Analysis on Inlet Nozzle Design Geometry of Tesla Turbine

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Abstract. Tesla turbine is a bladeless turbine that uses a set of discs arranged at a certain distance to rotate and one of the parameters controlling turbine performance is the inlet parameter. The purpose of this study is to optimize the design of the inlet nozzle and analyse its effects on the flow of the fluid. A total of four nozzle designs have been proposed using CATIA while the Solidworks Flow Simulator is used to analyse the fluid flow at various inlet velocities. Then, the most efficient design is then fabricated via 3D printing and put to test by connecting it with the actual Tesla turbine model. Through the results obtained from the analysis, it is observed that Design 4 is the most efficient of all tested nozzles and the highest RPM and output voltage achieved from the nozzle is 7940 RPM and 13.56 V. The difference in velocity and pressure increases as the area of the nozzle outlet reduces, whereas nozzle efficiency decreases as the inlet velocity increases. The result of this study is a source material for increasing the effectiveness of an alternative power turbine in generating electricity by manipulating the inlet design geometry.

1. Introduction

Due to the needs on power generation, researchers have been studying new alternatives to provide and generate power that is cheaper, more reliable, and less maintenance. First introduced in 1906 by Nikola Tesla, Tesla turbine uses kinematic viscosity and surface adhesion to convert the energy from fluid flow into rotation unlike a normal turbine does [1]. This turbine consists of two parts, the rotor and stator as noted by Zahid et al. [2]. Tesla turbine is made of a few discs fixed parallel to each other on a shaft and separated by thin gaps for the fluid to pass through. Meanwhile, the nozzle(s) are located at the periphery of the cylindrical casing and tangential to the shaft, and exhaust ports are located near the centre of the turbine. The casing, which is also a plenum chamber converts the angular momentum of the flow to the linear momentum that coming through the inlet nozzle [3]. In this turbine, the plenum chamber has the same function as the guide fans in a typical turbine [2]. Sengupta [4] and Guha et al. [5] believed that fabricating and maintaining a Tesla turbine is uncomplicated and that the turbine has a high power to weight ratio with significant emission while operating on a low noise level. Zahid et al. [2] believed that this turbine is environmentally friendly since non-polluting fluid is used. Due to the simple construction, Lampart et al. [6] said that the turbine is simpler to operate, as no operator is needed to run it and the on-off operation is simple.
A Tesla turbine has many advantages which makes it better compared to regular turbines especially in a small-scale power generation. Since patented in 1913, various research has been carried out to improve this machinery. For Tesla turbine, there are many parameters that will affect the performance, such as rotor geometry, the gap between the rotors, and the material used, for instance. By using alternative-powered driven turbines, energy can be generated when the conventional turbine is unsuitable; such as small scale power generation [7] or limitation of the fluid used [8]. It is highlighted by Guha et al. [5] that the nozzle and inlet is one of the restrictors for this turbine. Mainly, the problem is due to the challenging aspect of applying an efficient inlet nozzle to this turbine as many factors restrict the nozzle, thus limiting the use of this turbine [9].

2. Methodology
In this section, the research methodology is explored for achieving the stated objectives of the study. The methodology is essentially divided into two sections, simulation work and experimental setup.

2.1 Design and simulation
From studies by Bhattacharyya [8] and Guha [5], the nozzle design criteria for the Tesla turbine should:

1. Direct the working fluid between the disc gaps.
2. Allow multiple nozzle geometries to be tested without changing the turbine casing.
3. Allow nozzle efficiency to be tested separately from turbine efficiency.

For conditions 2 and 3, it can be achieved through the design of the casing and interchangeable nozzle as in figure 1 and figure 2. The interchangeable nozzles parameters are all the same, except for the geometries of the orifice. The effect of these differences is studied through simulation using Solidworks Flow Simulation.

Figure 1. Casing with an inlet slot.

Figure 2. Interchangeable nozzle design for casing integration.
Design of the Tesla turbine model is illustrated in figure 3 while the dimensions of the parameter are shown in table 1. The complete model of the turbine is generated by referring to the actual Tesla turbine model used for compress air generator.

![Tesla turbine assembly design](image1) ![Tesla turbine model in exploded view](image2)

**Figure 3.** Design of the Tesla turbine model used for this study.

| Parts                  | Size     |
|------------------------|----------|
| Diameter of inner turbine casing | 180 mm   |
| Diameter of disk       | 120 mm   |
| Diameter of shaft      | 10 mm    |
| Thickness of disk      | 1 mm     |
| Disk Gap               | 0.5 mm   |
| Number of disks        | 8        |

**Table 1.** Dimension of the Tesla turbine model.

Then, four different cavities and geometries were created to observe the relations between the nozzle designs of the inlet and outlet nozzle towards the velocity and pressure of the fluid flow. The nozzle designs and specifications are presented in figure 4 and table 2, respectively.

![Nozzle 1. Circular tube type nozzle.](image3) ![Nozzle 2. Rounded rectangle type nozzle.](image4)

**Figure 4.** Design of the Tesla turbine model used for this study.
Table 2. Design type of the inlet and outlet nozzle.

| Design | Nozzle inlet design | Nozzle outlet design type |
|--------|---------------------|--------------------------|
| 1      | Circular tube       | Circular tube            |
| 2      | Rounded rectangle   | Rounded rectangle        |
| 3      | Circular tube       | Rounded rectangle        |
| 4      | Circular tube       | Array of rounded rectangle |

For simulation, the turbine design is fixed except for the inlet nozzle. Each of the design is tested via simulation with a variation of inlet velocity of 20 m/s, 25 m/s, 30 m/s, 35 m/s, and 40 m/s as the inlet boundary conditions while the environment pressure (101.325 kPa) is set for the outlet. In the simulation, the air is used as the working fluid and the simulation is done in Solidworks Flow Simulation. The results are then analysed and discussed.

2.2 Calculation

2.2.1 Fluid flow

The flow of the fluid is affected by Reynolds number [9] and can be divided into two types, which are compressible and incompressible depending on the density of the fluid [10]. When the density of fluid relatively constant throughout the flow, it can be said as incompressible, and vice versa. The Reynolds number can be calculated by using Equation (1) and the hydraulic diameter can be obtained from Equation (2). Both equations can be referred to this article [6].

\[
Re = \frac{\rho V_{avg} D}{\mu}
\]  

(1)

Where:
- \(Re\) = Reynold number
- \(V_{avg}\) = velocity average
- \(D\) = hydraulic diameter
- \(\mu\) = viscosity

\[
D = \frac{4A_o}{p}
\]  

(2)

Where:
- \(D\) = hydraulic diameter
- \(A_o\) = outlet area
- \(p\) = wetted perimeter

2.2.2 Efficiency

The efficiency of this turbine is calculated by using the formula shown in Equation (3), where \(P_{01}\) is the head and \(\Delta P\) is the head loss. To get \(P_{01}\), Equation (4) from [10] can be used, and \(\Delta P\) can be calculated as stated in this article [11]. Noted that the efficiency of the turbine decreases with the increase in rotational speed [12].

\[
\eta_{system} = \frac{P_{01} - \Delta P}{P_{01}} \times 100
\]  

(3)

Where:
- \(\eta_{system}\) = efficiency
- \(P_{01}\) = total head
- \(\Delta P\) = head loss


Where:
\[ P_{01} = H = \text{total head} \]
\[ P = \text{pressure} \]
\[ \rho = \text{density} \]
\[ g = \text{gravity} \]
\[ V = \text{velocity} \]
\[ z = \text{elevation} \]

(4)

\[ \Delta P = \Delta P_{in} - \Delta P_{out} \]

Where:
\[ \Delta P = \text{head loss} \]
\[ \Delta P_{in} = \text{head loss at inlet} \]
\[ \Delta P_{out} = \text{head loss at outlet} \]

(5)

\[ \Delta P_{in} = \varepsilon \frac{V_{in}^2}{2g} \]

Where:
\[ \Delta P_{in} = \text{head loss at inlet} \]
\[ \varepsilon = \text{area ratio} \]
\[ V_{in} = \text{velocity at inlet} \]
\[ g = \text{gravity} \]

(6)

\[ \Delta P_{out} = \frac{V_{out}^2 - V_{in}^2}{2g} - \frac{\rho_{out} - \rho_{in}}{\rho g} \]

Where:
\[ P_{01} = H = \text{total head} \]
\[ P = \text{pressure} \]
\[ \rho = \text{density} \]
\[ g = \text{gravity} \]
\[ V = \text{velocity} \]
\[ z = \text{elevation} \]

(7)

\[ \varepsilon = \left(1 - \frac{A_{in}}{A_{out}}\right)^2 \]

Where:
\[ \varepsilon = \text{area ratio} \]
\[ A_{in} = \text{cross-sectional area at nozzle inlet} \]
\[ A_{out} = \text{cross-sectional area at nozzle outlet} \]

(8)

2.3 Experiment setup

From the simulation analysis, the most efficient nozzle is selected and fabricated using 3D printing (Fused Deposition Modelling) with ABS filament as the material. In this study, Nozzle 4 is printed to be tested on the actual Tesla turbine. Before testing, the printed nozzle is attached with a connector to connect it to the air supply from the compressor. The finished attachment of the nozzle is shown in Figure 5. The experiment setup and the descriptions are shown in Figure 6 and Table 3, respectively.
Figure 5. Finished printed nozzle.

Figure 6. Experimental setup

Table 3. Table of description for the experimental setup.

| Number | Name                          | Description                                                      |
|--------|--------------------------------|------------------------------------------------------------------|
| 1      | Tesla turbine                 | To test the nozzle design                                        |
| 2      | High torque brushless DC motor| To connect to turbine for voltage check                          |
| 3      | Air hose                      | To supply air from compressor to turbine through nozzle          |
| 4      | Pressure regulator            | Control pressure                                                 |
| 5      | Flowmeter                     | To measure the flow velocity                                     |
| 6      | Tachometer                    | To measure the RPM of turbine’s shaft                            |
| 7      | Multimeter                    | To measure the voltage produced                                  |
2.3.1 Velocity test
Due to the limitation of the flow meter used which can only measure velocity up to 45m/s, it is decided to run the experiment different from the simulation inlet velocity, to prevent damage to the flow meter. Therefore, the simulation is done with the variation of inlet pressure which is controlled through the pressure regulator. The inlet pressure varies from 1.0 - 2.0 kgf/cm² which is less than 15m/s when tested with the compressor air hose. The first velocity test is to find the outlet velocity coming from the nozzle with the given pressure. The flowmeter is placed in front of the nozzle outlet where the inlet is connected to the air hose. Then the compressor is turned on at 1.0, 1.2, 1.4, 1.6 and 2.0 kgf/cm². The reading is measured 3 times and the average is recorded. Then the nozzle is connected to the Tesla turbine. The flowmeter is placed in front of the turbine exhaust port. The compressor is switched on with the same inlet pressure as before. The exhaust velocity reading is measured 3 times and the average is recorded.

2.3.2 RPM test
This test is conducted to find out the RPM of the turbine without applying any load at given inlet pressure as stated in the velocity test. To conduct the test, a reflective sticker is placed on the shaft of the turbine. Then, the tachometer is pointed towards the shaft at a perpendicular level when the turbine spins, as shown in Figure 7. The reading from the tachometer is taken 3 times and the average value obtained is recorded.

In the final test, the output voltage produced is examined. Firstly, the shaft of the motor and the turbine is connected by coupling. Then, the compressor is turned on with the same inlet pressure as before. Then, the multimeter is connected to the motor as shown in Figure 8 to measure the output voltage. The reading is taken 3 times, and the average value obtained is recorded.

![Figure 7. Tachometer pointed towards shaft for RPM test](image)

![Figure 8. Multimeter measuring motor voltage.](image)
3. Result and discussion

3.1 Virtual analysis results

3.1.1 Nozzle velocity analysis

In figure 9, the outlet velocity is directly proportional to the inlet velocity for Nozzle 1 and 2 due to the same inlet and outlet velocity. Meanwhile, for Nozzle 3, the values of outlet velocity significantly increase for each inlet velocities. This applies for Nozzle 4 too. Out of the four designs, Nozzle 3 produced the highest outlet velocity for the inlet nozzle. However, at 40 m/s inlet velocity, Nozzle 3 and 4 have similar outlet velocity.

![Figure 9. Graphical result of nozzle outlet velocity at different inlet velocity.](image)

The velocity increments, especially in Nozzle 3 and 4 is similar due to the small outlet area compared to Nozzle 1 and 2. The fluid needs to move faster to maintain the same mass flow rate with that at the inlet nozzle. This phenomenon is known as the principle of mass conservation, where the mass flow rate will be constant in a closed system [10].

The hydraulic diameter is then calculated, and the Reynolds number is obtained. The graphical result of the Reynold number is illustrated in figure 10.

![Figure 10. Graphical result of Reynold number at different inlet velocity.](image)
In internal flow, when \( \text{Re} \leq 2300 \), the flow is laminar while the flow is turbulent when \( \text{Re} \geq 4000 \). Transitional flow occurs for the Re value is between laminar and turbulent. From figure 11, all the flows are turbulent since all the Re is above 4000 due to the low viscosity of air especially at high velocities. Therefore, the fluid motion tends to be disorganized and highly irregular, causing the velocity, pressure, and other parameters values to be varied.

3.1.2 Nozzle pressure analysis
From figure 11, a small pressure difference occurs in Nozzle 1 and 2. For Nozzle 3, a larger pressure difference occurs especially at 40m/s inlet velocity and the highest pressure drop occurs in Nozzle 4. This occurs due to Bernoulli’s principle where pressure will drop inversely to velocity. The kinetic energy in the system will increase proportionally with velocity. Since the total energy is constant for incompressible flow, the increase in kinetic energy, the pressure from the part of the flow energy will be reduced [13].

![Figure 11](image.png)

**Figure 11.** Graphical result of pressure difference at different inlet velocity.

3.1.3 Simulation of nozzle design applied to turbine model
From figure 12, there are significant changes in the fluid's velocity when it leaves the nozzles and when it exits the turbine. The drops in velocity are due to the fluids have travel into the turbine plenum, and spiral down along the discs of the Tesla turbine and exit through the exhaust ports. As it travels along the flow path line, the fluid loses kinetic energy, thus the velocity slows down.
3.1.4 Nozzle efficiency

From Figure 13, it is found that the nozzle efficiency decreases when the inlet velocity decreases. The decreasing of the inlet velocity is affecting all four nozzle designs. Meanwhile, it also can be seen that among the designs, Nozzle 2 is the least efficient whereas Nozzle 4 has the highest efficiency out of all four designs. The highest efficiency for Nozzle 4 occurs at an inlet velocity of 20 m/s.

The total head and pressure head also affecting the efficiency of the turbine. Based on the calculation, Nozzle 2 is the least efficient design out of the four is due to the least value of pressure head and velocity head, thus contributing to the smallest total head. This is because the velocity and pressure difference in this design is low. The opposite of Design 2 can be seen in Nozzle 4. Nozzle 4 is the most efficient because it has the lowest head loss compared to other designs, even though Nozzle 3 has a larger total head compared to Nozzle 4. The pressure difference between the inlet and outlet will increase when the velocity increase. The increment in the pressure difference contributes to larger head loss, explaining the drop-in efficiency with an increase in velocity [9]. Based on the simulation results, Nozzle 4 is selected as the best design to be fabricated with the Tesla turbine model.

Figure 12. The fluid flow trajectories from the inlet of the nozzle towards the exhaust turbine.
Figure 13. Graphical result of efficiency at different inlet velocity.

3.2 Experimental analysis

3.2.1 Experimental results of nozzle design applied to turbine model
Due to instrumentation limitation, the inlet velocities cannot be confirmed to match the simulation. The experiment is done with inlet pressure variations from 98.07-196.13 kPa. The test is not conducted beyond 196.13 kPa to avoid discs damage.

From table 4, velocity for both nozzle outlet and turbine exhaust increase when the inlet pressure increases. The increase in pressure means a larger mass flow rate went into the nozzle, gaining more kinetic energy and increasing RPM. The voltage increases when the pressure inlet increases. Since this corresponds to a faster shaft rotation, 12V output DC voltage is obtained, thus the minimum requirement as energy generation is achieved.

Table 4. Table of experimental results.

| Inlet pressure (kPa) | 98.07 | 117.68 | 137.29 | 156.91 | 176.52 | 196.13 |
|----------------------|-------|--------|--------|--------|--------|--------|
| Nozzle outlet velocity (m/s) | 14.30 | 18.60  | 23.50  | 24.60  | 25.30  | 30.10  |
| Turbine outlet velocity (m/s) | 2.70  | 3.06   | 3.31   | 3.97   | 4.37   | 5.03   |
| RPM without load | 4876  | 5603   | 60006  | 6634   | 7518   | 7940   |
| Output voltage (V) | 5.46  | 8.10   | 8.92   | 10.59  | 12.01  | 13.56  |

4. Conclusion
Four types of nozzles with different geometries were designed, utilizing an interchangeable nozzle concept to be tested independently and limiting the needs to change the turbine design to test different nozzle. Each design is tested with the same boundary conditions from an inlet velocity of 20 m/s to 40 m/s with an increment of 5 m/s per test. From the results, it is found that in Design 1 and 2, the inlet and outlet conditions have similar velocity and pressure. Design 3 and 4 show their capabilities to increase the outlet velocity significantly compared to their inlet velocity. When each of the nozzle designs is modeled into the turbine respectively and simulated, the results show the same patterns, although the values at the turbine exhaust significantly drop compared to the nozzle outlet. This is
predictable since the fluid loses kinetic energy as it travels inside the turbine plenum. Then, the total head and head loss is calculated to find the efficiency.

In this research, the fluid is injected into the turbine is at a horizontal angle of 180°, therefore, to optimize the performance of the Tesla turbine, further study can be done to test the most efficient fluid injection angle to deliver the most power to the turbine discs.

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