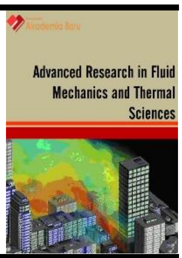
Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 62, Issue 1 (2019) 122-137

Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



The Tesla Turbine – A Comprehensive Review

Open Access

Mohammad Zuber[1,*] , Adithya Ramesh[1], Darpan Bansal[2]

[1] Department of Aeronautical & Automobile Engineering, Manipal Institute of Technology, Manipal, India
[2] Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal, India

ARTICLE INFO

Article history:
Received 23 March 2019
Received in revised form 3 May 2019
Accepted 23 September 2019
Available online 24 October 2019

Keywords:
Nikola Tesla; bladeless turbine; Tesla turbine; microscale power generation; Prandtl turbine; boundary layer

ABSTRACT

One of Nikola Tesla's greatest inventions which never saw mass production was a revolutionary bladeless turbine, commonly referred to as 'Tesla turbine'. The lack of technology and knowledge during Tesla's time handicapped the development of this radical design. With no blades, this turbine uses frictional and viscous forces to drive a set of stacked discs. These forces are responsible for losses in conventional turbines. Researchers have tried to develop the turbine, but have never achieved the efficiencies predicted by Nikola Tesla. Tesla's original design was meant to replace the then inefficient full-scale turbines. However, research over the years on various scaled designs of the Tesla turbine has shown that it is most effective for microscale power generation. Though this is in contrast to Tesla's original vision, it is still a great revelation as conventional turbines suffer large losses in the microscale domain. The Tesla turbine is also called the Prandtl turbine and the boundary layer turbine, as it uses the phenomenon of the boundary layer as the main driving force. This paper aims to compile the works done on this turbine over the years and to present important information under the categories of different parameters that have been studied.

1. Introduction

The ever increasing demand for energy coupled with environmental deterioration is defining the macroeconomic world order of today. There is a greater impetus towards renewable energy sources to mitigate the increasing global energy consumption. The utilisation of low grade heat sources, such as geothermal energy [1, 2], solar energy [3, 4], biomass energy [5, 6], and waste heat [7, 8], has attracted broad attention in recent years. The conventional turbines make use of superheated steam as the working fluid. These types of systems require high grade turbines, and their performances are limited due to the use of saturated steam. Also, when scaled down, traditional turbines need to run at very high rotational speeds to achieve favourable pressure ratios. This, when combined with a small mass flow rate condition limits their practical applications [9, 10]. Sub-watt scale power generation has applications in scenarios where fuel or electricity are not available [11], and energy

* *Corresponding author.*
E-mail address: mohammad.zuber@manipal.edu (Mohammad Zuber)

must be harvested from the environment. Potential applications include small flying systems that need to recharge between missions, especially those deployed for extended periods, or sensor nodes and other repeaters. Ho-Yan [12] describes the potential of the turbine as a means of generating electricity in rural areas using hydropower. With a MATLAB code using equations derived by Rice 1965 [13], Ho-Yan [12] was able to predict the efficiency of the turbine in this application and underscore the potential.

Currently, most portable devices use batteries for deriving their power needs, but they have several disadvantages, such as, limited specific energy and long recharge times. However, fuel, on the other hand, has comparatively very large specific energy and can also be quickly refilled. This can significantly minimise the downtime of devices [14].

The power density of a turbomachine can be shown to be inversely proportional to the turbine size [14], as described by Eq. (1)

$$\frac{P}{V} \propto \frac{1}{D} \tag{1}$$

where P is pressure, V is volume, and D is diameter.

Therefore, using multiple smaller machines can result in a reduction in the total mass and volume to produce power. Another advantage is the small inertia of these devices, which enables them to be quickly started or stopped. Therefore, by a pulsed operation, it is possible to run them only at their most optimum design conditions. This avoids inefficiencies associated with operation at off-design conditions [15, 16]. Lastly, by using multiple micropower generation devices instead of a single larger system, there is an increase in reliability due to redundancy [14]. Decuypere *et al.,* [17] while talking about the advantages of small gas turbines reaffirms the same. Smaller gas turbines offer higher power densities and increased redundancy and reliability. This also offers weight savings.

On the contrary, a major problem of developing scaled down versions of conventional gas turbines is that the rotational speed required to produce a certain pressure ratio increases to extremely high values (870,000 RPM [10]). This is because the pressure ratio of a centrifugal compressor is a function of the rotor tip speed [10]. These high rotational speeds can limit the possible applications for the system, as the stability, safety and performance of the bearings and mounting apparatus become critical. Although the power density increases with miniaturisation, the Reynolds number decreases with it, which in turn reduces the power density [14]. In addition to this, the fabrication of small turbines is complicated and not as accurate as their large scale counterparts [14].

An attractive alternative to conventional micro-turbines for power generation is the simpler Tesla turbine, which was a radical design patented by Nikola Tesla in 1913. The turbine consists of a set of stacked discs, as opposed to the blades present in a conventional turbine. The Tesla turbine is also known as a bladeless turbine. It was first designed as a replacement for the then inefficient conventional turbines generating electricity from steam. The Tesla turbine uses the boundary layer of the working fluid to transfer momentum between the fluid and the discs. Therefore, it relies on the frictional and viscous forces, which are the factors that cause losses in conventional turbines. It is also known as a Prandtl or a boundary layer turbine.

Several studies have been carried out on the Tesla turbine, both with numerical/ analytical [12, 13, 18, 26-30, 35, 38-40, 44, 45, 47-52] and experimental contents [9, 10, 22-24, 27, 28, 31-33, 35-37, 39, 43]. Almost all numerical simulations consider the working fluid as incompressible. In experimental tests, the working fluids are generally air or water. Tesla turbines have a simplified mechanical structure as compared to conventional turbines, which results in lower manufacturing and maintenance costs. Another noted advantage is its ability to use viscous fluids and fluids with particulate matter as the working medium. The turbine can also be used as a pump by reversing the inlet and exhaust holes. Since it utilises the viscous forces, fluids like blood that have a high viscosity can be pumped through it efficiently. According to Tesla, the bladeless turbine could reach efficiencies very high efficiencies [18]. Only a few full-scale turbines were manufactured for testing, in which Tesla noticed that the discs warped under high loads. Restricted by the metallurgical capabilities of that time, Tesla could not successfully implement this design for large scale production.

Boyd and Rice [19] identified the nozzle design and nozzle-rotor interaction as the main contributors to efficiency loss. Several idealisations are also associated with the performance calculation, including assumptions of laminar, incompressible Newtonian fluid flow, and accounting only for losses due to the flow between discs. Losses resulting due to the nozzle design, nozzle-rotor interaction, rotor-housing disc friction, bearings, and exhaust passage pressure change are also not accounted for [20-21]. With a proper design for the nozzle, the Tesla turbine can achieve yields similar to those found in conventional turbines for micro-power generation. The overall performance of Tesla turbines can be increased through the development of more efficient nozzles [22]. Most authors agree that this turbine is a pure impulse turbine since a large pressure drop occurs across the nozzle, and a small drop across the rotor discs [23, 24].

In this review, the advances in the construction of the Tesla turbine are discussed. The underlying issues in developing a highly efficient Tesla turbine are articulated.

2. Construction and Working

The turbine is made up of a set of stacked circular discs referred to as a rotor. The spacing between the discs when optimised is equal to twice the boundary layer formed by the fluid on the disc [25]. The discs are mounted on a central shaft with spacers in between them providing the necessary gap. This rotor stack is enclosed in a casing with minimal gap (for maximum efficiency of freely rotating discs [26]) present between the casing and the rotor. The discs have exhaust holes close to the shaft to allow the fluid to leave the gap between the discs. The size and position of these holes are optimised to allow the longest circular path of the fluid before it exits, for maximum energy transfer. At either end of the rotor is a stator. The stators are fixed and also have exhaust holes to allow the fluid to leave the turbine. Figure 1 shows a blown up view of the turbine with its major components, as envisioned by the authors of this paper.

The fluid enters the turbine in the spaces between the discs through nozzles at a suitable angle. When it comes in contact with the disc surface, a boundary layer develops. Shear stresses are generated due to the viscosity of the fluid and gives rise to a torque, allowing for work to be done by the fluid [22]. The rotor is set in motion due to this transfer of energy and momentum, and picks up speed over time as the fluid settles in the turbine. The fluid follows a spiral path as it loses energy and moves toward the shaft. When it encounters the exhaust holes, it flows out through them to the adjoining inter-disc gap. The fluid collects in the gap and continues moving outward till it reaches the stator. Through the exhaust holes in the stator, the fluid exits the turbine.

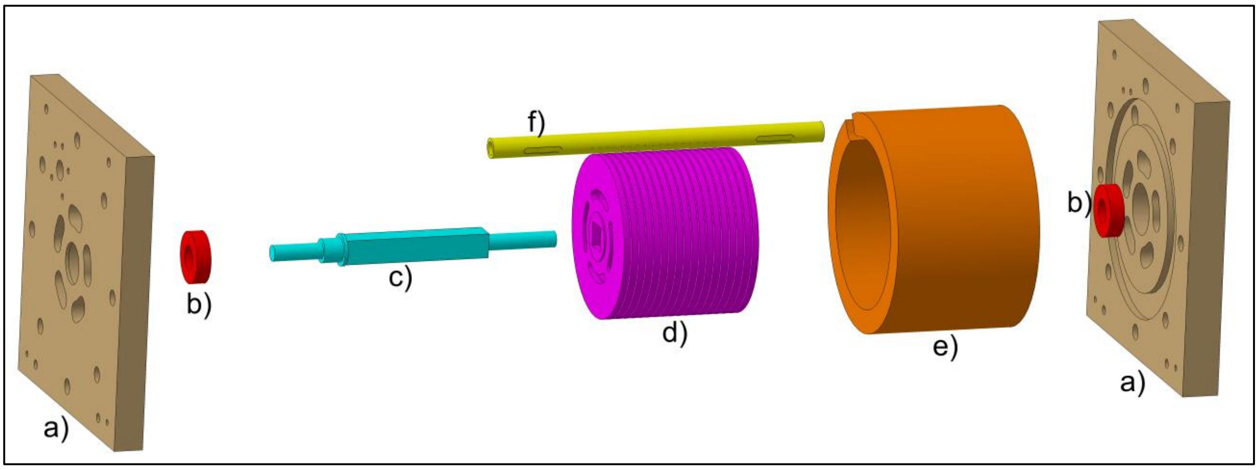


Fig. 1. The authors' rendition of the Tesla turbine with all major components – (a) brown: stators x2 (b) red: bearings x2 (c) blue: shaft (d) purple: rotor (e) yellow: nozzle and (f) orange: casing

The most important parameters of disc turbomachinery as listed by Rice [25] are

- Inlet nozzle angle
- Number of inlet nozzle ports
- Inlet pressure
- Disc thickness
- Spacing between the discs
- Number of discs
- Diameter of disc
- Surface roughness of disc
- Clearance between disc and casing
- Exhaust profile on discs
- Exhaust profile on stators
- Diameter of shaft
- Position of exhaust hole with respect to the centre
- Ratio of exit area to disc areas

3. Effect of Design Parameters

3.1 Nozzle Considerations

Krishnan [27], tested a total of eight different nozzles. Four of the nozzles had a circular entry, but an oblong exit. The area, width, and length of these nozzles were constant. However, the width arc and the angle made with the rotors were different. One of the nozzles had a similar circular entry but had five smaller circular tubes as the exit. Another nozzle was shaped like a funnel, with a decreasing area along the length, but with a small increase at the exit to cover a wider arc. Its length and width were only marginally bigger than the others, but the area was almost double. Four different nozzle angles were tested. From these experiments, it was found that for nozzle angles further away from the tangent, the RPM of the turbine reduced. This decrease was attributed to the increase in radial velocity and a faster exit rate, resulting in lower energy transfer. The nozzles with smaller areas developed a higher RPM which was a result of the higher kinetic energy of the fluid entering the rotor.

Guha and Smiley [22] carried out experimental and numerical tests to study the losses occurring in nozzles, to improve their efficiency. New nozzles were developed by modifying nozzles that were used in a previous test. While other authors like Lawn and Rice [26] have mentioned that rotor efficiency can reach values close to 95% [21, 28], Guha and Smiley [22] developed an experimental setup to measure it for the first time. The efficiency of the turbine was around 25%, and from CFD analyses, Guha and Smiley [22] found the nozzle and inlet of this old design to contribute to 35% of the loss in stagnation pressure. Guha and Smiley [22] tested a new nozzle which had a rectangular outlet area and an accompanying plenum chamber. The stagnation pressure loss in this nozzle was less than 1%. The nozzle had inserts to make it compatible with rotors containing different number of discs by blocking the excess outlets. The inserts, however, were suspected of failing to prevent the leakage. The decrease in stagnation pressure loss was attributed to the plenum chamber, as it allowed for a more uniform flow through the nozzle.

Lampart *et al.,* [29], improved on the computational work carried out previously [30]. Two models were considered for numerical simulation. The simpler model considered symmetrical flow in the gap between the discs. Four, six, and eight nozzles at angles of 10° and 15° were designed for the model. For simplicity, the shaft area was treated as the exhaust. There were no dedicated exhaust holes on the discs as seen on realistic models. An infinite number of discs were considered. The highest efficiency obtained by Lampart *et al.,* [29] was with the four nozzle configuration at 10° inlet angle, at a rotational speed of 18,000 RPM. A further increase in the number of nozzles had an adverse effect on the efficiency. The finding was similar to the previous work by Lampart *et al.,* [30], which also found the four nozzle configuration to be the most efficient. An increase in the angle from 10° to 15° caused an efficiency drop of 8%.

Kristian Holland [31] used 3D printed nozzles made from glass filled nylon. The nozzle design was easily interchangeable with the turbine assembly, but was complex, which justified the use of 3D printing. A total of five nozzle angles were tested - 2.5°, 5°, 7.5°,12.5° and 45°, with respect to the tangential direction. Contrary to other literature, maximum torque and acceleration were observed when the nozzle was radial (45°) to the discs. Kristian Holland [31] commented that additional study is required to understand its underlying reason.

James H. Armstrong [24] tested a variety of nozzles. Initially, a short length of a pipe with an inside diameter of 0.269 inch was used as the nozzle, and later several diverging nozzles were used. These consisted of a 0.125 inch diameter nozzle with a 15° diverging section, a 0.188 inch nozzle with a 15° diverging section, and lastly a 0.269 inch nozzle with a 7° diverging section. All nozzles were aligned to admit steam “approximately tangentially to the periphery of the rotor discs”. The 0.125 inch nozzle was found to be too small for efficient operation. The maximum brake horsepower and torque were obtained with the diverging 0.269 inch nozzle. Armstrong [24] concluded that testing just four nozzles cannot determine the most efficient one, but it showed that the nozzle design had a significant impact on turbine performance.

Hoya and Guha [23] used an interchangeable insert type of nozzle. It consisted of a circular hole with a radial slot acting as the nozzle exit. The unused area of the slot was blocked with shaped inserts when the turbine was being tested with rotors of different widths. Hoya and Guha [23] considered Eq. (2) to calculate efficiency as the ratio of the actual power to the power of the input stream. A near tangential nozzle angle was found to be optimum, with the efficiency remaining nearly constant between 5° and 15° with respect to the tangential direction. The width of the nozzle did not have a significant effect on the efficiency

$$\eta_{\Omega,stream} = \frac{\tau \cdot \omega}{Q \cdot p_{01}} \tag{2}$$

where, 01 conditions at the inlet of the nozzle, τ torque, p pressure, Q volume flow rate, ω rotor angular velocity

From the above studies, it can be concluded that nozzle design is a major factor influencing turbine efficiency. This was particularly evident from Guha and Smiley's [22] study, which marked a decrease in the stagnation pressure loss from 35% to 1% by optimising the nozzle design. In addition to this, most authors found that a near tangential nozzle angle was suited for the best performance. A large deviation from it towards the radial direction caused the efficiency to decrease.

3.2 Feed Requirements

Hoya and Guha [23] suggested that the losses in the nozzle can be dependent on the velocity of the fluid. In this experimental study, it was observed that the losses in the nozzle decreased with an increase in the velocity. A possible explanation was that higher velocities led to higher Reynolds numbers, and thus to smaller thicknesses of the boundary layer. This made it possible to reach higher efficiencies in the nozzle. The turbine was tested in the pressure range of 2 to 4.5 bar and was observed to perform most optimally at 3.8 bar.

Li *et al.,* [32] also studied the effect of input parameters on the turbine through experimental testing. The turbine was tested at six pressure values in the range of 0.21 to 0.26 MPa. The efficiency of the turbine was found to decrease with a decrease in the inlet pressure. At a particular pressure, the turbine performed most efficiently only at a particular RPM. A higher RPM corresponded to higher inlet pressure.

E. Lemma *et al.,* [33] and Deam *et al.,* [34], through theoretical analyses, found that the efficiency of the turbine reached its maximum value when the rotational speed of the disc was equal to the inlet velocity of the fluid.

Romanin *et al.,* [35] used a flow rate over a range of 1 to 20 mL/sec to test an experimental setup. A higher input velocity resulted in more efficient operation, but losses in the nozzle became more significant. It was also found that in the case of a laminar nozzle flow, lower Reynolds numbers resulted in higher losses. Whereas in a turbulent nozzle flow, higher surface roughness results in higher losses.

Krishnan [27] tested turbine configurations with two different inlet flow rates. One had a gravity fed low-head of 1 m that provided a maximum flow rate of 3 cm^3/s. This was used for turbines having volumes less than 4 cm^3. Another source of 10 m head providing a flow rate of 20 cm^3/s was used for turbines having volume up to 17 cm^3. Krishnan [27] found that an increase in the flow rate caused a decrease in efficiency. The power output had a different trend and increased as the flow rate increased. The percentage gain of power was one or two orders higher than the loss in efficiency. According to Krishnan [27], the rotors do not rotate below a flow rate that corresponds with opposing effects of centrifugal and frictional forces. Lower flow rates resulted in increased momentum transfer.

Krishnan *et al.,* 2011 [36] while testing a turbine with discs 1 cm in diameter, concluded that Tesla turbines achieve high efficiencies with low pressure heads. A case similar to the ascent of sap in trees and the pressure difference developed in trees due to evaporation was studied. The turbine was developed to work on this evaporative flow, which was considered to be laminar with a low Reynolds number. The pressure head was decided by the nozzle. Experimental results pointed to achieving higher efficiencies at lower flow rates.

Peshlakai [28] plotted the change in rotor efficiency with the mass flow rate of air, water and steam. Peshlakai [28] considered the same turbine for this, which was not optimised for any particular medium and used Eq. (3) to calculate the turbine efficiency. While testing with air, rotor efficiencies were low for flow rates less than 4 g/s. A sudden jump occurred at 4 g/s, where the rotor efficiency increased from 20% to a peak of value of 95% at 7 g/s. A steady drop was noticed after this.

Two brass nozzles of different sizes were used by Peshlakai [28] while comparing different fluids. These nozzles were designed to be easily removable from the turbine. An assumption of a 15% loss in the nozzle was considered while calculating the overall efficiency of the turbine. Though limited by the range of the measuring equipment, Peshlakai [28] found that the larger nozzle was able to maintain the peak rotor efficiency over a longer range of flow rates than the smaller nozzle. Peak rotor efficiency was maintained over a 2 g/s range in the larger nozzle as compared to a 1 g/s range in the smaller nozzle.

$$\eta_{Rotor} = \frac{\dot{\mathrm{W}}}{W_f} \tag{3}$$

where

$\dot{\mathrm{W}} = \frac{1.15}{0.93} \times$ (Voltage × Ampere) = turbine output work

$\dot{\mathrm{W}}_f = 0.85 \times \dot{\mathrm{m}} \left[(h_2 - h_3) + \frac{1}{2(V_2^2 - V_3^2)} - g \times h_{L,Nozzle} \right] - \dot{Q}_k$ = mechanical fluid work

m is the Mass flow rate [g/s], h is the enthalpy [kJ/kg], V is the working fluid velocity [m/s]

Tan *et al.,* [37] attempted to optimise the turbine to generate electricity from overhead tanks with a minimum head loss, in houses in Malaysia. The large heads and low feed rates available were deemed desirable and advantageous to this effort. The study was a theoretical calculation of the number of discs, disc gap, and disc size and relied heavily on the previous works of Rice [25]. Water was the working medium in this design, similar to the study by Rice [25]. The study verified Rice's [25] conclusion that lower flow rates produced higher efficiencies. The maximum efficiency achieved by Tan *et al.,* [37] was 6.8%, which was attributed to the laminar flow achievable at low flow rates. In these tests, the variation in inlet flow rates at houses located at different distances from the reservoir was studied. The lowest flow rate was chosen. Tan *et al.,* [38] carried out simulations using computational fluid dynamics to optimise the turbine that was designed and developed in the previous work [37]. By optimising the inlet pressure through iterative designs, the efficiency of the turbine was increased to 10.7%.

Romanin [18] conducted an analytical treatment of flow through the rotor and strived to correlate data between the integral perturbation approach, experimental testing, and computational solutions. An assumed parabolic velocity profile postulated as a function of the Poiseuille number was substituted into momentum equations and integrated across the microchannel width. The resulting equations were simplified in terms of non-dimensional parameters. Romanin [18] tested nozzles and disc gaps similar to those of Krishnan [27]. Romanin [18] also validated the integral perturbation approach by varying the feed rate. Good correlation was found between the experimental data, computational data, and the numerical solution.

Conflicting data have been reported with regard to the trend of efficiency versus changing inlet feed rates. When water has been used as the working fluid, decreasing inlet flow rates cause an increase in efficiency, but the opposite has been recorded for air. This highlights the effectiveness of the turbine for power generation in small streams or creeks for portable devices.

3.3 Turbine Losses

Hoya and Guha [23] used two parameters to estimate losses in the nozzle. The first parameter, described by Eq. (4), was based on using the inlet and outlet pressures of the nozzle to analyse the loss in expansion. The main losses are closely related to the loss in the total pressure across the nozzle.

$$\pi_N = \frac{p_{02}}{p_{01}} < 1 \tag{4}$$

The second parameter was the loss coefficient (Eq. (5)), which expresses the proportion of energy degraded by friction. The results obtained by Hoya and Guha [23] indicate a significant loss of total pressure in the nozzle. For example, the value of the loss coefficient obtained was approximately 0.4, whereas its typical value for gas turbine nozzles is close to 0.05 [23].

$$Y_N = \frac{\left(\frac{p_{01}}{p_{02}}\right) - 1}{1 - \left(\frac{p_2}{p_{02}}\right)} \tag{5}$$

where p_{02} is pressure at outlet of the nozzle/inlet of rotor, p_{01} is pressure at inlet of the nozzle.

Li *et al.,* [32] extensively analysed the turbine's losses and classified them as losses at the entry, exit, and in the bearings. Bearing loss, being self-explanatory, should be minimised as much as possible at the design and manufacturing stages. At the entry, a shock loss occurs due to the interaction between the fluid and the disc edges. Also, the local expansion caused due to fluid entry in the turbine cavity contributes to it. At the exit, the major loss happens due to the sudden change in the flow state, from radial to a direction parallel to the shaft. In addition to this, a shock loss is generated due to the fluid impacting the edge of the disc along the exit profile. The entry and exit losses were calculated based on the principle of conservation of energy.

Krishnan *et al.,* 2013 [39] studied the effect of scaling, and the associated losses. The experimental and theoretical model considered were the same as in [18, 35, 36]. The paper noted the following observations. The head loss, also called nozzle loss, can be reduced by having rough nozzles for low Reynolds numbers, and smooth ones for higher Reynolds numbers. Shaft power loss comprising of gap loss and tip friction can be reduced with better sealing and by reducing the thickness of the disc respectively. Thin discs also reduce the impact loss. Shaftless rotors have optimised exhausts and high power transfer. Krishnan *et al.,* 2013 [39] found that the experimentally derived values of the inlet and outlet losses were approximately the same as the theoretically calculated values, hence validating the formulae used. The outlet loss was much higher than the inlet loss, and hence had a major effect on the turbine efficiency. But this holds true only when the working medium is incompressible, as water had been used. The inlet loss becomes more significant for turbine efficiency when a compressible working medium is used [23].

Overall, two major kinds of losses have been identified, the first being at the entry, related to expansion in the nozzle, and the second being at the outlet, due to the sudden change in the flow direction. The former was found to be predominant when a compressible working fluid was used, the latter becoming more significant in case of an incompressible fluid. Both of these losses have a notable effect on the turbine efficiency, and thus are important parameters to be worked upon to improve the efficiency.

3.4 Disc Thickness

Tesla's original design had discs with tapered edges, as Tesla believed that this would increase efficiency by reducing tip losses [29]. Losses occur at the tips due to fluid trying to shift from one side of the disc to the other, similar to the behaviour of flow around the wingtips of an aeroplane. Tesla implemented this idea by using very thin discs [25-26], but they warped under the stresses generated at high RPMs. With limited knowledge of materials and manufacturing techniques, Tesla was not able to test discs that were strong enough to withstand the high pressures.

Li *et al.,* [32] selected an extremely small disc thickness of 0.5 mm for an experimental study. Li *et al.,* [32] argued that a shock loss occurs when the working fluid impacts the edge of the disc. Therefore, Li *et al.,* [32] attempted to reduce this loss by minimising the thickness of the discs. By choosing the specified small disc thickness, the shock losses could be safely neglected.

In general, there are only a few studies that discuss the effect of disc thickness. Further research is required to address the appropriate disc thickness for various applications of Tesla turbine.

3.5 Disc Gap

Krishnan [27] tested a total of 3 inter-disc gap configurations - 125 µm, 250 µm and 500 µm with varying number of discs and exit profiles among a total set of 6 rotor stacks. The overall turbine size was kept constant. Increasing the gap led to higher RPM generation due to the lower mass of the stacks with lesser discs. And as described by Romanin *et al.,* [35], decreasing inter-disc space increases efficiency. This inference was supported with data from computer simulations in ANSYS, experimental data, and analytical calculations. The increase in efficiency was associated with an increase in Reynold's number. This leads to more momentum transfer from the fluid to the discs due to the increased viscous forces. According to Rice [25], the ideal gap between the disc should be twice the boundary layer, for most efficient momentum and transfer.

Peshlakai [28] tried three different working mediums - air, water and steam, on the same turbine design to compare the performance of the different fluids. A disc gap of 1.3 mm was chosen for the turbine. The maximum rotor efficiencies reported for air and water were 95% and 0.49% respectively. The efficiency of steam was not calculated due to low power outputs. Peshlakai [28] attributed this massive difference to the relation between the disc gap and boundary layer thickness, as reported by Rice [25]. To get higher efficiencies for water, the gap between the discs had to be increased to accommodate the larger boundary layers.

Borate [9] studied the effect of spacing by varying the gap from 0.5 mm to 2.5 mm in steps of 0.5 mm and used water as the working fluid. Borate [9] observed that in stacks with larger gaps, the water boundary layer and the jet boundary layer were separated. This led to lesser energy transfer from the water to the discs. For the case with the least spacing, the two boundary layers overlapped and resulted in the most efficient energy transfer. The speed of the turbine was found to decrease with increasing spacing.

Breiter and Pohlhausen [40] numerically analysed laminar flow between two rotating discs having the same constant angular velocity. The inlet conditions and the path of the fluid studied resembles a Tesla turbine minus the rotor stack. The objective was to formulate equations for the pressure and momentum of the fluid. The disc gap, given by Eq. (6), is critical in the design of the turbine. The Pohlhausen parameter, given by Eq. (7), determines to what extent the bulk fluid follows the rotation of the disc and also predicts the flow profile. It is an important parameter that influences the performance. Large numbers imply that the boundary layer is decoupled and that there is a region of non-rotating fluid in between. Extremely small numbers approach the case of solid body rotation.

$$b = \pi \times \sqrt{\frac{v}{\omega}} \tag{6}$$

where b is disc gap, v is kinematic viscosity, ω is angular velocity

$$P_h = \frac{b}{\sqrt{\frac{\omega}{v}}} \tag{7}$$

where P_h is Pohlhausen parameter, b is disc gap, ω is angular velocity, v is kinematic viscosity.

Hoya and Guha [23] also analysed the effect of varying the inter-disc spacing on the efficiency of the turbine. Hoya and Guha [23] used air as the working medium and found that the set up reached peak efficiency at a disc spacing of 0.6 mm. For disc spacings less than 0.4 mm or greater than 1 mm, the efficiency decreased rapidly. This can be justified due to the deviation from the “ideal” disc gap as explained by Rice [25] previously.

Couto [41] suggested a numerical approach to calculate the number of discs needed for the desired performance by estimating laminar or turbulent flows. Couto [41] stated that for most effective momentum transfer, the flow has to be laminar and the disc gap twice the boundary layer. The work comprised of calculating the boundary layer thickness for laminar and turbulent flows. Additionally, number of gaps between the discs for a given mass flow, moment coefficient, and the torque produced by n number of discs were also calculated.

Therefore, from the above studies, it can be inferred that there exists an ideal disc gap, which is approximately twice the boundary layer thickness. A larger gap between the discs implies that there is an increase in the volume of the fluid that is not doing any work and hence decreases the efficiency. Smaller gaps result in highly turbulent interactions of the viscous boundary layers which also decrease the efficiency.

3.6 Number of Discs

From an analytical conclusion in 1991, Rice [25] claimed that laminar flow can achieve a rotor efficiency of over 95%. But, to achieve this high efficiency, the flow rate of the fluid should be low. Lower flow rates can be obtained by increasing the number of discs for a given inlet feed. Hence, this high efficiency is achieved at the expense of using a large number of discs and possibly a large rotor.

Romanin *et al.,* [35] tested rotors with 8, 13, and 20 discs. The efficiency increased significantly when the number of discs were increased from 8. The efficiency obtained with 8 discs was between 0 to 10%, whereas the efficiency with 13 and 20 discs was approximately in the range of 10 to 20%, the maximum being obtained with 13 discs. Hoya and Guha [23] observed similar findings in another study, with the efficiency increasing with more discs.

Tan *et al.,* [38] attempted to optimise the number of discs of the previous works of [37] by using a computational fluid dynamics approach. By decreasing the number of discs from 21 to 13, a reduction in head loss was achieved. The head loss occurs when the fluid has to perform a 90° turn when exiting the disc gap to the outlet. The flow separates at the corners, and is constricted to the vena contracta region.

3.7 Disc Diameter

Lampart *et al.,* [30] first conducted computational analyses on single disc models to study the effects of varying disc diameter and number of nozzle inlets. The models used the central shaft area as the exit and did not have any dedicated exhaust profiles as found on realistic turbines. A total of 6 models having a rotor diameter of 100 mm were analysed with varying nozzle numbers and inlet angles. The maximum efficiency obtained was 30% at 18,000 RPM, which was not competitive with conventional turbines. Lampart *et al.,* [29] increased the diameter to 300 mm in an attempt to increase the efficiency. The numerical simulations of the larger rotor were carried out at 9,000 RPM only. Improvements in the streamline path were seen. The highest efficiency of the new study was greater than 50%. This model had two nozzles with inlet angles of 10°. The fluid particles were found to execute 6 revolutions before exiting the turbine.

The full model tested by Lampart *et al.,* [29] considered a gap between the disc and the nozzle, thereby making it more realistic and accurate. Four exhaust holes were present on each rotor instead of the shaft area acting as the exhaust. Half of the 11 disc turbine was considered by using a symmetry condition. The nozzle angle was fixed at 10° and the inter-disc gap was 0.25 mm. A much lower efficiency of 16% was achieved, by considering leaks. The number of revolutions carried out by the fluid particles on the 100 mm diameter discs were less than that in the simple analysis. Strong eddies and swirls forming at the exit, and changes in the fluid direction from radial to axial were the reasons for the drop in efficiency.

Kristian Holland [31] discussed several parameters which can be considered in deciding the disc size, such as the feed velocity, pressure, temperature and the inertia of the system. Larger inertia of the rotor would help in the case of sudden loading as it would prevent excessive deceleration of the turbine. For this study, discs with outer and inner diameters of 95 mm and 17 mm respectively were selected. This value was suitable for the low pressures being used. Readily available hard disc platters were used as disc instead of manufacturing them. This was also a major factor in deciding the disc diameter for Holland [31].

Hence, several factors have to be considered for selecting the disc diameter. Lampart *et al.,* [29], through computational analyses, observed an increase in the turbine efficiency with a disc of larger diameter. But overall very few studies have examined the correlation between the disc diameter and the turbine's performance. Thus, more research is required in this area.

By using computational fluid dynamics, Tan *et al.,* [38] attempted to optimise the diameter of discs in the previous works [37]. In the optimised turbine, the diameter of the discs was increased from 50 mm to 70 mm. This resulted in an increase of 57% in the torque generated. Larger discs produced more torque as the fluid was able to travel over longer paths. However, they could not be so large that the initial torque required to set the discs in motion could not be generated by the low feed rates considered.

3.8 RPM

Krishnan [27], from a computational model, concluded that higher RPM resulted in greater centrifugal forces and longer flow paths. The maximum efficiency achieved was 36.6%, but Krishnan [27] states that the turbine has the potential to reach an efficiency of 40%.

Lampart *et al.,* [29] analysed the simple model (as described previously in section 3.7.) at 9,000 and 18,000 RPM. According to the study, the speed of the rotor affected the shape of the streamlines and the time spent by the fluid in the turbine. A longer path is desirable, as it increases the momentum transfer, and hence, the efficiency of the turbine. The numerical simulations displayed that the pathlines were 50% longer when the calculations were conducted at 18,000 RPM. As expected, the efficiency was higher for the higher RPM. Lampart *et al.,* [30] from numerical simulations concluded that the bladeless turbine cannot match the RPM of conventional turbines.

Most experimental results show a parabolic relationship between turbine efficiency and rotor RPM, with the efficiency reaching a maximum value at a particular RPM [31, 32, 42]. Various authors studied the trend of torque and rotor RPM, and found the torque to decrease in a nonlinear trend with an increase in the RPM [14, 23, 31, 32, 43]. It was also noted that the torque approaches a steady state value as the disc tip speed approaches fluid flow velocity [31].

Hoya and Guha [23] and Li *et al.,* [32] also found that an optimum RPM value exists for the operation of the turbine at a specific pressure. This is because the efficiency first increases with an increase in the RPM, and then decreases.

Li *et al.,* [32] who studied various turbine losses experimentally, observed that the inlet and outlet losses showed only a little change with varying RPM. The outlet loss reached its minimum value at the optimal rotor speed. The turbine was tested up to a maximum of 25,000 RPM.

3.9 Surface Roughness

The computational model developed by Krishnan [27] considered surface roughness, which was given as a function of the flow profile. The flow profile varied from parabolic to uniform, and this represented the flow over smooth and rough discs. Krishnan [27] stated that the performance of small rotors could be increased by micro structuring the surface, but did not carry out any work to support the claim and instead worked with the flow profile.

An experimental investigation of the effect of surface roughness was studied by Borate [9]. Spiral grooves were etched onto three of the six sets of discs being tested, using a lathe. The surface roughness was 500ra. The grooves were machined to direct the incoming jet along specific spiral paths. This ensured long spiral paths to utilise the majority of the kinetic energy of the jet flow. A 5% to 6% increase in the efficiency was noticed with the etched discs.

3.10 Power

Tesla's first turbine used 8 discs of 6 inch diameter and produced a power of 30 HP. Tesla then developed a turbine having 18 inch diameter discs that could produce a power of 200 HP when run with steam [23, 44]. Most turbines investigated could not compete with the power output of Tesla's original design, their output power not exceeding 2 HP. Li *et al.,* [32] observed a parabolic trend between the output power and the rotor speed of the turbine, indicating an optimum value of RPM for maximum output power.

Overall, from the literature covered by the authors of this paper, it was found that the relation between the output power with other parameters of the turbine was not studied extensively, and therefore this is another area which needs more work.

4. Applications of the Tesla Turbine

The Tesla turbine is suited for power generation in numerous fields [20]. As the design of the turbine is easily scalable, portable versions of it can be fabricated for use in streams and rivers. It can be incorporated into automobiles, running on free stream airflow, for generating electrical power. The turbine's design is much simpler than conventional turbines, hence they are much more economical to manufacture, operate and maintain. As the turbine can be run on a variety of working fluids, without requiring any prior processing of the fluid, it can be safely used in naval applications as well.

The Tesla turbine can be used to power an MAV by positioning it behind a propeller [45]. The prop wash generated will send accelerated air into the turbine which can generate electricity onboard during flight. Since the Tesla turbine is efficient in the small-scale domain, it certainly makes for an interesting application.

As the world moves towards renewable sources of energy, upgrading the traditional electricity grids into “smart grids” is also being undertaken. A smart grid is digital in nature, and by constantly monitoring various parameters like the changes in demand and failures, it can act instantaneously to make suitable changes. This makes the grid very efficient and will allow it to meet future power demands. Since efficient utilization of renewable energy sources, like wind [53] and water, requires us to tap them at multiple locations in discrete quantities, the Tesla turbine fits in perfectly in our vision of the future, as it can be set up at multiple locations at a comparatively lower cost.

5. Limitations Associated with Tesla Turbine

It has often been stated that the efficiency of the turbine is low due to inefficient nozzle designs. The design of efficient nozzles warrants separate studies, and can greatly improve the overall efficiency of the turbine [22]. In the majority of the work covered in this review, the authors have opted to design nozzles that can be easily manufactured or replaced to aid with their experimental process [28, 31]. In numerical simulations, the nozzles have been greatly simplified as a constant velocity inlet [29], and have not been modelled to account for any expansion losses. In most cases, it is seen that the rotor efficiency is very high, but the nozzle efficiency is low [19-22], and thus the overall performance of the turbine is affected. A few researchers like Krishnan [27], have carried out experiments with different nozzle configurations and published the relations between the RPM of the turbine with the nozzle angle and nozzle area, but have failed to give an overall understanding of how it affects the efficiency.

Another major limitation is associated with the turbine’s inherent design. It has been noted by most authors that the Tesla turbine achieves high efficiency at very high RPMs [23, 29]. Thinner discs also reduce the shock loss when the fluid enters the turbine and strikes the discs. When such thin discs are subjected to high RPMs, they have a very high tendency to warp [21, 25, 26, 31]. Thus, there is a potential need to manufacture the discs from advanced materials. This can introduce additional raw material and engineering costs, thereby reducing the economic advantage of the turbine.

6. Future of the Tesla Turbine

Various studies have shown promising outcomes for the future of Tesla Turbines. In the context of increasing attention towards renewable and clean energy resources, Tesla turbine is the way forward. This turbine is most effective for power generation at the microscale level. With large losses occurring in conventional turbines scaled to the micro level, the Tesla turbine which uses loss inducing forces to run has been touted as a viable solution. The recent studies on the turbine have been focused on its application at the microscale level, with designs having rotor diameter as small as 1 cm [27]. Working on renewable sources, it can soon act as an alternative to batteries in locations where it is not feasible to recharge or replace them on slightly larger scales. The Tesla turbine has been hinted as a source for generating clean renewable energy to power small settlements with water supplies [37, 38, 46]. Its simple design, ease of manufacturing and small size will make it a favoured and modular turbine that can be used in various applications. It is a very versatile design and can use a multitude of fluids as the working medium, greatly increasing its range of applications. With more emphasis given on the nozzle design, the efficiency of the turbine can certainly be boosted to make it more feasible. This will require an application specific approach since the parameters differ as per the fluid choice and size of the turbine. This turbine provides an exciting alternative where conventional turbines prove impractical.

References

[1] Zare, V. "A comparative exergoeconomic analysis of different ORC configurations for binary geothermal power plants." *Energy Conversion and Management* 105 (2015): 127-138.

[2] Heberle, Florian, and Dieter Brüggemann. "Exergy based fluid selection for a geothermal Organic Rankine Cycle for combined heat and power generation." *Applied Thermal Engineering* 30, no. 11-12 (2010): 1326-1332.

[3] Pei, Gang, Jing Li, and Jie Ji. "Analysis of low temperature solar thermal electric generation using regenerative Organic Rankine Cycle." *Applied Thermal Engineering* 30, no. 8-9 (2010): 998-1004.

[4] Delgado-Torres, Agustín M., and Lourdes García-Rodríguez. "Analysis and optimization of the low-temperature solar organic Rankine cycle (ORC)." *Energy Conversion and Management* 51, no. 12 (2010): 2846-2856.

[5] Drescher, Ulli, and Dieter Brüggemann. "Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants." *Applied Thermal Engineering* 27, no. 1 (2007): 223-228.

[6] Al-Sulaiman, Fahad A., Feridun Hamdullahpur, and Ibrahim Dincer. "Greenhouse gas emission and exergy assessments of an integrated Organic Rankine Cycle with a biomass combustor for combined cooling, heating and power production." *Applied Thermal Engineering* 31, no. 4 (2011): 439-446.

[7] Zhou, Naijun, Xiaoyuan Wang, Zhuo Chen, and Zhiqi Wang. "Experimental study on Organic Rankine Cycle for waste heat recovery from low-temperature flue gas." *Energy* 55 (2013): 216-225.

[8] Maalouf, Samer, Elias Boulawz Ksayer, and Denis Clodic. "Investigation of direct contact condensation for wet flue-gas waste heat recovery using Organic Rankine Cycle." *Energy Conversion and Management* 107 (2016): 96-102.

[9] Borate, Hanumant P., and Nitin D. Misal. "An effect of spacing and surface finish on the performance of bladeless turbine." In *ASME 2012 Gas Turbine India Conference*, pp. 165-171. American Society of Mechanical Engineers Digital Collection, 2013.

[10] Isomura, Kousuke, Motohide Murayama, Susumu Teramoto, Kousuke Hikichi, Yuki Endo, Shinichi Togo, and Shuji Tanaka. "Experimental verification of the feasibility of a 100 W class micro-scale gas turbine at an impeller diameter of 10 mm." *Journal of Micromechanics and Microengineering* 16, no. 9 (2006): S254.

[11] Paish, Oliver. "Small hydro power: technology and current status." *Renewable and Sustainable Energy Reviews* 6, no. 6 (2002): 537-556.

[12] Ho-yan, Bryan P. "Tesla turbine for pico hydro applications." *Guelph Engineering Journal*, no. 4 (2011): 1–8.

[13] Rice, Warren. "An analytical and experimental investigation of multiple-disk turbines." *Journal of Engineering for Power* 87, no. 1 (1965): 29-36.

[14] Peirs, Jan, Dominiek Reynaerts, and Filip Verplaetsen. "A microturbine for electric power generation." *Sensors and Actuators A: Physical* 113, no. 1 (2004): 86-93.

[15] Totty, P., M Zubair, and KA Ahmad. "CFD investigation of transonic axial compressor rotor blade at various off-design condition." *Pertanika Journal of Science and Technology* 24, no. 2 (2016): 451–463.

[16] Epstein, A., S. Senturia, O. Al-Midani, G. Anathasuresh, A. Epstein, S. Senturia, and O. Al-Midani. "Micro-heat engines, gas turbines, and rocket engines-The MIT microengine project." In *28th Fluid Dynamics Conference*, p. 1773. 1997.

[17] Decuypere, R., and D. Verstraete. "Micro turbines from the standpoint of potential users." *Micro Gas Turbines* 15 (2005): 14-18.

[18] Romanin, Vincent D. "Theory and performance of Tesla turbines." PhD diss., UC Berkeley, 2012.

[19] Boyd, K. E., and W. Rice. "Laminar inward flow of an incompressible fluid between rotating disks, with full peripheral admission." *Journal of Applied Mechanics* 35, no. 2 (1968): 229-237.

[20] Gupta, H. E., and SHYAM P. Kodali. "Design and operation of Tesla turbo machine—a state of the art review." *International Journal of Advanced Transport Phenomena* 2, no. 1 (2013): 7-14.

[21] Logan, Earl, and Ramendra Roy. *Handbook of Turbomachinery, Second Edition*. 2nd ed. New York: Marcel Dekker, 2003.

[22] Guha, A., and B. Smiley. "Experiment and analysis for an improved design of the inlet and nozzle in Tesla disc turbines." *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 224, no. 2 (2010): 261-277.

[23] Hoya, G P, and A Guha. "The design of a test rig and study of the performance and efficiency of a tesla disc turbine." *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 223, no. 4 (2009): 451–465.
[24] Armstrong, James Hal. "An investigation of the performance of a modified Tesla turbine." PhD diss., Georgia Institute of Technology, 1952.
[25] Warren, Rice. "Tesla Turbomachinery." In *Conference Proceedings of the IV International Tesla Symposium*. 1991.
[26] Lawn, M. J., and Warren Rice. "Calculated design data for the multiple-disk turbine using incompressible fluid." *Journal of Fluids Engineering* 96, no. 3 (1974): 252-258.
[27] Krishnan, Vedavalli Gomatam. "Design and Fabrication of cm-scale Tesla Turbines." PhD diss., UC Berkeley, 2015.
[28] Peshlakai, Aaron Ron. "Challenging the versatility of the Tesla turbine: working fluid variations and turbine performance." Master's thesis, Arizona State University, 2012.
[29] Lampart, Piotr, and Łukasz Jędrzejewski. "Investigations of aerodynamics of Tesla bladeless microturbines." *Journal of Theoretical And Applied Mechanics* 49, no. 2 (2011): 477–499.
[30] Lampart, Piotr, Krzysztof Kosowski, Marian Piwowarski, and Łukasz Jędrzejewski. "Design analysis of Tesla micro-turbine operating on a low-boiling medium." *Polish Maritime Research* 16, no. Special (2009): 28-33.
[31] Holland, Kris. "Design, construction and testing of a Tesla turbine." PhD diss., Laurentian University of Sudbury. 2016.
[32] Li, Ruixiong, Huanran Wang, Erren Yao, Meng Li, and Weigang Nan. "Experimental study on bladeless turbine using incompressible working medium." *Advances in Mechanical Engineering* 9, no. 1 (2017): 1–12.
[33] Lemma, E, R T Deam, D Toncich, and R Collins. "Characterisation of a small viscous flow turbine." *Experimental Thermal and Fluid Science* 33, no. 1 (2008): 96–105.
[34] Deam, R. T., Engida Lemma, B. Mace, and R. Collins. "On scaling down turbines to millimeter size." *Journal of Engineering for Gas Turbines and Power* 130, no. 5 (2008): 052301.
[35] Romanin, Vince D., Vedavalli G. Krishnan, Van P. Carey, and Michel M. Maharbiz. "Experimental and Analytical study of sub-watt scale Tesla turbine performance." In *ASME 2012 International Mechanical Engineering Congress and Exposition*, pp. 1005-1014. American Society of Mechanical Engineers Digital Collection, 2013.
[36] Krishnan, Vedavalli G., Zohora Iqbal, and Michel M. Maharbiz. "A micro tesla turbine for power generation from low pressure heads and evaporation driven flows." In *2011 16th International Solid-State Sensors, Actuators and Microsystems Conference*, pp. 1851-1854. IEEE, 2011.
[37] Foo, S. J., W. C. Tan, and M. Shahril. "Development of tesla turbine for green energy application." In *Proceeding of National Conference in Mechanical Engineering Research and Postgraduate Studies (2nd NCMER 2010)*, pp. 671-680. 2010.
[38] Choon, Tan Wee, A. A. Rahman, Foo Shy Jer, and Lim Eng Aik. "Optimization of Tesla turbine using computational fluid dynamics approach." In *2011 IEEE Symposium on Industrial Electronics and Applications*, pp. 477-480. IEEE, 2011.
[39] Krishnan, Vedavalli G, Vince Romanin, Van P. Carey, and Michel M Maharbiz. "Design and scaling of microscale Tesla turbines." *Journal of Micromechanics and Microengineering* 23, no. 12 (2013).
[40] Mark C. Breiter, and Karl Pohlhausen. "Laminar flow between two parallel rotating disks." Wright-Patterson Air Force Base, 1962.
[41] Couto, H. S., J. B. F. Duarte, and D. Bastos-Netto. "The tesla turbine revisited." In *Proceedings of the Eighth Asia-Pacific International Symposium on Combustion and Energy Utilization*. 2006.
[42] Sengupta, Sayantan, and Abhijit Guha. "A theory of Tesla disc turbines." *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 226, no. 5 (2012): 650-663.
[43] Bloudíček, Petr, and David Paloušek. "Design of Tesla Turbine." In Konference Diplomových Prací p. 1-6. 2007.
[44] Carey, Van P. "Assessment of Tesla turbine performance for small scale Rankine combined heat and power systems." *Journal of Engineering for Gas Turbines and Power* 132, no. 12 (2010): 122301.
[45] Zhen, Tan Kar, Muhammed Zubair, and Kamarul Arifin Ahmad. "Experimental and numerical investigation of the effects of passive vortex generators on Aludra UAV performance." *Chinese Journal of Aeronautics* 24, no. 5 (2011): 577-583.
[46] Carey, Van P. "Computational/theoretical modeling of flow physics and transport in disk rotor drag turbine expanders for green energy conversion technologies." In *ASME 2010 International Mechanical Engineering Congress and Exposition*, pp. 31-38. American Society of Mechanical Engineers Digital Collection, 2012.
[47] Guha, Abhijit, and Sayantan Sengupta. "A non-dimensional study of the flow through co-rotating discs and performance optimization of a Tesla disc turbine." *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 231, no. 8 (2017): 721-738.
[48] Schosser, Constantin, and Michael Pfitzner. "A numerical study of the three-dimensional incompressible rotor airflow within a Tesla turbine." In *Conference of Modelling Fluid Flow CMFF*, (2015): 1-4.

[49] Ladino, Andrés Felipe Rey. *Numerical simulation of the flow field in a friction-type turbine (Tesla Turbine)*. na, 2004.
[50] Guha, Abhijit, and Sayantan Sengupta. "The fluid dynamics of the rotating flow in a Tesla disc turbine." *European Journal of Mechanics-B/Fluids* 37 (2013): 112-123.
[51] Zuber, Mohammad, M. S. B. Hisham, N. A. M. Nasir, A. A. Basri, and S. M. A. Khader. "A computational fluid dynamics study of combustion and emission performance in an annular combustor of a jet engine." *Pertanika Journal of Science and Technology* 25, no. 3 (2017): 1019-1028.
[52] Long, A. K., M. Zubair, and K. A. Ahmad. "Static thrust measurement of two types of perforated solid propellant grain configurations." *Journal of Aerospace Engineering* 25, no. 4 (2011): 653-659.
[53] Mohamed, Abdel-Aziz Farouk Abdel-Aziz. "Hybrid Nanocrystal Photovoltaic/Wind Turbine Power Generation System in Buildings." *Journal of Advanced Research in Materials Science* 40, no. 1 (2018): 8-19.