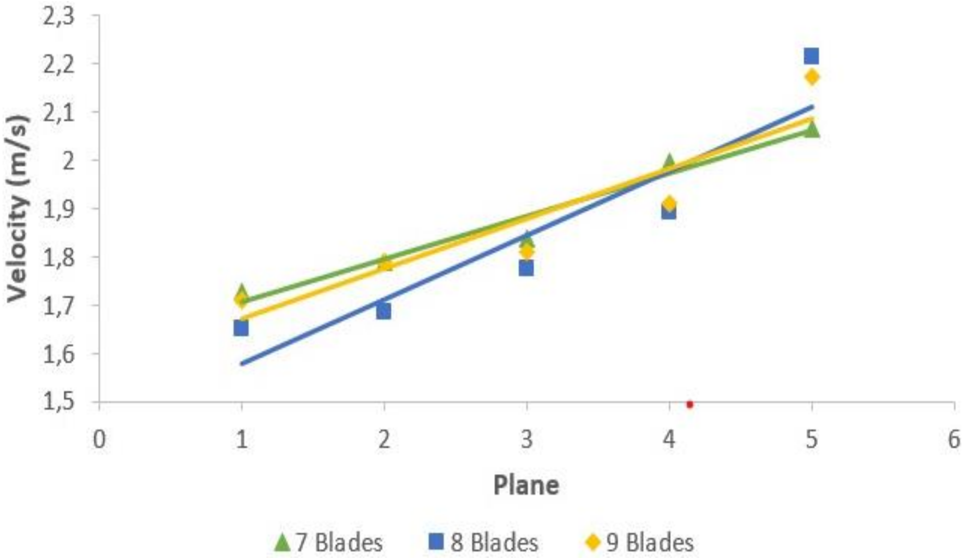


**Fig. 13.** The relationship between velocity and blade number

The influence of turbulent kinetic energy is depicted through the numerical model results for vertical planes with varying blade numbers, as shown in Figure 14. Upon careful analysis, it is evident that screw turbines with 8 blades reach peak turbulent kinetic energy due to the substantial acceleration in fluid flow velocity. The amount of kinetic energy produced increases with the flow velocity.

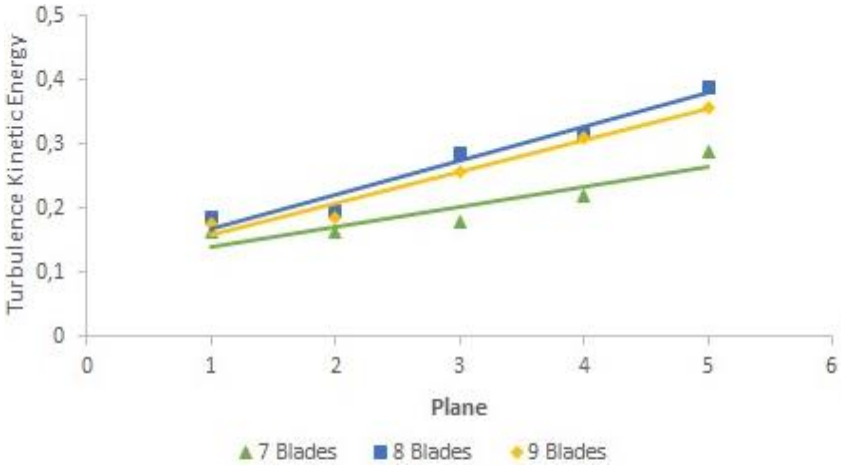


**Fig. 14.** The relationship between turbulent kinetic energy and blade number

## 4. Conclusions

The characteristics of the Archimedes screw turbine have been examined using Ansys Fluent for numerical analysis, where modifications in the fluid flow rate and blade quantity were made to observe changes in pressure, velocity, and turbulent kinetic energy distribution.

With varying flow rates, the corresponding pressure response is directly linked to the turbine's length, and the pressure reduces in a straight line as the distance increases. The distribution of the pressure, flow velocity and optimum turbulent kinetic energy in screw turbines has a better effect if the flow rate reaches the maximum value.

It was found that the performance of the Archimedes double screw turbine was increased with increasing the flow rate because it had the most uniform distribution of pressure, flow velocity, and turbulent kinetic energy. Optimal results were observed in a turbine configured with 8 screws, regardless of differing screw counts.

The number of blades affects the pressure and the turbulent kinetic energy. Optimal results were observed in a turbine configured with 8 screws, regardless of differing screw counts. The number of blades on the turbine is a determining factor in its performance.

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