Design Optimization of Vertical Axis Wind Turbine

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Abstract- *This paper consists of designing and testing the performance of a Savonius Vertical Axis Wind Turbine. The project compares the performance of existing savonius Turbines and establishes the factors for improvement in performance and efficiency to develop a completely new design. A Computer Aided Design (CAD) tool was used to design the Savonius Rotor. Computer simulations, both 2D and 3D, were run to understand the characteristics the rotor, and to obtain its pressure profile when subjected to a wind flow. Then necessary modification were done to the design to optimize the efficiency and power input*

I. INTRODUCTION

Increasing demand for energy facilitated need for clean energy such as wind energy. Wind energy is the most potential alternative source for renewable energy

This mostly pollution free andabundantly available in the earth's atmosphere.The interest in wind energy has been growing and many researchers have to introduce and develop cost-effective and reliable wind energy conversion systems.

Residents, buildings, and commercial establishments need more power everyday and also continuous power. Important facilities such as wireless or radio sets also require small amounts of energy continuously.

This study was done to investigate the design and development of Vertical Axis Wind Turbine(VAWT) – Savonius type.

1.1 Objective of proposed system

Following are the some objectives of the proposed system;

1. Optimization of blade shape for more power generation.
2. To generate a better power in presence of low wind speed.
3. Implementation expenses are low.
4. No additional space is required for implementation.
5. No environmental effects.

1.2. Scope of proposed system

Following are the scope of the proposed system;
1. This system is useful where low wind speed is available.
2. It can generate power in less cost.

1.3. Methodology Adopted

In this paper a new vertical axis wind turbine of modified aerodynamic shaped Savonius type is designed. A new vertical axis wind turbine of modified Savonius rotor type has been designed, constructed, and tested. Conventional Savonius or modified forms of the conventional Savonius rotors are being investigated in an effort to improve the coefficient of power and to obtain uniform coefficient of static torque. This turbine has been designed to operate in low wind speed and it can capture wind at any direction due to the shape and design of the rotor blade. The wind turbine model has rotor diameter of 350 mm and rotor height of 1420 mm. Tests were carried out to measure and evaluate the performance of the rotor. During the test, the parameters that were measured are wind speed, rotor torque and power output. The experimental results were compared with both conventional Savonius rotor system and modified Savonius rotor system. In this project an innovative vertical axis wind turbine of Savonius type is designed, constructed, and then tested to evaluate its performance. This innovative rotor is able to rotate at low wind speed (2 m/s ≤wind speed ≤ 8 m/s) and able to produce a good mechanical power that could be used to generate electricity.

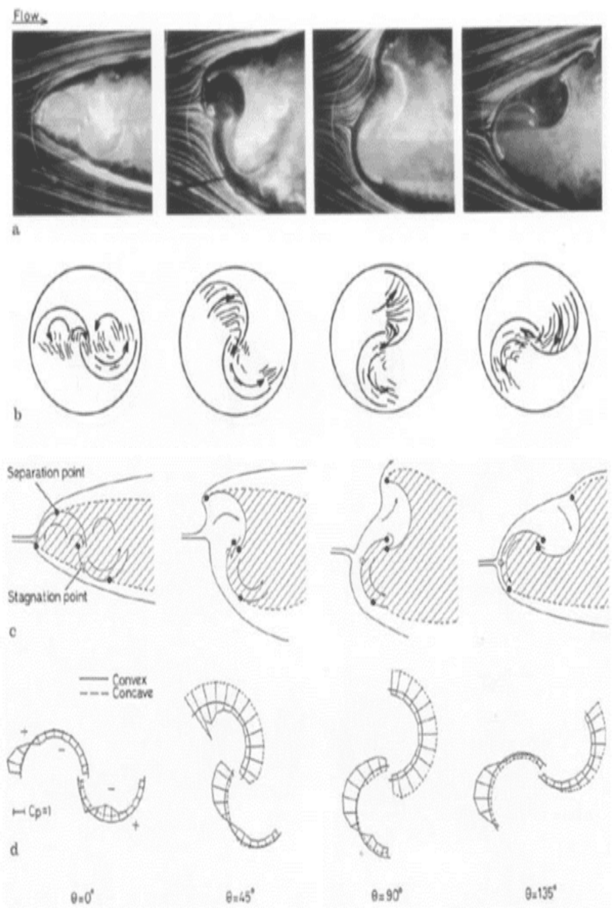
II. WIND FLOW IN SAVONIUS ROTOR

The flow field in the Savonius rotor is closely related to the torque and power performance and helps to understand the power producing mechanism. Several experiments have been performed by researchers to determine the flow pattern inside a Savonius rotor. The experiment is designed to investigate the instantaneous flow field in and around the rotor. Various tip speed ratios are considered and the flow and pressure distribution around these rotors is studied. The rotor considered in the experiment has the following geometrical parameters:

$\alpha = 1$, $\beta = 0.15$, $D_o = 1.1D$ and $H = D = 300$ mm

The experiments are carried out at a air flow velocity of U = 1.5 m/s.

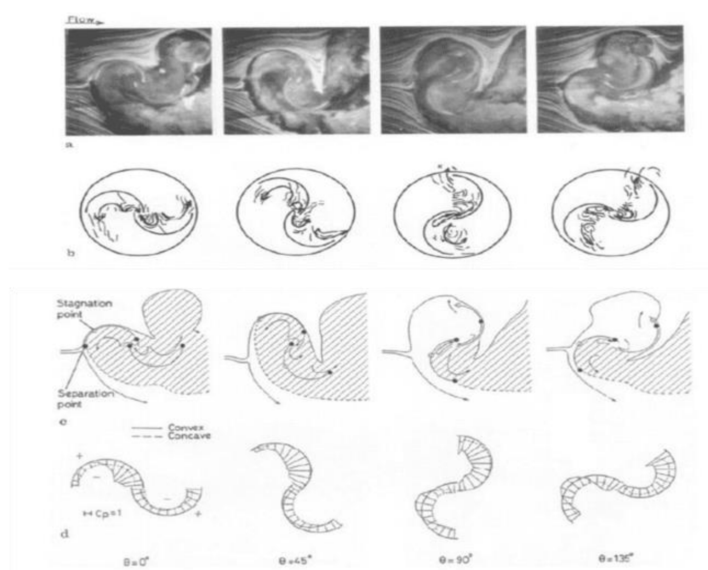
Figure – 2.1 (a) shows the flow around a still Savonius rotor at four rotor angles, θ = 0°, 45°, 90°, 135°. It presents the visualized external flow (a), smoke patterns inside the rotor (b), flow models showing the main features of the flow field (c) and the pressure coefficient on the blade surfaces (d). It can be seen that the external flow on the rotor separates on both the sides of the rotor. On the front side in (a), a stagnation point appears and moves from the advancing edge at small rotor angles, θ = 0° - 45° to the returning one at large rotor angles θ = 90°- 135°. Therefore, the stagnation force is expected to be maximum around rotor angles of θ = 45° to 90°. The difference in pressure coefficient on both the concave sides causes flow through the overlap, which proceeds from the advancing to the return blade.



a. Visualized flow field, b. Flow inside the rotor, c. Flow model, d. Surface Pressure

Figure: 2.1 Flow in and around a still Savonius Rotor. Flow through the overlap induces a pressure recovery effect on the concave side of the returning blade thereby decreasing the drag force on the returning blade. The flow is strengthened for the rotor angles θ = 45° to 90° as expected from the pressure distributions near the overlap (d).

The flow pattern for a moving rotor differs significantly from the pattern of a stationary rotor, as shown in Figure – 2.1 (b). The separation point moves downwards and the pressure coefficient on the convex side of the advancing blade are reduced. This attached flow tends to separate at larger rotor angles due to the outward flow motion at the tip of the advancing blade. This flow is induced by the pressure gradient induced on the concave side of the advancing blade. The injected flow grows into a vortex circulating in the rotating direction of the rotor and increases in size downstream. These attached flow patterns in the rotor contribute to the rotating torque. The stagnation points moves towards the centre of the rotor due to the rotation effect. In comparison with the still rotor, the flow through the overlap is reduced due to the production of resisting flow. It is also found that the tip speed ratio has a significant effect on the torque characteristics of the rotor. With increasing tip speed ratios, the points of separation vary shown in Figure – 2.1 (b). [10]



a. Visualized flow field, b. Flow inside the rotor, c. Flow model, d. Surface Pressure parameters.
Figure: 2.2 Flow in and around a Savonius Rotor rotating at TSR = 0.9

This is due to poor modelling of the separation of flow at the rotor blade edges. Parametric investigation was performed in order to determine the optimum configuration of various parameters like overlap ratio, aspect ratio etc. by numerical simulations. The following geometrical characteristics of the rotor were considered for the numerical simulations:

$\alpha = 1$, $\beta = 0.242$, $Do = 1.1D$ and $ReD = 1.56 \times 103$

Figure – 2.2 (c) shows the pressure distribution in Pascal's obtained by the numerical simulations performed on a conventional shaped rotor with semi-circular blades without a central shaft. The values of pressure coefficients and efficiency predicted by numerical methods are substantially higher than the experimental values. The velocity field is simply the inverse of the pressure field as shown.

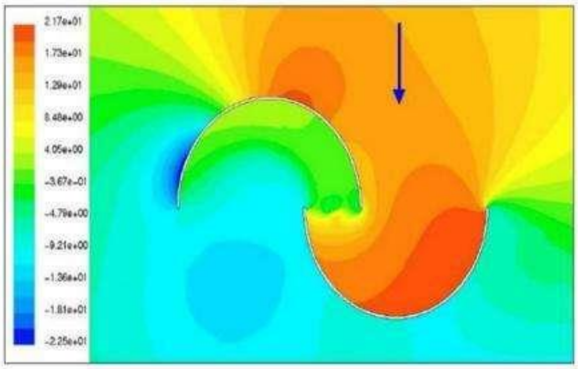


Figure: 2.3 Pressure Distributions in Pascal's for a Savonius Rotor [10]

Therefore, the velocity field inside and around a Savonius rotor is closely related to the torque and performance characteristics of the rotor. The following chapter lists the optimum configuration of the rotor geometrical parameters to obtain the best possible performance.

III. DESIGN AND CALCULATIONS

3.1 Factors to be considered

Following factors are to be considered,

3.1.1 Suitable site

While selection of suitable site we must keep a note that it must be placed where plenty of air flows without obstructions i.e. at a certain elevated height.

3.1.2. Types of wind mill

From different types of wind mill the multi back flow is selected. As we have sufficient speedy air and also losses for this type of wind mill is minimum.

3.1.3. Aerodynamics design

While studying on the design of wind mill we come to conclusion that blade should be kept in a certain angle to still away the momentum from the approaching wind. Thus the wind come horizontally hits the blade which is kept at fixed angle.

3.2. DEFINITIONS OF PARAMETERS

Several performance parameters govern the performance of a Savonius rotor.

3.2.1. Overlap Ratio (β)

It is the ratio of the overlap distance (a) to the diameter of the rotor blades. It gives an indication of the extent of blade overlap for a particular configuration of the blades. It is given by:

$$B = \frac{a}{2R}$$

3.2.2. Aspect Ratio (α)

It is the ratio of the height of the rotor to its diameter. It is a measure of the extent to which the maximum dimension of the rotor differs from the minimum dimension.

$$A = \frac{H}{D}$$

3.2.3. Tip Speed Ratio (λ)

Tip speed ratio or TSR, is the ratio of the rotational speed of the blade to the actual velocity of the air stream. A higher tip speed ratio is indicative of higher efficiency but is also related to higher noise levels and the need for stronger blades. TSR is quite important in the design of any wind turbine. If the rotor of the wind turbine turns too slowly, most of the wind will pass undisturbed through the gap between the rotor blades. Alternatively, if the rotor turns too quickly, the blades appear stationary to the wind. Therefore, wind turbines are designed with optimal tip speed ratios to extract as much power out of the wind as possible.

$$\lambda = \frac{\omega . D}{2U}$$

3.2.4. Reynolds Number (Re)

Reynolds number is the non-quantity that gives a measure of the inertial forces to the viscous forces in a given flow. They are used to perform a dimensional analysis of a given problem. The length scale that is used to obtain the

Reynolds number is different in different situations. In each of the cases discussed in the report, the length scale is given by the diameter of the rotor, and the Reynolds number is hence, given by:

$$Re = \frac{\rho U D}{\mu}$$

3.2.5. Torque Coefficient (Ct)

Torque Coefficient is the dimensionless torque of the rotor. The formalizing term is the product of the dynamic pressure due to the wind, an area term and a length equivalent of the rotor. The starting torque coefficient (Cts) is another non dimensional quantity associated with the performance of a rotor. It is obtained by replacing the torque in the torque coefficient equation by the starting torque. It is given by:

$$Ct = \frac{4T}{\rho U2D2H}$$

3.2.6. Coefficient of Power (Cp)

Coefficient of power is the non-dimensional power that is generated in the rotor. It is the ratio of the power produced in the rotor to the total kinetic energy of the air interfaced by the rotor. It is given by; [2]

$$Cp = \frac{\text{Power produced by rotor}}{\text{Energy in interfaced air}}$$

$$Cp = \frac{P}{(1/2\rho\ U3)\ (DH)}$$

$$Cp = \frac{2\ T\ \omega}{\rho D\ H\ U3}$$

$$Cp = Ct.\ TSR$$

3.3. Different dimensions for the Conventional rotor system and Modified rotor system

Table: 3.1. Calculation table for conventional and Modified Savonious rotor system for 42 Watt power [11]

Sr. No.	Parameter consider	Calculated Dimension (conventional)	Calculated Dimension (Modified)
1	Rotor overlap (a)	52.5 mm	No overlap
2	Rotor Diameter (D)	657.5 mm	180mm
3	Rotor Height (H)	7320 mm	4570mm
4	Number of plates	25	19
5	Flange diameter (Do)	316.25 mm	198mm
6	Volume of material used (V)	5.53×10^6 mm^3	5.05×10^6 mm^3
7	Mass of rotor (M)	7.85 Kg	6.05 Kg
8	Power/unit mass	5.34 W/Kg	6.94 W/Kg
9	Intercepted area (A)	2.1045×10^6 mm^2	1.08×10^6 mm^2
10	Power/unit area	20 Watt/ m^2	38.88 Watt/ m^2

3.4. Theoretical power generated by conventional Savonius rotor

Standard Overlap Ratio (β) 0.15

Rotor blade inner radius (R) 175mm

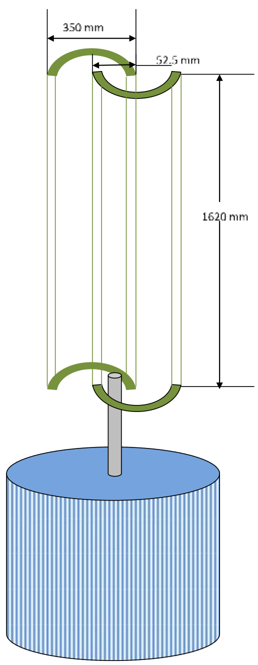
Thickness of blade material (t) 5 mm

(I)Calculation of rotor overlap (a)

Overlap ratio (β) = a / 2 R = 0.15
a = 0.15 x 2R
= 0.15 x 2(175)
∴ a = 52.5 mm

(II)Calculation of rotor diameter

The following relation can be derived from the rotor geometry
D = 4R + 2t – a
= 4 (175) + 2(5) - 52.5
= 657.5 mm
D = 0.6575 m
Height of blade H = 1620 mm = 1.62 m
Area of wind turbine A = D x H = 0.657 x 1.62
=1.064 m2
Power output (P) = 0.5 A x ρ x V3
x Cp
= 0.5 x 1.064 x 1.2 x 63
x 0.154
∴ P = 21.24 watt



Length of Blade = 1620 mm
Width of Blade = 350 mm
Number of Blade = 3 NOS
Radius of Turbine = 1 Meter
Air Velocity = 6 m/s
Material = FRP (Fibre Reinforced Plastic)
Weight of Blade = 5.5 Kg
Arm Section = 50 × 25 × 3 mm
For air velocity = 6 m/s
RPM generated by turbine blade from software at 6 m/s = 33 rpm
V tip = 3.14 x D x N / 60
V tip = 3.14 x 2 x 33 / 60
V tip = 3.45 m/s
TSR = V tip / v = 3.45 / 6 = 0.57 (Cp = 0.154)

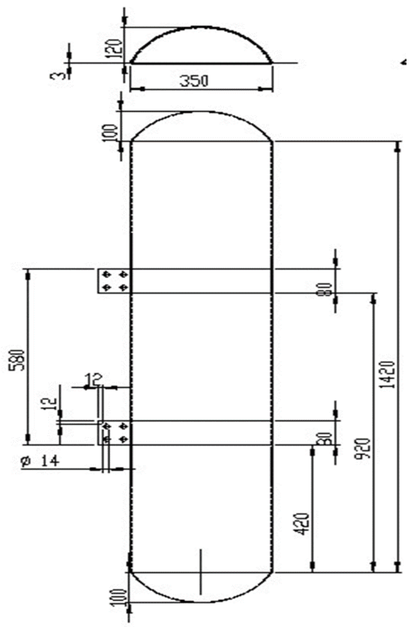


Figure: Modified Wind Mill Rotor

Power Output = P = 0.5 x A x ρ x v3 x Cp
∴ P = 0.5 x 1.62 x 2 x 1.2 x 63 x 0.154
∴ P = 65 watt

3.5Theoretical power generated by modified Savonius rotor:

Length of Blade = 1620 mm
Width of Blade = 350 mm
Number of Blade = 3 NOS
Radius of Turbine = 1 Meter
Air Velocity = 6 m/s
Material = FRP (Fibre Reinforced Plastic)
Weight of Blade = 5.5 Kg
Arm Section = 50 × 25 × 3 mm
For air velocity = 6 m/s
RPM generated by turbine blade from software at 6 m/s = 33 rpm
V tip = 3.14 x D x N / 60
V tip = 3.14 x 2 x 33 / 60
V tip = 3.45 m/s
TSR = V tip / v = 3.45 / 6 = 0.57 (Cp = 0.154)

3.6. Design of Arm

Section of arm = 50 x 25 x 3 mm
Force generated by blade,
F = 0.5 x v2 x A x density x drag coefficient
F = 0.5 x 62 x 1.62 x 0.35 x 1.2 x 2.3
F = 28.16 N
Length of arm = 470 mm
Torque of arm = F x L = 28.16 x 470 = 13235.2 N mm

T = 13.2 N- m

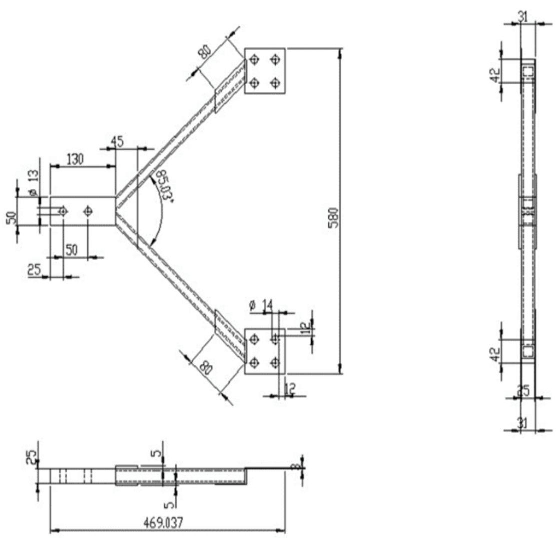
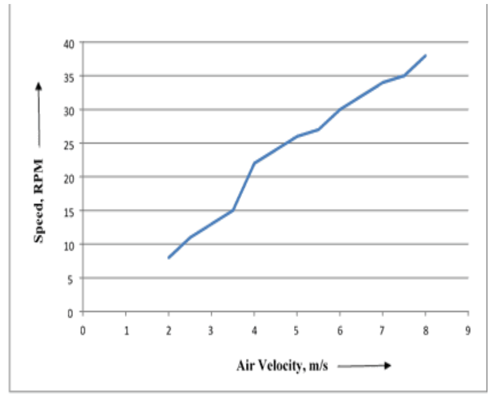


Figure: 3.3 Cross section of arm

Dimensions for the rectangular bar:
Rectangle (tube)

Width, aa = 50 mm
Height, bb = 25 mm
Wall thickness, ta = 3.00 mm
Wall thickness, tab = 3.00 mm
Y NA = 12.5 mm
Area = 414 mm2
We know that,
Maximum bending moment
M = WL/4
M = 28.16 x 470 /4
M = 3308.8 N-mm,
Also, we know that,
induced = M/Z
Z = (BH3- bh3) / 6 h
Z = (25 x 503 – 19 x 443) / 6 x 44
Z = 5706 mm3
F_b induced = 3308.8/5706 = 0.57 N/ mm2
F_b allowable = 70 N/mm2
As induced stress is less than allowable stress design of arm is safe.

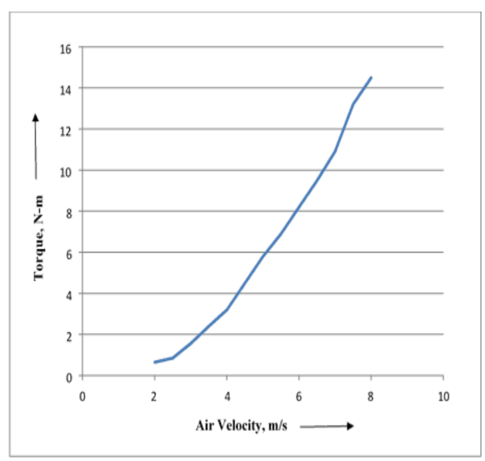
3.7.Reading taken forConventional Savonius Rotor system:



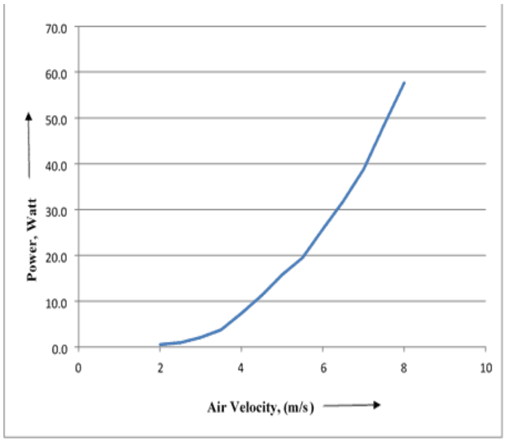
Graph: 1 Air Velocity (m/s) Vs Speed (RPM) for conventional savonius rotor system

Table: 3.2. Experimental readings for conventional Savonious Rotor System [2]

SR. NO.	AIR VELOCITY m/s	SPEED RPM	TORQUE N-m	POWER Watt
1	2	8	0.65	0.5
2	2.5	11	0.85	1.0
3	3	13	1.56	2.1
4	3.5	15	2.4	3.8
5	4	22	3.2	7.4
6	4.5	24	4.5	11.3
7	5	26	5.8	15.8
8	5.5	27	6.9	19.5
9	6	30	8.2	25.7
10	6.5	32	9.5	31.8
11	7	34	10.9	38.8
12	7.5	35	13.2	48.4
13	8	38	14.5	57.7



Graph: 2 Air Velocity (m/s) Vs Torque (N-m) for conventional Savonious rotor system

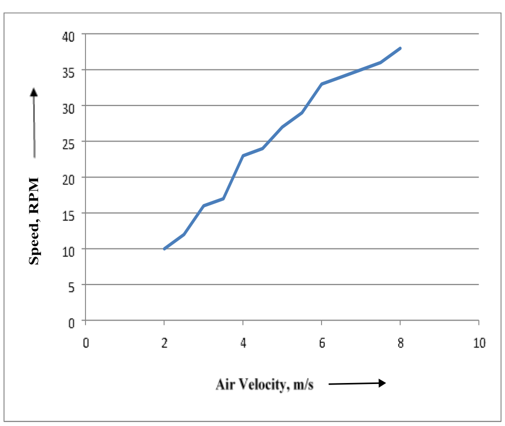


Graph: 3 Air Velocity (m/s) Vs Power (Watt) for conventional Savonius rotor system

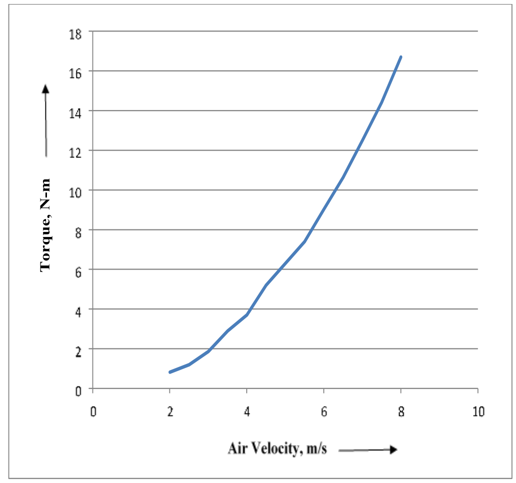
3.8. Reading taken for Modified Savonius Rotor System:

Table: 3.3. Experimental readings for Modified Savonious Rotor System [2]

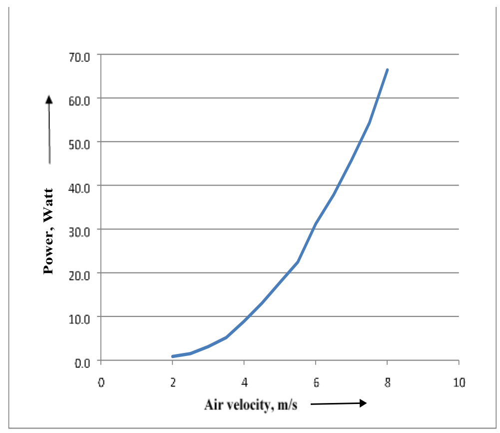
SR NO	AIR VELOCITY	SPEED	TORQUE	POWER
	m/s	RPM	N-m	Watt
1	2	10	0.82	0.9
2	2.5	12	1.2	1.5
3	3	16	1.86	3.1
4	3.5	17	2.9	5.2
5	4	23	3.7	8.9
6	4.5	24	5.2	13.1
7	5	27	6.3	17.8
8	5.5	29	7.4	22.5
9	6	33	9.03	31.2
10	6.5	34	10.63	37.8
11	7	35	12.5	45.8
12	7.5	36	14.41	54.3
13	8	38	16.7	66.4



Graph: 4 Air Velocity (m/s) Vs Speed (RPM) modified Savonius rotor system



Graph: 5 Air Velocity (m/s) Vs Torque (N-m) modified Savonius rotor system



Graph: 6 Air Velocity (m/s) Vs Power (Watt) modified Savonius rotor system

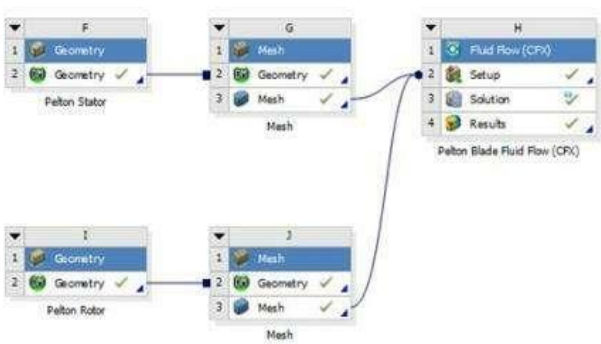
IV. COMPUTATIONAL ANALYSIS

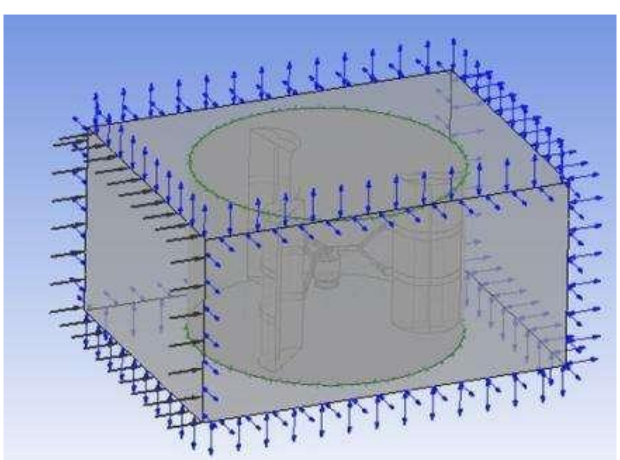
This simulation is obtained from CFD analysis.The torque at the rotor surfaces for modified Savonius rotor induced. The pressure difference between concave and convex blade surfaces induces force that turns the blade. The torque induced was obtained by implementing Computational Fluid Dynamics (CFD) analysis on solid Works Flow simulation. The flow types in this work are internal flow analysis. The analysis was static analysis. The engineering goals for the internal flow analysis and external analysis are two surface goals and four global goals are dealing with total pressure for both concave and convex surface. The four global goals are dealing with total pressure, for both concave and convex surface. The four global goals are deal with total pressure, velocity, normal force and force.

In this work the flow analysis was done for the different inlet velocities on the rotor blade and the torque generated for the different velocities are use to calculation of the power to find out the improvement in power transmission capacity of modified Savonius rotor as compare to the conventional savonius rotor. The factors affecting the performance of savonius rotor is as follows;i. Density of airii. Width of blade iii. Length of blade iv. Diameter of blade v. Rotational effect of air velocityvi. Atmospheric Temperature vii. Humidity in atmosphere

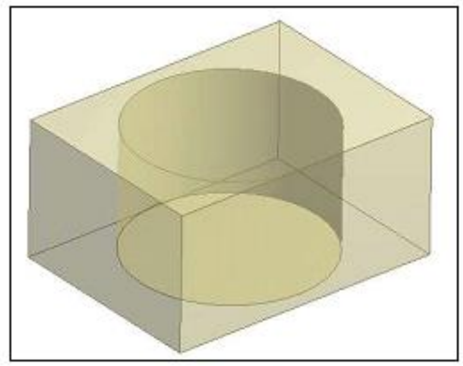
The flow analysis for the modified Savonius rotor is done for the range of wind velocity from 2 m/s to 8 m/s, and the computational domain is 5 m x 5 m x 15 m for the internal flow analysis. Flow through the savonius rotor blade, and then exit through the outlet that is set to environmental conditions. The savonius rotor blade is placed in the middle of wind tunnel. In internal analysis, the computational Domain is automatically enveloped the model wall, which is the wind tunnel size for this work. The lids are used to apply boundary condition. The lid thickness for an internal analysis is usually not important. However, the lid should not be so thick until the flow pattern is affected downstream in some way. If the lid is created to be too thin, this will make the number of cells to be very high.

Rotor and stator assembly are mesh separately and then assemble together in CFX

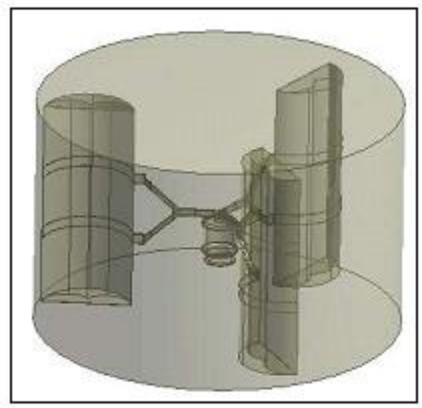




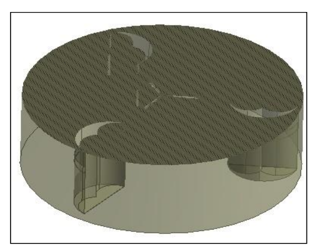
CFX Combine View



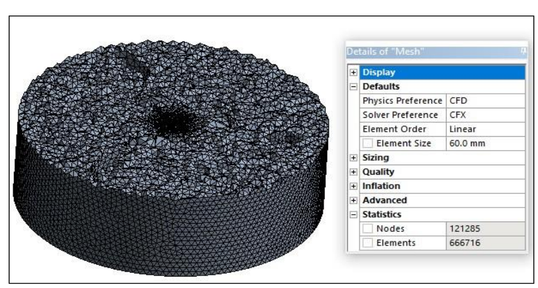
Stator



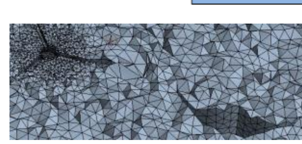
Rotor



Rotor Cut View



Rotor Mesh

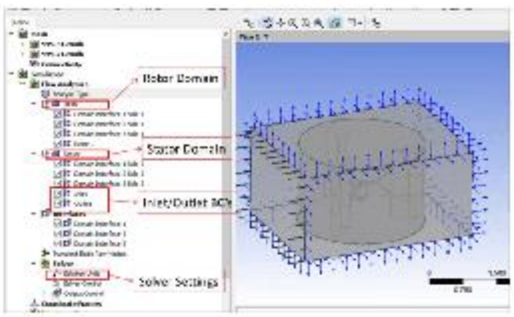


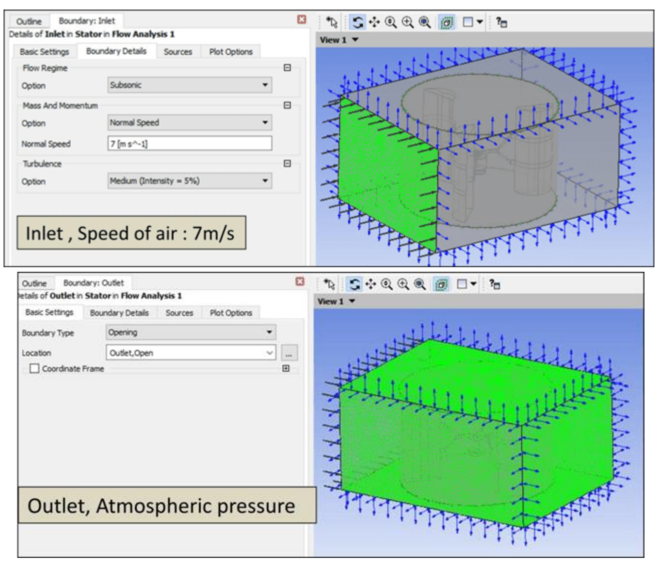
Nodes: 121285
Elements: 666716

Stator Mesh

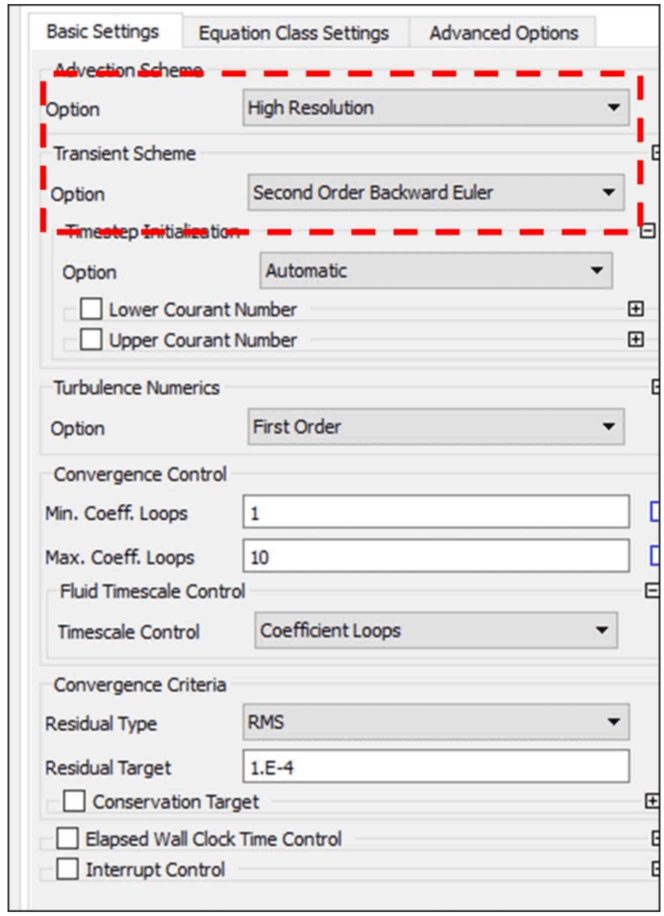
Nodes: 44022
Elements: 224339

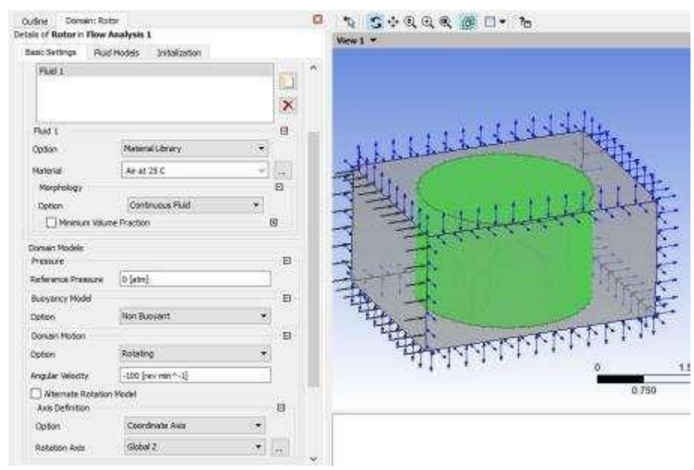
Loads and BC's Layout

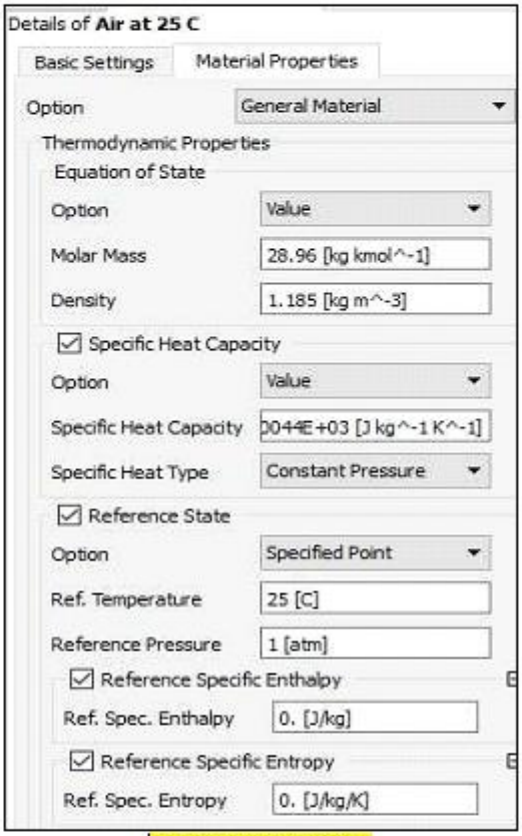




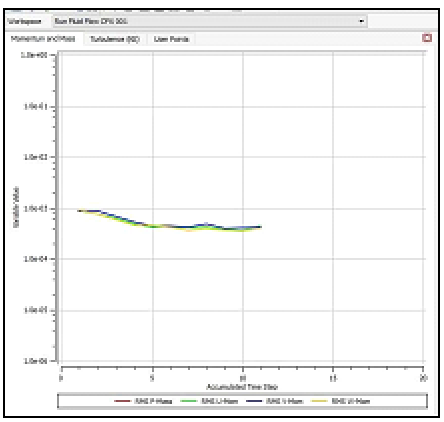
Solver Settings

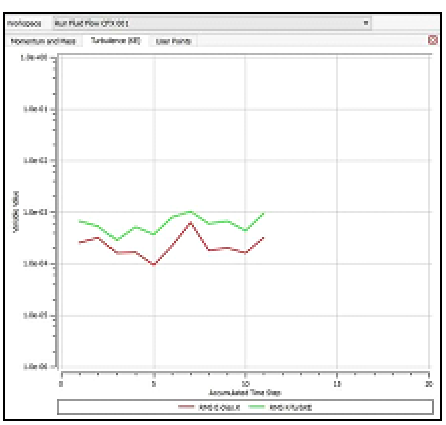






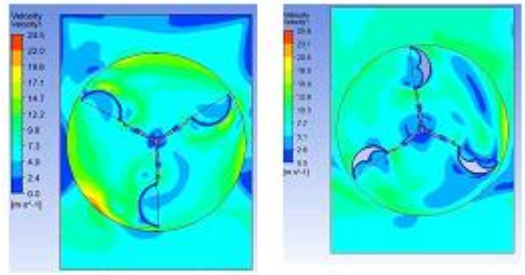
Air Material Definition

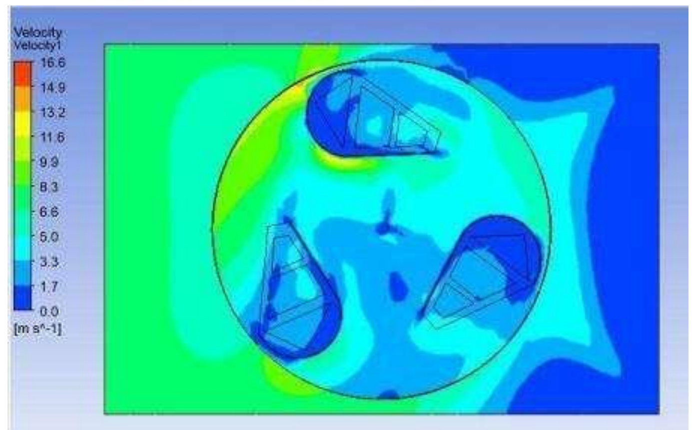




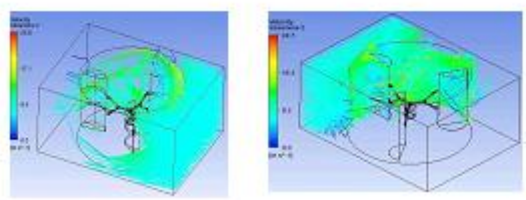
10 Iteration are required to stabilise the solution.

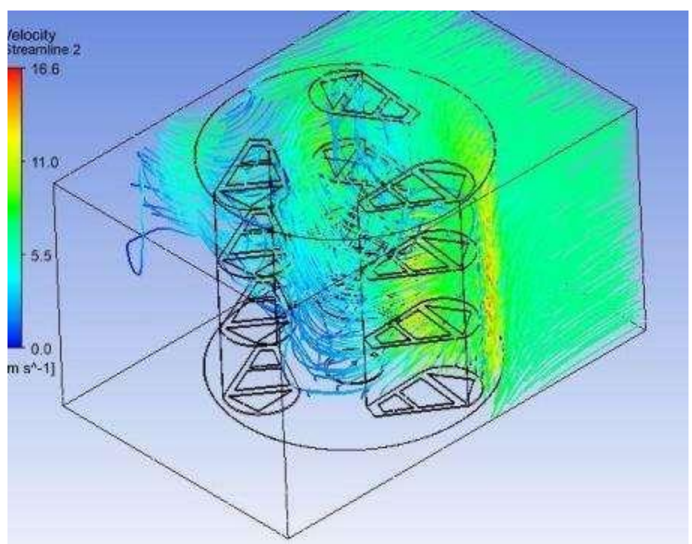
Velocity Plot:



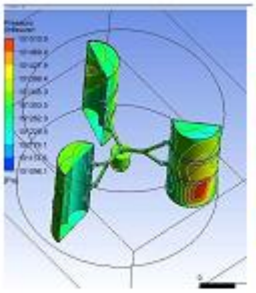


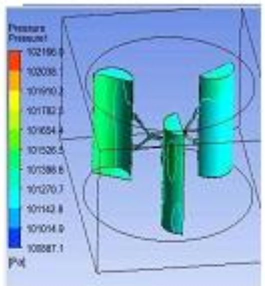
Velocity Pathline Plot:

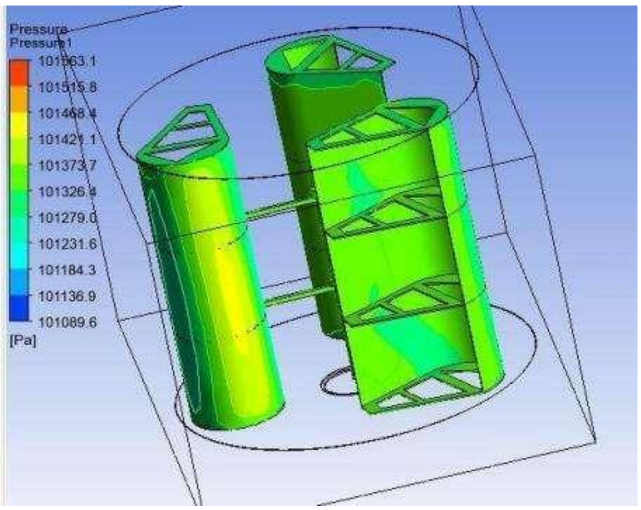




Pressure Plot:





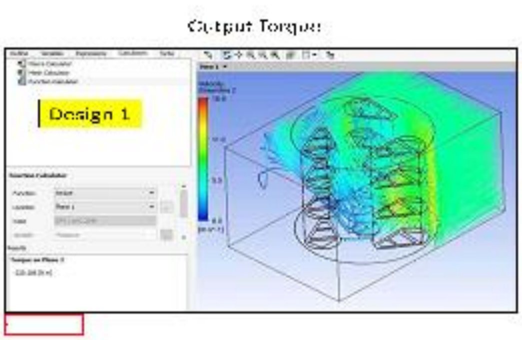


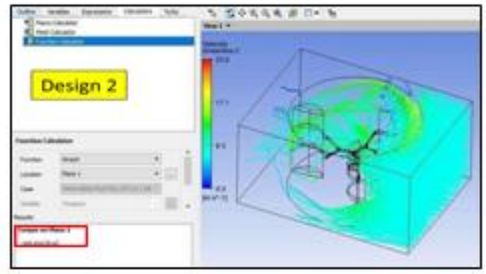
V. RESULT

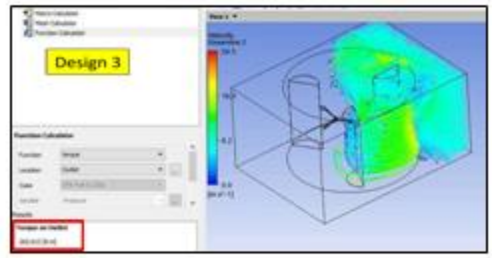
From the above computational analysis, Torque obtained for various design as follows:

SR NO	Air Velocity	Design 1	Design 2	Design 3
		Torque	Torque	Torque
	m/s	N-m	N-m	N-m
1	7	220	342	265

As per above observation the blade design 2 gives maximum torque so design 2 will give as maximum power.







VI. CONCLUSION

The flow analysis for all three different shape blade is done for the wind velocity 7 m/s. For this wind velocity calculating the power obtained by the experimental reading and compares it with the power of conventional Savoniusrotor system. Also, it will compare with the valuesobtained from the computational analysis. Following table shows the comparison of torque and power for conventional Savonius rotor system, and different shape blade rotor system and values obtained from the computational analysis.

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