Numerical and Experimental Investigations on a Dimpled Savonius Vertical Axis Wind Turbine

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Abstract - This research deals with the design and fabrication of novel designs as a means to harness wind energy using 'Savonius' Turbine. It is generally employed to harvest the low to extremely low wind speed potentials. They can be particularly of high use in the regions where the wind speeds are not high enough for installing conventional horizontal axis wind turbines. The paper introduces a novel concept of testing a Savonius wind turbine with dimple structures on its blades and investigating its effect on the turbine's efficiency. The study also deals with the experimental validation of the effect of using a converging ducted structure with a single stage and double stage configurations of Savonius wind turbine, apart from comparing the turbine's performance with and without endplates. The results of the study prove that power coefficient increases with the addition of dimple structures on the blades and it can be further augmented by using a ducted structure with the Savonius turbine.

Keywords: Vertical Axis Wind Turbine; Savonius; Single Stage, Double Stage; Golf Ball, Dimples; Experimental Testing

1. Introduction

The world is getting hotter over the decades [1], and the emission of greenhouse gases being the major reason behind it. Thermal energy sector contributes significantly to the sources of these emissions [2] and if we want to resolve the problem we must move towards renewable sources of energy. One such renewable energy resource worth being harvested is Wind Energy. Wind energy is one of the cost-effective technologies and is targeted sector by today's Government electricity production units for the future. Wind energy found its first application in propelling boats and ships long back. From pumping water in China using Horizontal Axis Wind Turbines (HAWT) to grinding grain in Persia and the Middle East using Vertical Axis Wind Turbines (VAWT), wind energy has been an answer to the undying needs of man for a long time now. The potential of wind is an unevenly distributed commodity in the world. The Northern and Western parts of India experience much higher wind speeds than the south-western part of India [3]. As a consequence, conventional wind turbines cannot be installed everywhere. The relatively unexplored Vertical Axis Wind Turbines could prove to be very useful to bridge the energy crisis in such regions. However, the question arises that if we are able to exploit the low wind potential, can we use it everywhere? This is where the unconventional wind turbines come into play.

HAWT are the most common types of wind turbines built across the world to tap potential from high wind velocities. VAWT (Vertical Axis Wind Turbine) which has two or more blades and the main rotor shaft runs vertically. Ryoichi S. Amano [4] and Ashwani K Gupta [5] have explained in detail about the research carried on Vertical Axis Wind Turbines in the current century. Nur Alom and Ujjwal K. Saha did a compilation on the research into the augmentation techniques of a Savonius turbine in the last forty years [6]. A Savonius Turbine is a VAWT, resembling a cup anemometer, as shown in Fig.1 below, in its design and working.

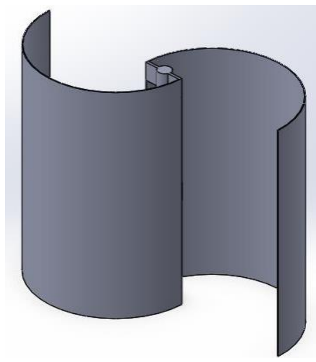
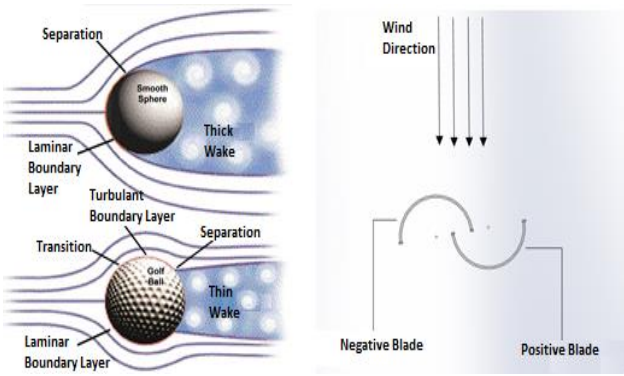


Figure 1. CAD model of a Savonius Turbine

It has many advantages over other turbines because its construction is simpler and cheaper. It rotates in fixed direction regardless of the flow of wind direction and has a good starting torque at lower wind speeds. The performance of Savonius rotor has been studied by many researchers to determine the optimum design parameters of this rotor. Michele Mari et al proposed a novel geometry for VAWT based on the Savonius concept [7] because of its ability to tap wind energy at low wind speeds. N.H.Mahmoud et al [8] concluded that two blades rotor is more efficient than three and four ones. They also concluded that the rotor with end-plates gives higher efficiency than those without end-plates, while the blade aspect and overlap ratio were studied by Alexander et al [9]. Taking inputs from our literature study, an effort is made here to experimentally compare the results obtained for Savonius turbine with and without endplates.

A Savonius turbine can be a single stage, double stage, and a multi stage turbine. Research has been carried out in the past to test the performance based on stages [10, 11], however not much open literature is available on testing based on the best overlap and aspect ratio. Based on the overlap and aspect ratios suggested for different stage rotors [12-14], experimental investigations have been carried out in the present research to compare the performance between single and a double stage rotor Savonius turbine.

It has been proven that dimple structures on a golf ball reduces drag on the surface enabling it to cover longer flight distance [15-18]. The size of the wake region behind the moving ball greatly affects drag force on it by the air. If this wake region is decreased by delaying the separation of air from the surface of the ball the total pressure behind the ball will increase. Therefore, the pressure difference in front of the ball and behind the ball will decrease resulting in a decrease of drag force constituted by air. These researches provided us with key insights into the analysis of the dimples and also led to think that if the same concept can be applied to reduce the drag on the negative blade of the Savonius Turbine. Spherical dimples were created on the negative surface and the turbine's performance was compared with and without the use of dimples.



(a) (b)

Figure 2. (a) Comparing golf ball and simple ball [19] (b) Blades of Savonius Turbine

2. Experimental Set-up

The experiment takes into account various models of Savonius wind turbine with different configurations such as single stage, double stage and turbines with dimple structures. These models were tested in combination with a converging duct in the wind tunnel. The overlap and aspect ratios of single and double stage turbines were chosen according to the literature survey [5-8] and the details are mentioned for each case as below:

The schematic diagram of the test rig used in the set-up is shown in Fig. 3 (a) and (b) below.

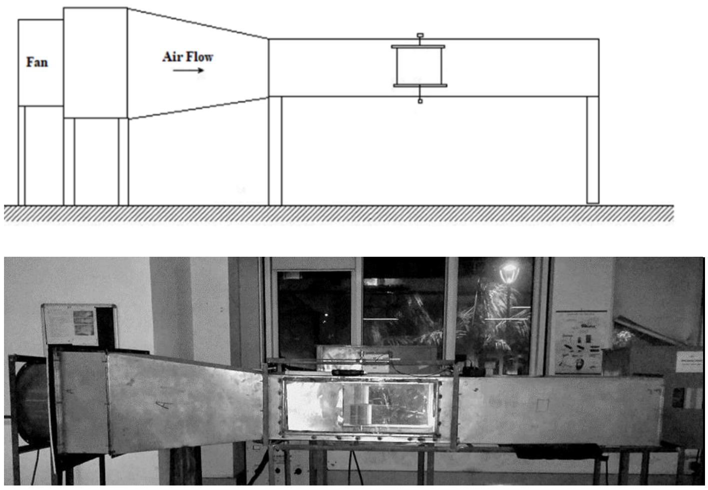


Figure 3. (a) Schematic of the test section (above) (b) Wind tunnel (below)

All the different models of the Savonius turbines were placed in the test section of the wind tunnel and tested for their performance. An anemometer measured the velocity of the wind. The rotation of the rotor was measured by a tachometer. Experiments were conducted for comparison between two bladed –

(i) Single stage turbines and double stage turbines - with and without dimple structures

The wind speed ranging for all the above mentioned testing was kept from 0.7 m/s to 6 m/s. This speed was taken in accordance with the design parameters and considering the use of duct, as higher wind speeds could have resulted in the breakage of the small scale model of the turbines made of plastic polymers. Also, the primary motto of this research was to capture and test the performance of a Savonius turbine for low to very low wind speeds which is otherwise not possible through any other wind turbines.

Design parameters of the different geometry configurations used in the investigations are described below.

2.1 Case 1: Single stage and double stage turbines

(a) (b)

Figure 4. Savonius turbines with endplates (a) single

stage (b) double stage

Parameters for single stage rotor as shown in Fig. 4 (a):

Wing spread of rotor (D) = 15.6 cm

Height of blades/shaft (h) = 24 cm

Diameter of turbine blades (d) = 8.5 cm

Spacing between blades (e) = 1.4 cm

Parameters for double stage rotor as shown in Fig. 4 (b):

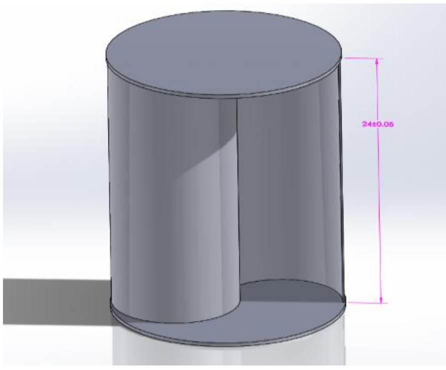
Wing spread of rotor (D) = 14.2 cm

Height of blades/shaft (h) = 24 cm

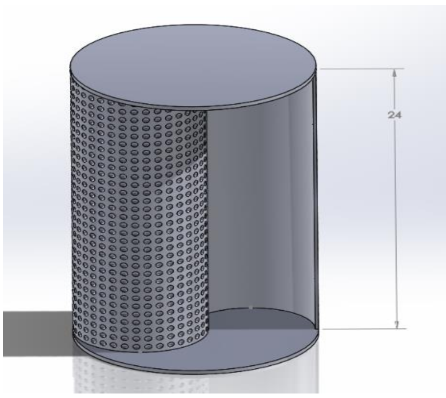
Diameter of turbine blades (d) = 8.5 cm

Spacing between blades (e) = 2.7cm

2.2 Case 2: Single stage and double stage turbines - with and without dimple structures



(a)



(b)

Figure 5. CAD Models of Savonius turbines (a) With Dimples (b) Without Dimples

The models were created on solid works of equal height and simulated on Ansys 16.2 fluent. Both the models were kept static in order to study the effect of wind on negative blades as well as to understand the development of wake region behind the turbine. Static analysis of the model was performed, to study the formation of wake regions behind the turbine blades. The aim was to observe the effect of dimples affecting the wake region and thus the drag forces on the turbine.

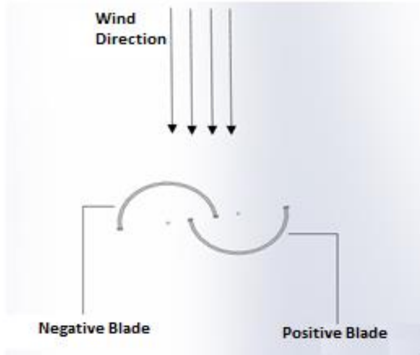
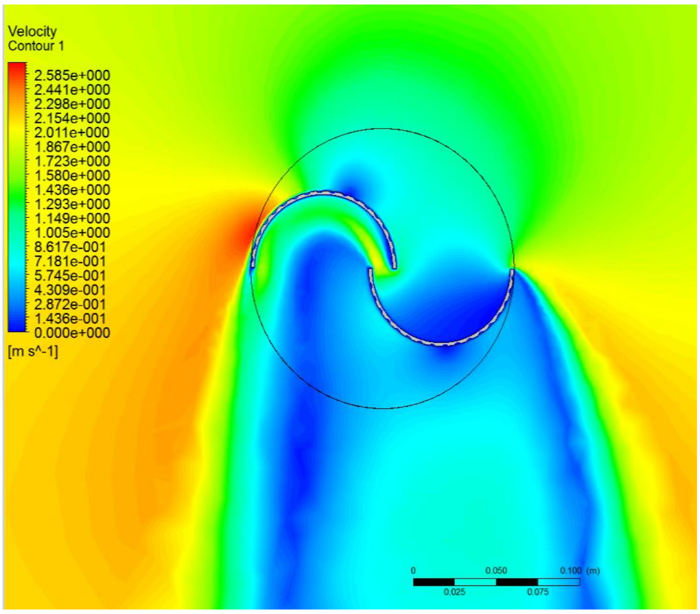
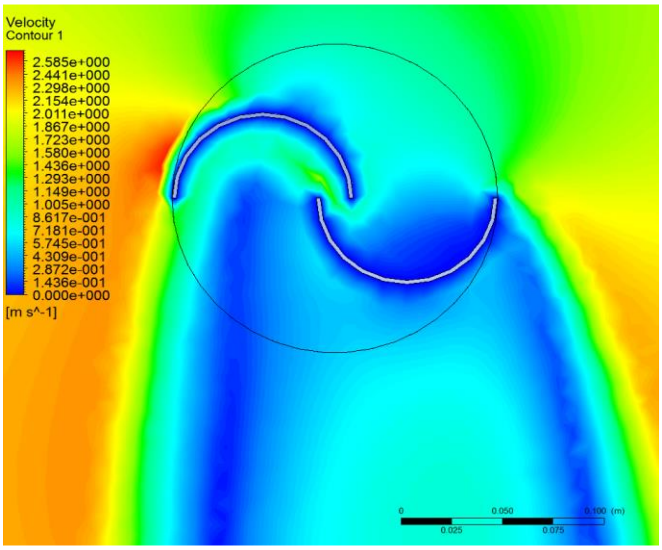


Figure 6. Direction of wind flow to simulate on Savonius turbines



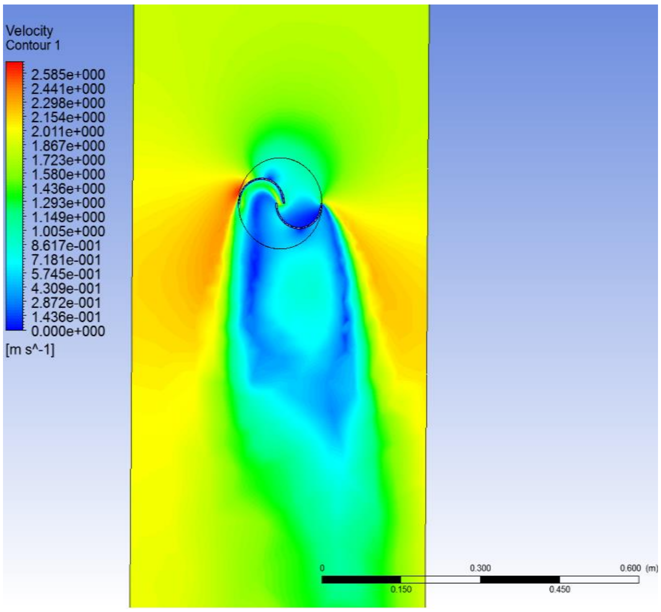
(a)



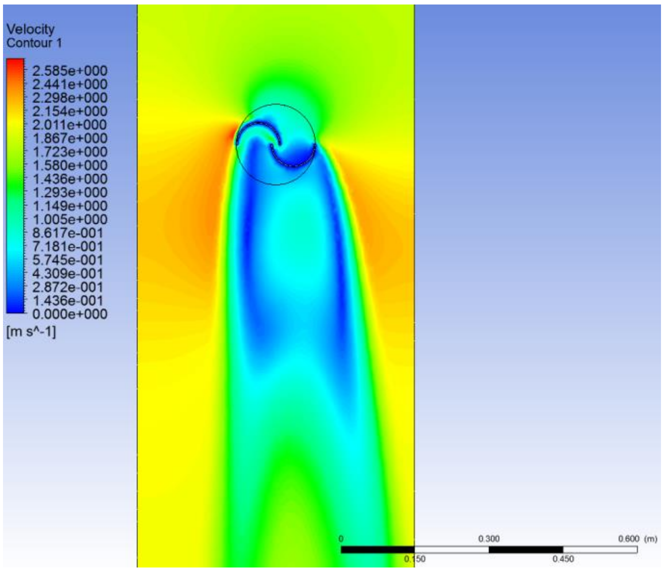
(b)

Figure 7. Static Simulation on Savonius Turbine (a) Dimpled Turbine (b) Without dimples

From Fig. 7 (a) and (b) it can be observed that on the negative blade of a simple turbine the accumulation of wind particles is higher than a dimpled turbine. Therefore, the wind has a greater impact on simple turbine negative blade compared to dimple turbine wherein the wind easily glides on the dimple negative blade.



(a)



(b)

Figure 8. Static Simulation on Savonius Turbine (a) Dimpled Turbine (b) Without dimples

From Fig. 8 it was also found that the wake region diminished in the case of dimpled turbine compared to simple turbine.

After obtaining these results, experimental investigation was done with the PVC models.

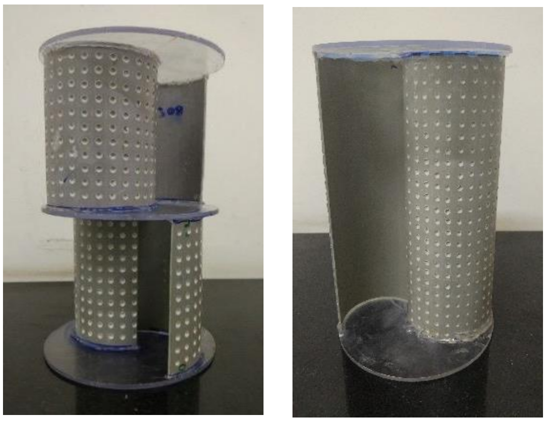
A set of single stage and double stage turbines with the same parameters as in previous Case 2, were fabricated and dimples created on them. The literature review on dimples helped finalize the size and the spacing between the dimples. Specifications of the dimples are:

Depth = 1 mm

Diameter of dimples = 4.5 mm

Spacing between the dimples = 1 cm

Experiments were performed to compare the performance of the turbines with and without dimples.



(a) (b)

Figure 9. Turbines with dimples (a) single stage (b) double stage

2.3 Case 3: Single stage and double stage turbine (PVC models) - with dimple structures

Parameters for single stage rotor with dimples as shown in Fig. 9 (a):

Wing spread of rotor (D) = 15.6 cm

Height of blades/shaft (h) = 24 cm

Diameter of turbine blades (d) = 8.5 cm

Spacing between blades (e) = 1.4 cm

Parameters for double stage rotor with dimples as shown in Fig. 9 (b):

Wing spread of rotor (D) = 14.2 cm

Height of blades/shaft (h) = 24 cm

Diameter of turbine blades (d) = 8.5 cm

Spacing between blades (e) = 2.7cm

3. Mathematical Formulations

Total amount of power, P that is available in the wind is

$$P_{\omega} = \frac{\rho \times A \times V^3}{2} \quad (1)$$

Where, ρ = density of the air, A = swept area of the turbine, and V = wind speed.

According to Betz law no wind turbine can convert more than 59.3% of the kinetic energy of the wind. The power coefficient, C_p is defined as the ratio of the total power output P_o by a wind turbine with the total power P_ω available to the wind turbine.

$$C_p = \frac{P_O}{P_\omega} \qquad (C_{p,max}=0.59) \qquad (2)$$

The theoretical maximum power efficiency of any design of wind turbine is 0.59 (i.e. no more than 59% of the energy carried by the wind can be extracted by a wind turbine). C_p value is unique for each setup and depends on the wind turbine's strength and durability as well as surrounding conditions like air density and turbulence, due to which C_p comes out to be much lower than 0.59 and incorporating other engineering systems which are used in a wind turbine setup like gearbox, generator, bearings, the efficiency gets further reduced. C_p represents only the aerodynamic efficiency of the wind turbine and thus takes losses due to turbulence and other environmental conditions as well as turbine's physical properties into account and not the mechanical losses [20-26]. Therefore, P_o converted from the wind into rotational energy in the turbine can be found Eq. 3

$$P_O = \frac{\rho \times C_P \times A \times V^3}{2} \qquad (3)$$

C_p depends on how the turbine behaves in a particular condition i.e. for different rotational speeds of turbine, C_p is different. That implies that C_p is a function of the Tip Speed Ratio (TSR) λ, which is defined as

$$\lambda = \frac{TipSpeedoftheBlade}{WindSpeed} = \frac{(\omega \times R)}{V} \qquad (4)$$

The output power P_O is found experimentally,

$$P_O = \frac{V^2}{R} \qquad (5)$$

Here,
V = Voltage measured across the terminal the circuit
R = 50 Ω External Resistance attached to the circuit. As the resistance of DC motor is negligible when the external resistance is attached in series with the motor.

The following graph shows the relations obtained using the turbine with different configurations between various parameters for single stage, double stage, ducted and dimpled turbines. The power here was measured with the help of dynamo and taking a load resistor of 50 ohms. The torque was calculated with the help of power using the relation mentioned in Equation 6, while the wind speed was calculated with the help of an anemometer.

4. Comparison Between Single Stage and Double Stage Turbines - with and without Dimple Structures

The following data were recorded during the experiments.

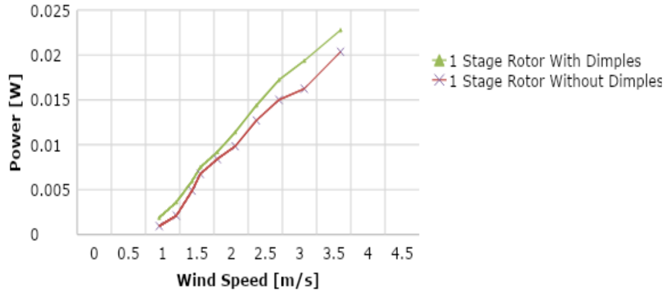


Figure 10. Variation in power with wind speed for 1-stage rotor with and without Dimples.

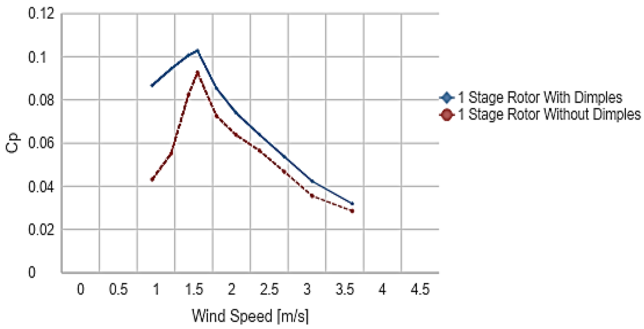


Figure 11. Variation in C_p with wind speed for single stage rotor with and without Dimples

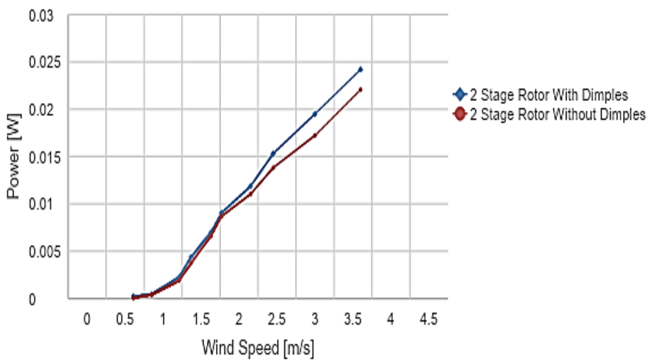


Figure 12. Variation in power with wind speed for two stage rotor with and without Dimples

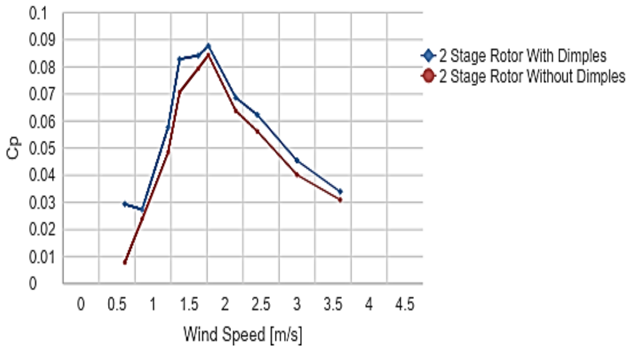


Figure 13. Variation in C_p with wind speed for two stage rotor with and without Dimples

Figs. 10, 11, 12 & 13 show that the performance of the turbine is enhanced greatly when the rotors are used with dimple structures for all wind speed ranges.

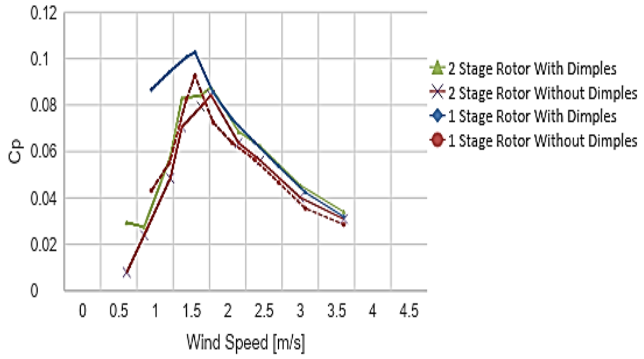


Figure 14. Variation in C_p with wind speed for single and double stage rotors – with and without Dimples

Fig. 14 shows performance of all rotor configurations. It can be seen that a single stage rotor with dimple structures performs best at wind speeds lower than 2.5 m/s, and then gradually a double stage rotor with dimple structures takes over.

Table 1. Wind speed versus % Cp increase

(a)

Wind Speed	% Cp increase 1 stage rotors
1.2	101%
1.45	71%
1.68	22%
1.8	11%
2.05	18%
2.31	16%
2.62	13%
2.95	15%
3.32	19%
3.85	12%

(b)

Wind speed	% Cp increase 2 stage rotors
0.86	272%
1.1	15%
1.46	19%
1.62	17%
1.88	6%
2.02	4%
2.4	8%
2.7	11%
3.25	13%
3.85	10%

Table 1 (a) shows % increase in Cp for 2 stage rotor by the implementation of dimples, and (b) shows % increase in Cp for 1 stage rotor by the implementation of dimples

5. Conclusion

In this work following concepts have been introduced and tested experimentally in a wind tunnel –

- A Comparison between the use of a single stage and double stage rotors is also done.
- A concept of using dimple structures has been introduced.

Following can be concluded from the experimental results:

- Single stage performs better at lower wind speeds (less than ~ 2m/s), and the double stage turbine outperforms, however marginally, at higher wind speeds.
- The results obtained shows that the dimple structures gave higher output power, in both single stage and double stage rotor.

Innovative design and development of vertical axis wind turbine with dimples for given power output has been accomplished. The combination of these concepts in design show much promise to lower the cost to manufacturers with enhanced performance which may give viable solution to green energy production.

Acknowledgements

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Abbreviations, Notations and Nomenclature

Pω	Total Wind Power available
ρ	Density of the air
A	Swept Area of the Turbine
Po	Power Output by the wind turbine
C_p	Coefficient of Power
λ	Tip Speed Ratio
ω	Angular velocity of turbine in rad/sec
R	Radius of the Turbine
H	Height of Turbine
D	Diameter of the Turbine
rpm	Turbine speed in revolutions per minute
VAWT	Vertical Axis Wind Turbines
e	Spacing between blades
d	Diameter of turbine blades

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