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Experimental Studies of an IceWind Turbine

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Abstract

IceWind turbine, a new type of Savonius Wind Turbine, is proposed by an Iceland based startup. It is a product without any published scientific research. As an innovative type, it desires explorations. This paper investigates experimentally its performance. It also makes a parametric study. An optimum design is discovered and a comparison between the proposed two blades IceWind and Savonius wind turbine of the same swept area is completed. Experiments are conducted taking into account these parameters; number of blades, existence of end plates, number of stages, aspect ratio and blade arc angle. The experiments are performed in a wind tunnel at five wind speeds (8.4, 9.4, 11.5, 13.7 and 15.8 m/s). Turbines are built using Aluminum sheets. Static torque in Nm and rotational speed in rpm are measured using digital torque meter and digital tachometer, respectively. From steps, it can be concluded that a single stage three blades IceWind turbine with end plates, aspect ratio of 0.38 and blade arc angle of 112^o gives greater performance. IceWind turbine shows similar performance with slightly higher values of static torque and rotational speed when compared with Savonius wind turbine. Dynamic similarity, uncertainty analysis and comparison with previous data are informed.

Keywords: IceWind Turbine, Savonius Turbines, Experimental, Wind Tunnel, Rotational speed, Static Torque and Coefficient of Static Torque.

1. INTRODUCTION

IceWind is a new type of Savonius Vertical Axis Wind Turbine. The prefix Ice, in its name "IceWind", is related to "Iceland" its home town. Through navigating its website [1], the language of Iceland "Islenska" appeared beside English language in the upper right corner._Currently, there are two products; IceWind CW turbine, Fig.1, and IceWind RW turbine, Fig.2, without a single published paper. Due to lack of data for IceWind turbine to compare its performance, Savonius wind turbine's previous studies will help.

- Mohamed et al. [2], Menet [3], Saha et al. [4], Mahmoud et al. [5], Bhayo and Al-Kayiem [6] and Al-Kayiem et al. [7] studied the effect of number of blades. Comparisons between two and three blades rotor were made. They concluded that a two blades rotor gives higher efficiency and higher power coefficient.

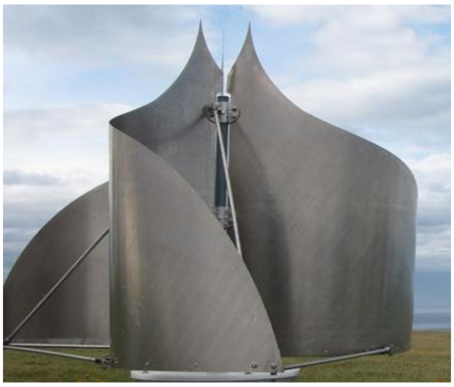

Fig.1. CW IceWind turbine.

Fig.2. RW IceWind turbine.

- Saha et al. [4], Mahmoud et al. [5], Nasef et al. [8] and Blackwell et al [9] studied the effect of single, double and triple stages rotors. Double stages rotors got the optimum efficiency.

- Aspect Ratio (AR) is defined as the ratio between rotor height and rotor diameter. Bhayo and Al-Kayiem [6] revealed that aspect ratio increased from 0.77 to 2.0. Al-Kayiem et al. [7], Alexander and Holownia [10], Sivasegaram [11] and Kamoji et al. [12] realized that there is an increase in power coefficient with the rise in aspect ratio. Some of them concluded that the optimum value of AR is 0.77.

- Blade arc angle (ψ) describes the angular curvature of the cross-section of blade. Kamoji et al. [12] declared that a rotor with a blade arc angle of 124° is having power coefficient higher than rotors with other blade arc angles. However, Mahamarakkalage [13] and Kumar and Saini [14] concluded that the optimum value of blade arc angle is equal to 135° and 150°, respectively.

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- Menet [3], Mahmoud et al. [5] and Alexander and Holownia [10] showed that end plates improve the aerodynamic performance, and the efficiency of the rotor, hence power coefficients obtained are higher. Moreover, according to Kang et al. [15], end plates have also a structural purpose because they strengthen the rotor structure. Investigations of Menet [3] concluded that the optimum value for the diameter of the end plates (De) is around 10% greater than the rotor diameter (D).

The objective of the present work is to investigate experimentally the IceWind turbine. It has been designed, fabricated and tested at Fluid Mechanics Laboratory, Mechanical Department, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport. Several arrangements for rotor height and diameter of 75 mm were studied. The models are assembled to have practically no overlap or separation gap. The tests are carried out inside a suction type low wind speed open circuit wind tunnel with wind speed varies from 8 to 16 m/s.

2. EXPERIMENTAL ANALYSIS

In order to experimentally design an optimum IceWind turbine, a number of parameters are considered; such as number of blades, end plates, number of stages, aspect ratio and blade arc angle. Savonius wind turbine will be discussed as the nearest design for IceWind turbine since there are no previous studies for this kind of turbine. The shape is taken from its website [1]. No dimensions are available since it is a commercial site. Aymane [16] gave it reasonable dimensions in his thesis. Here in this paper, dimensions are selected to be suitable to place inside the wind tunnel. When measuring air velocity inside wind tunnel, the velocity distribution of turbulent flow appeared; velocity values changed from zero to its maximum value beside the wall through only 10% of its width and length. The general arrangement of the experimental set-up layout is shown in Fig.3.

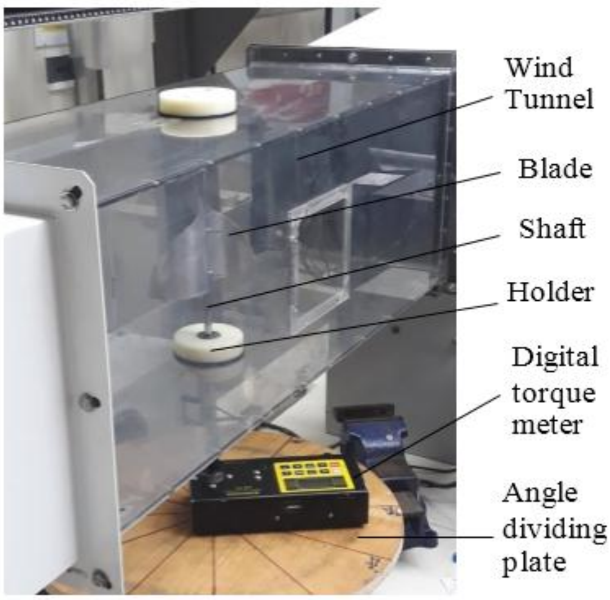

Fig.3. A photo of the test rig.

Fig. 4 shows the final used IceWind blade. Its dimensions are d = 75 mm, H = 75 mm plus 25 mm blade tip height, blade arc angle of 112° and its swept area A_s = 4250.51 mm². For manufacturing this shape, Sheet plate is cut and then rolled (the length of the sheet will be a perimeter of a part of the circle). Fig. 5. shows First SolidWorks drawing of flat IceWind blade. It consists of three circles and three lines arranged as shown in Fig. 5, then trim is used and dimensions are applied. Fig. 6 shows IceWind blade dimensions before rolling. The horizontal dimension (L = 88.36 mm) is calculated as a perimeter (L = r θ).

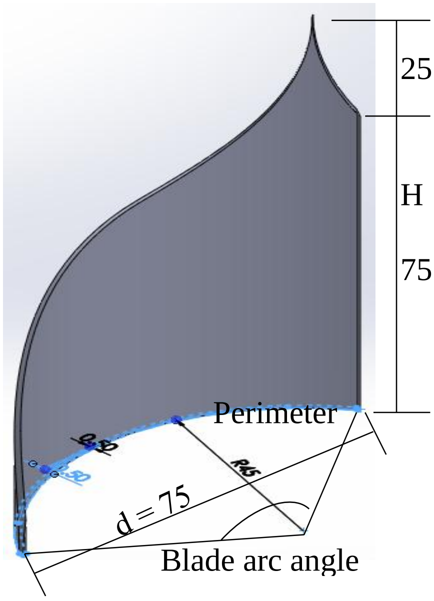

Fig.4. IceWind blade (Dimensions in mm).

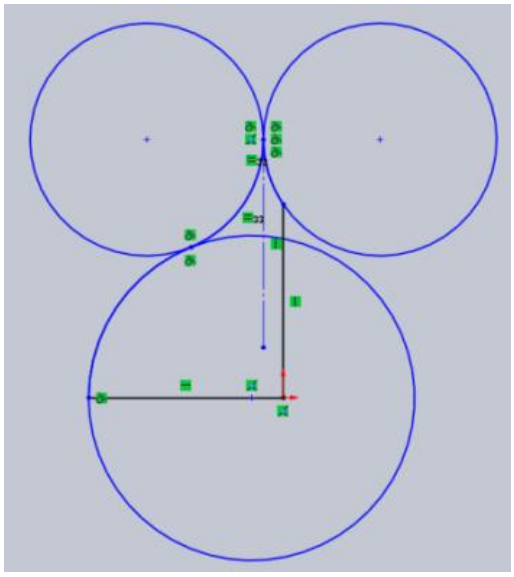

Fig. 5. First SolidWorks drawing of flat IceWind blade.

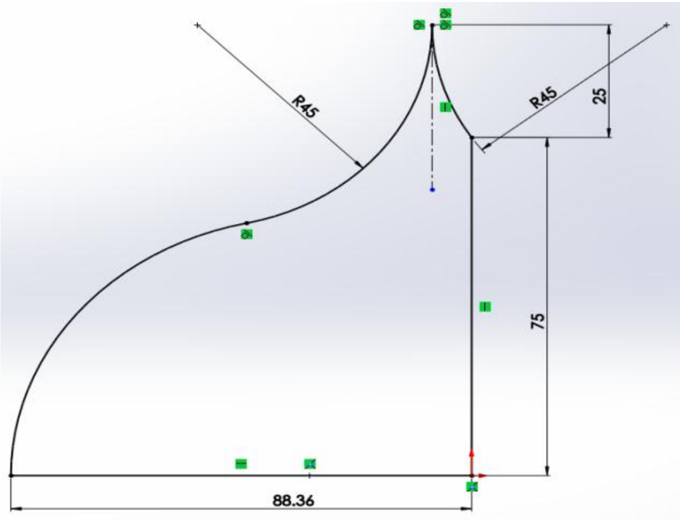

Fig.6. IceWind blade design before rolling (Dimensions in mm).

2.1 Measurements and Instrumentation

- Angle dividing plate is a circular disk that is split into twelve divisions (30° each) about its center to ensure the IceWind's orientation. The accuracy of the plate is ±1°.
- The tests were carried out downstream of a suction type Hampden wind tunnel model H-6910-12. The center of the rotating rotor is kept in- line with the center line of the wind tunnel test section area in x and y directions. The dimensions of wind tunnel test section are 30 cm x 30 cm x 100 cm. Air velocity is measured using a Pitot tube that is calibrated at Air Defense Faculty.
- Static Torque (Ts) is measured using digital torque meter (Kingsom KS-100) with a range from 0.015-1.00 N.m and a sensitivity of ±0.005 N.m. The shaft is mounted on the toque test head. As the airflow passes through the blades, the digital torque meter gives a digital reading on its screen. It is calibrated by comparing its reading with the calculated torque of a weight at a distance.
- The rotor rotational speed is measured by Mastech MS6208B digital tachometer which has laser ray pointed to a reflector stacked on the rotor blade whose speed is to be measured. All the measured rotor speeds are with sensitivity of ±0.1rpm.

2.2 Experiment Procedures

1- Put the angle dividing plate under the torque meter device below the wind tunnel, as shown in Fig.3.

2- Install the shaft in wind tunnel and mount the IceWind blades (with the required arrangement).

3- Connect the end of the shaft on the digital torque meter test head.

4- Run wind tunnel fan at a certain speed.

5- Operate the digital torque meter device. At each division starting from 0° until 360°, read the shown number on the digital torque meter screen (average of three readings to reduce error) in N.m. The zero angle is considered when the blade tips are in line with the wind tunnel's air flow, as shown in Fig. 7.

Fig.7. The zero angle of the turbine.

6- Release the turbine to rotate freely. Then measure IceWind rotational speed using tachometer device (average of three readings to reduce error) in rpm.

7- Repeat steps 5 and 6.

8- Repeat steps 4, 5, 6 and 7 for each selected speed.

9- Repeat steps 2, 3, 4, 5, 6, 7 and 8 for each arrangement.

2.3 Calculations

After the previous measurements are carried out, the following parameter can be calculated.

$$C_{ts} = \frac{T_s}{T_w} = \frac{T_s}{0.25*\rho*A_s*D*v^2} \qquad (1)$$

Where

C_{ts} = static torque coefficient

T_s= actual rotor static torque (N.m)

T_w = wind available torque (N.m)

ρ = air density (kg/m^3) = 1.225 (kg/m^3)

A_s = swept area (from SolidWorks) (m^2)

D = the diameter of the IceWind rotor (m)

v = wind speed (m/s)

3. RESULTS AND DISCUSSION

3.1 Comparison with Savonius turbine with the same swept area

Savonius, Figs. 8 and 9, and IceWind, Figs. 10 and 11, turbines with the same swept area of A_s = 4250.51 mm^2 are used. With the same d = 75 mm, Savonius blade height equals to 56.67 mm.

The flow structure around the Savonius rotor is called "*Coanda-like flow*" by [17, 18], which controls the flow separation on the convex side. A low pressure region is formed on this side of the advancing blade contributing to the torque generation of the rotating rotor [19].

From Figs. 12 to 17, results of IceWind turbine and Savonius turbine show almost a similar performance for static torque

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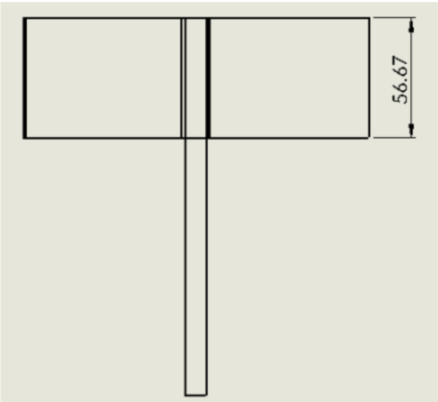
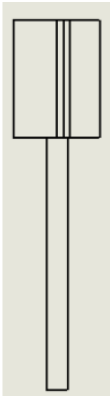
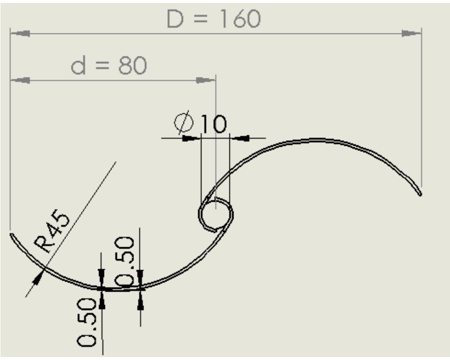
and static torque coefficient. However, IceWind turbine has slightly higher values. Figs. 12 and 13 show the relation between static torque and rotation angle for IceWind and Savonius turbine, respectively. Both figures show two peaks but they are not at the same angles. IceWind and Savonius turbines reach maximum value of 0.064 Nm and 0.06 Nm, respectively. This slight difference may be because the flow field near the Savonius rotor is two-dimensional, whereas, near the IceWind rotor is three-dimensional [19].



a) Elev.



b) Side view



c) Plan

Fig.8. Savonius turbine's three views (Dimensions in mm).

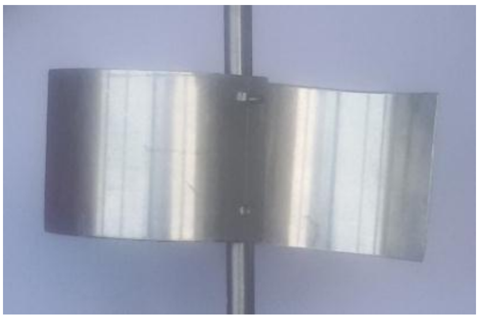
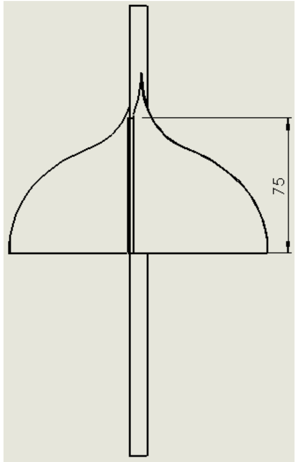
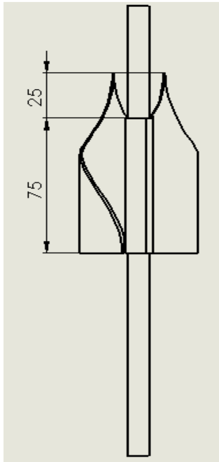


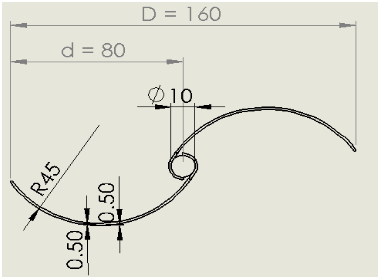
Fig.9. Savonius wind turbine.



a) Elev.



b) Side view



c) Plan

Fig. 10. IceWind turbine's three views (Dimensions in mm).

Fig. 11. IceWind turbine.

Figs. 14 and 15 show the relation between static torque coefficient and rotation angle for IceWind and Savonius turbine, respectively. IceWind and Savonius turbines reach maximum value of 0.6 and 0.62, respectively. An average value of this coefficient of static torque is obtained at each wind velocity and is called mean coefficient of static torque. Its relation with wind velocity indicted that IceWind turbine gives a higher value along the studied wind velocities, as shown in Fig.16.

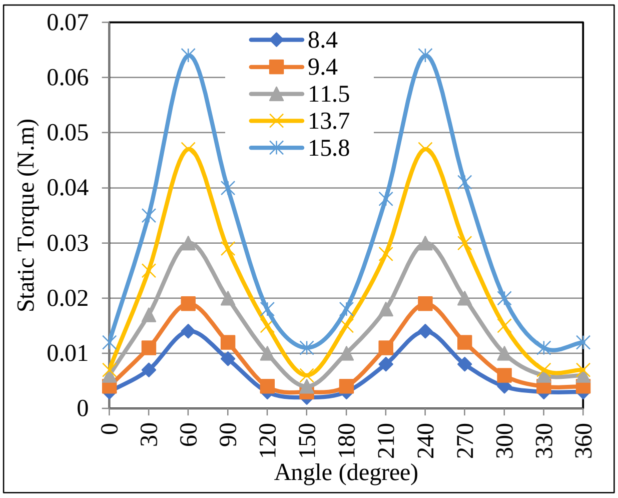


Fig.12. Relation between static torque and rotation angle for IceWind turbine.

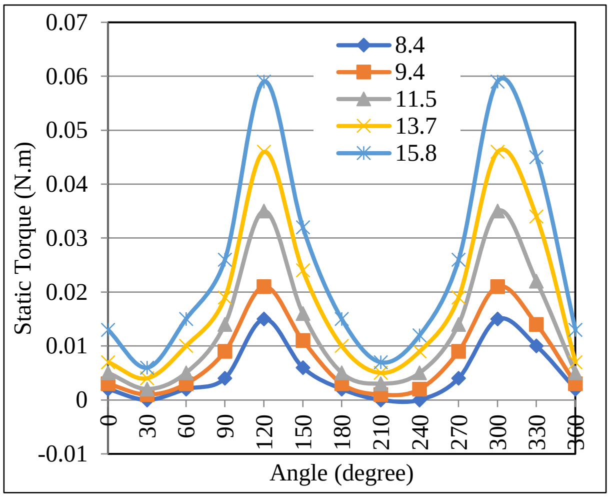


Fig.13. Relation between static torque and rotation angle for Savonius Wind turbine.

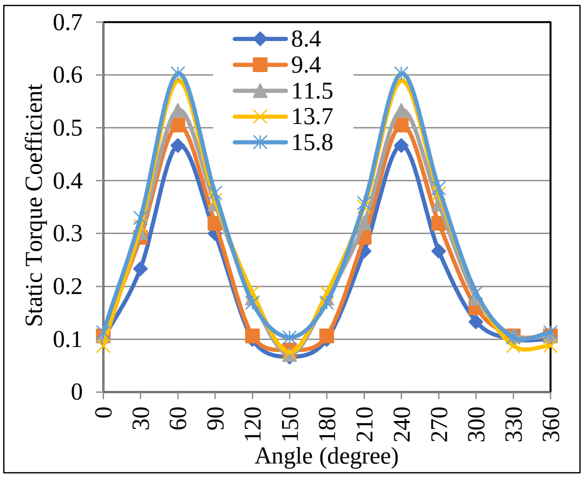


Fig.14. Relation between static torque coefficient and rotation angle for IceWind turbine.

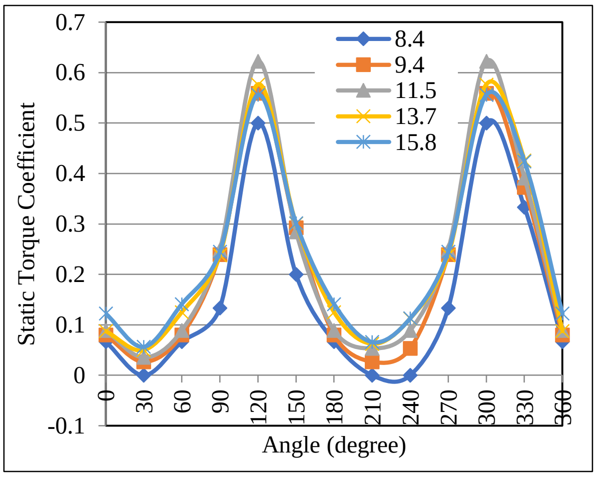


Fig.15. Relation between static torque coefficient and rotation angle for Savonius Wind turbine.

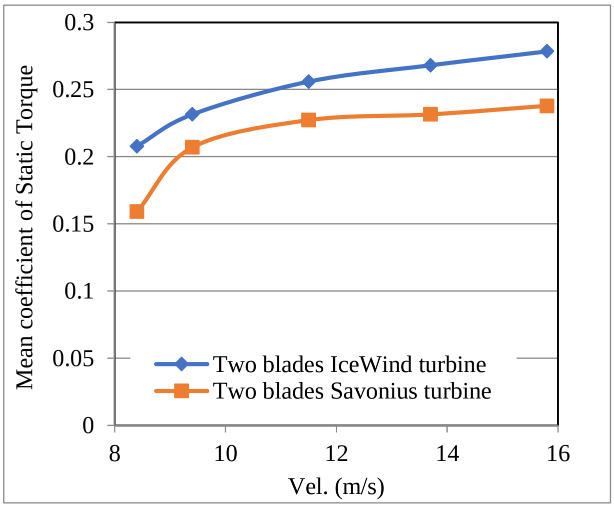


Fig.16. Relation between mean coefficient of Static torque and wind velocity for IceWind and Savonius Wind turbines.

Moreover, IceWind turbine rotational speeds are slightly higher than those of Savonius turbine at all wind velocities, as shown in Fig.17.

IceWind turbine isn't as simple in manufacturing as Savonius wind turbine but its shape has a better looking. Furthermore, noise of IceWind turbine is less than that of Savonius turbine [16]; the authors confirmed that a product should not only show a good performance but should also have a wide acceptance from the public. They asked participants to fill a survey about overall appearance, noise level, and efficiency. Participants of 85% declare that IceWind turbine has less noise than Barrel Savonius. Turbine's noise isn't measured because the noise generated from Wind tunnel is much larger.

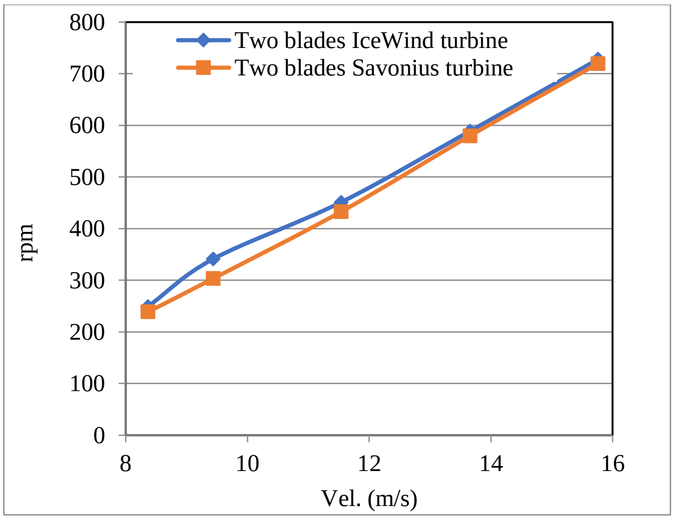


Fig.17. Relation between rotational speed and wind velocity for IceWind and Savonius Wind turbines.

3.2 Number of blades

A single blade rotor won't acquire turbine's balance. For that, double and triple blades rotors are considered. Adding more blades creates an interference of one on another. Besides it increases costs more than the benefits of making more power, which is called "*diminishing return*" [20].

For double blades rotor, the angle between blades is 180° as IceWind rotor is symmetric, shown in Figs. 10 and 11. Furthermore, for triple blades rotor, the angle between blades is 120°, shown in Fig. 18. For double blades reversed rotor, IceWind rotor is not symmetric as one of the two blades is reversed, shown in Fig. 19. As shown in Fig. 20, the triple blades rotor gives a maximum mean coefficient of static torque. Although double blades Savonius turbine is better than triple blades ones [2-7], the new shape of the IceWind turbine blade produces a low pressure which increase air flow towards turbine blade and therefore increase the drag force. Double blades IceWind turbine rotational speeds are lower than those with three blades and two blades reversed, as shown in Fig.21.

Fig. 18. Three blades IceWind turbine.

Fig. 19. Two blades reversed IceWind turbine.

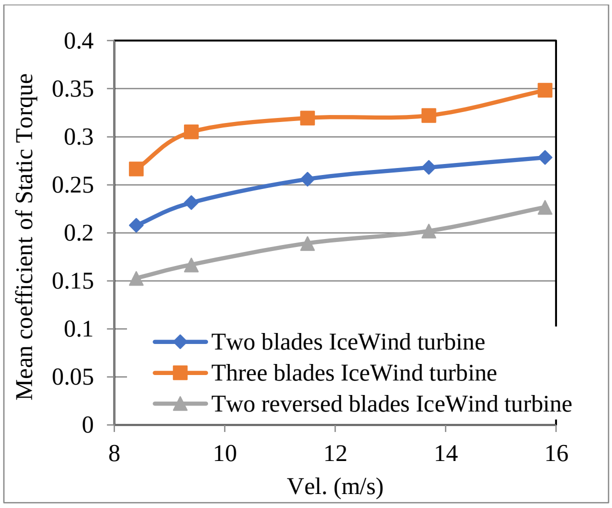


Fig. 20. Relation between mean coefficient of Static torque and wind velocity for IceWind two, three and two reversed blades turbines.

3.3 End plates

Two end plates with 180 mm diameter are used with the double reversed blades arrangement, as shown in Figs. 22 to 24. Fig. 22 shows a plan of the end plate with two reversed blades IceWind turbine. If the diameter of turbine is subtracted from the end plate diameter, 10 mm will be established at each side between the turbine and edge of end plate.

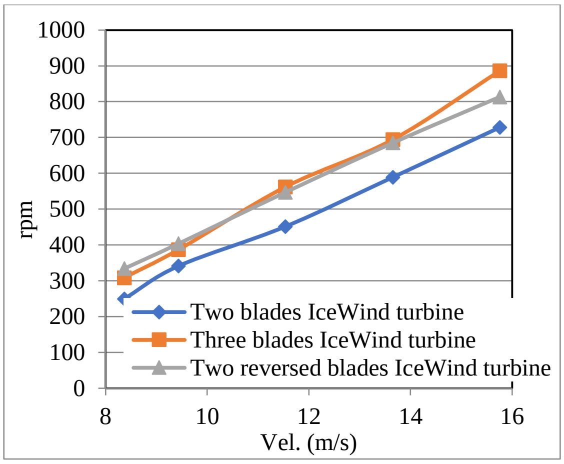


Fig. 21. Relation between rotational speed and wind velocity for IceWind two, three and two reversed blades turbines.

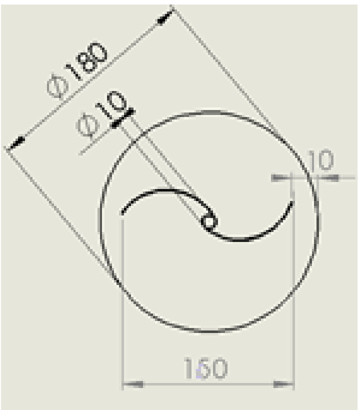


Fig.22. A plan of the end plate with two reversed blades IceWind turbine.

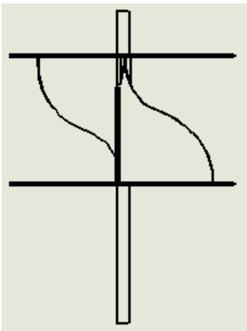


Fig.23. SolidWorks drawing of two end plates with two reversed blades IceWind turbine.

In Fig. 25, it can be noticed that mean coefficient of static torque for the arrangement with a disk is extremely higher than that without. All of static torque, mean coefficient of static torque and rotational speed, shown in Fig. 26, for the IceWind turbine with end plate are greater than those without end plate. This is because the existence of end plates modifies the streamlines of air which strikes the blades of the IceWind turbine. They give better aerodynamic performance and high efficiency [3, 5 and 10].

Fig.24. Two end plates with two reversed blades IceWind turbine.

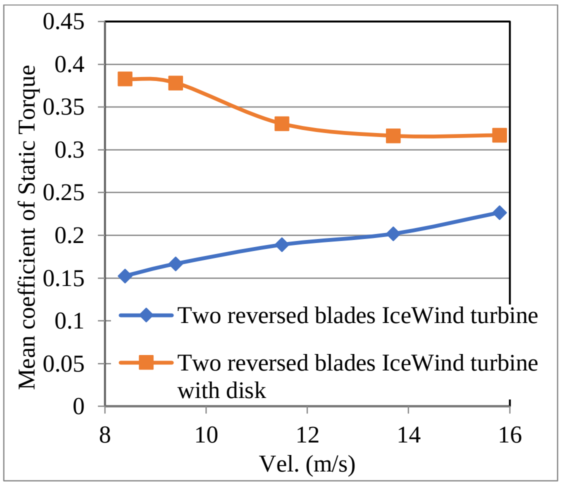


Fig. 25. Relation between mean coefficient of Static torque and wind velocity for IceWind turbines with two reversed blades without and with disk.

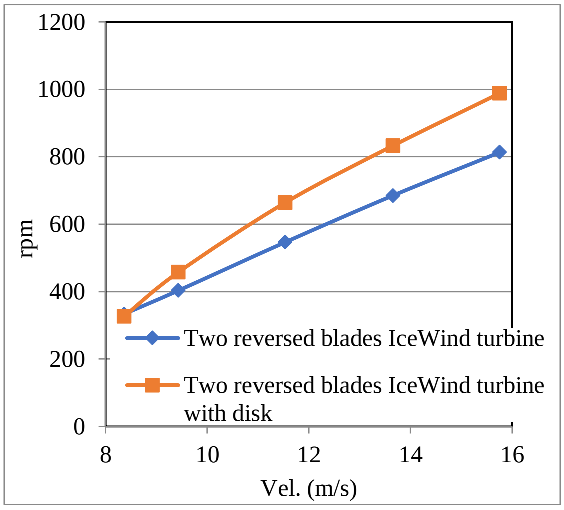


Fig. 26. Relation between rotational speed and wind velocity for IceWind turbines with two reversed blades without and with disk.

3.4 Number of stages

It is the number of IceWind turbines arranged vertically. Three arrangements were used: two stages 2CW with the same orientation, Fig.27, two stages 2CW90 (means two stages with the perpendicular orientation), Fig.28, and RW, Fig.29, IceWind turbines. Relation between mean coefficient of static torque and wind velocity is shown in Fig. 30. Mean coefficient of static torque has a higher value at two stages CW with the perpendicular orientation arrangement than two stages CW with the same orientation, whereas, RW arrangement has the lowest value. In RW arrangement, interferences of air with blades appears significantly which leads to decrease in the net drag force affected on the rotor resulted in decrease in torque. Single stage still has a higher coefficient of static torque values. This may be because the interference of air streamlines between the two stages rotor. From Fig. 31, rotational speed for the arrangements are descending as follows, IceWind turbines with two blades two stages 2CW90, 2CW, single stage and two stages RW.

Fig. 27. Two stages 2CW two blades IceWind turbine.

Fig. 28. Two stages 2CW with perpendicular orientation two blades IceWind turbine.

Fig. 29. RW IceWind turbine.

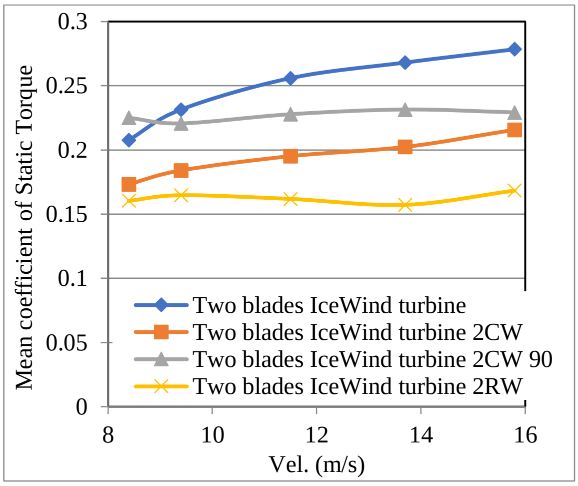


Fig. 30. Relation between mean coefficient of Static torque and wind velocity for single and two stages (2CW, 2CW90 and RW) IceWind turbines with two blades.

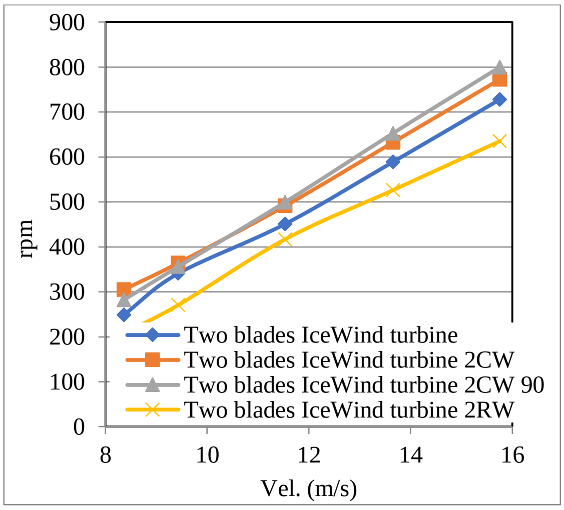


Fig. 31. Relation between rotational speed and wind velocity for single and two stages (2CW, 2CW90 and RW) IceWind turbines with two blades.

3.5 Aspect ratio (AR)

For the blade, shown in Fig. 4, its dimensions are d = 75 mm, H = 75 mm plus 25 mm blade tip height and a swept area A = 4250.51 mm^2. The height of the rotor is tricky as the shape of the turbine is not a complete half circle. For that, its swept area, obtained from SolidWorks, is used to calculate an equivalent height if the blade is complete half circle. It has an AR of 0.38. Moreover, AR of 0.55 is tested. The blade's dimensions are d = 75 mm and H = 97.4 mm plus 32.47 mm blade tip height, shown in Figs. 32 and 33. The swept area has been increased to be 6181.22 mm^2. This increase of the swept area doesn't lead to an increase in the mean coefficient of static torque; nevertheless, it increases the rotor's rotational speed, as shown in Figs. 34 and 35, respectively. This may be because the generated shape of 0.55 AR has a distance from center of mass to the axis smaller than that of 0.38 AR.

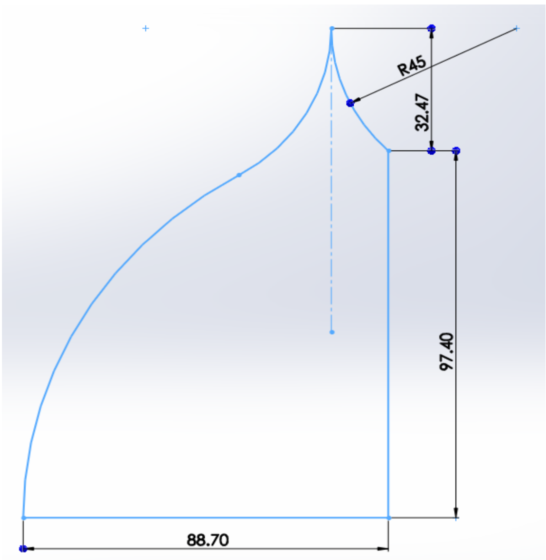


Fig. 32. IceWind blade design Aspect Ratio before rolling (Dimensions in mm).

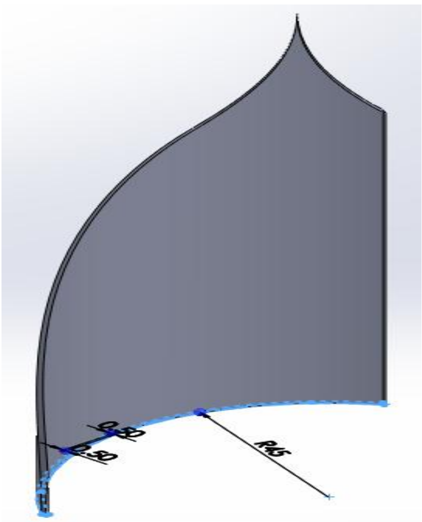


Fig. 33. IceWind blade (Dim. in mm).

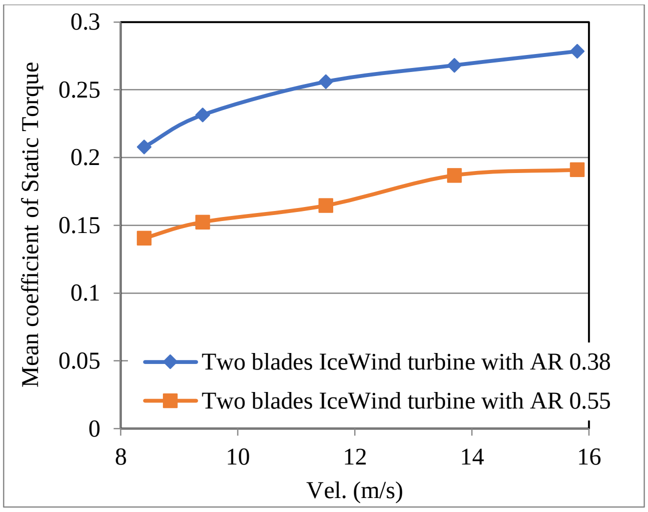


Fig. 34. Relation between mean coefficient of Static torque and wind velocity for IceWind turbines with two blades with AR = 0.38 and 0.55.

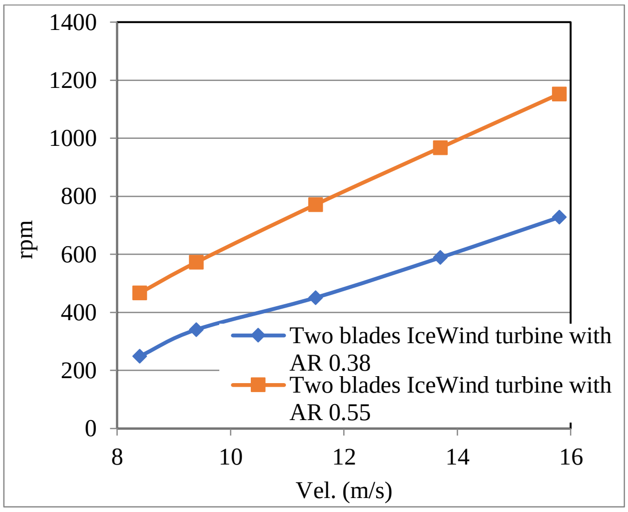


Fig. 35. Relation between rotational speed and wind velocity for IceWind turbines with two blades with = 0.38 and 0.55.

3.6 Blade arc angle (ψ)

It is a geometric parameter that describes the angular curvature of the cross-section of blade. The blade, shown in Fig. 4, has a blade arc angle of 112º. Blade arc angle of 135º is shown in Figs. 36 and 37 before and after rolling, respectively. It has dimensions of d = 75 mm, L = 95.68 mm.

On the contrary, Savonius blade arc angle of 135º was recommended, IceWind blade arc angle of 112º has rather better values of both mean coefficient of static torque and rotational speed, as shown in Figs. 38 and 39, respectively. The reason may be the size of the created vortices created by advancing and retracting blades; the bigger the vortices' size the smaller the coefficient of static torque and rotational speed.

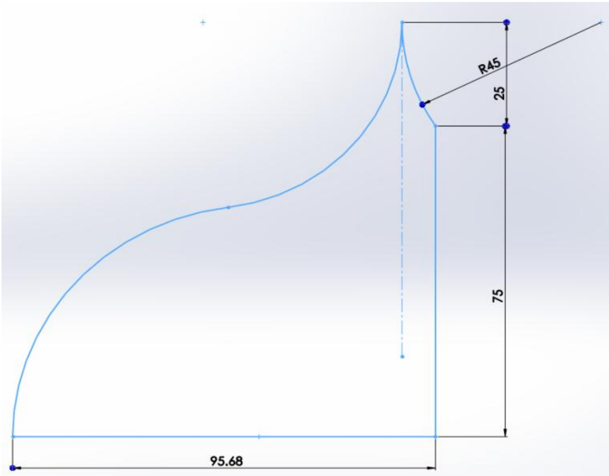


Fig. 36. IceWind blade design Blade Arc Angle before rolling (Dimensions in mm).

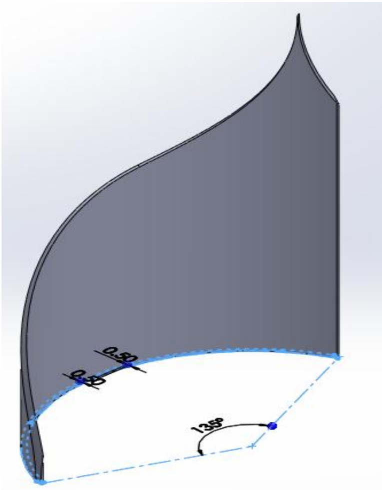


Fig.37. IceWind blade (Dim. in mm).

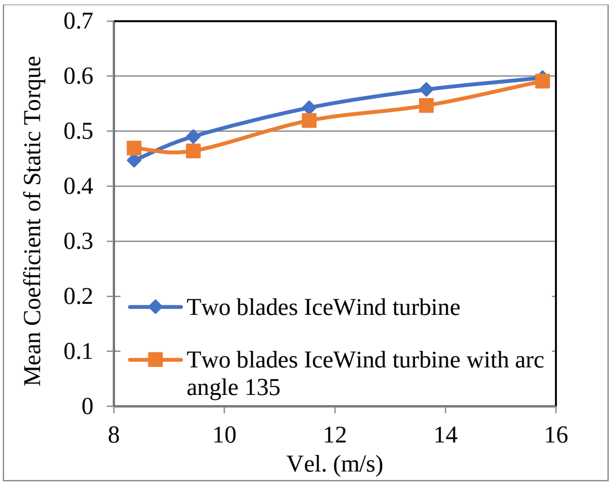


Fig. 38. Relation between mean coefficient of Static torque and wind velocity for two blades IceWind turbines with Blade arc angle (ψ) = 112° and 135°.

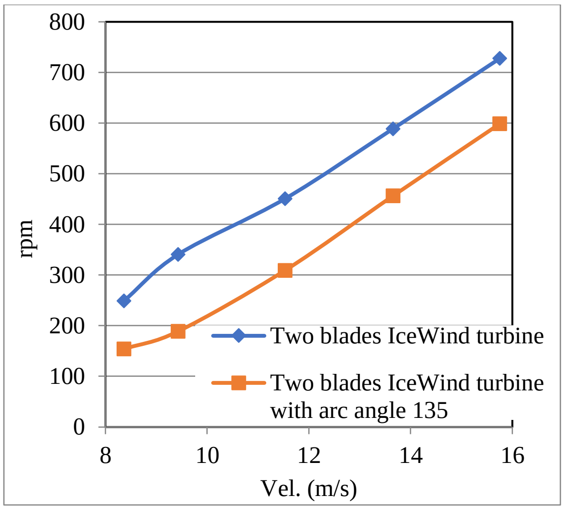


Fig. 39. Relation between rotational speed and wind velocity for two blades IceWind turbines with Blade arc angle (ψ) = 112° and 135°.

4. DYNAMIC SIMILARITY

It allows imitation of the same flow pattern by matching Reynolds numbers.

$$Re = \frac{\rho v d}{\mu} \qquad (2)$$

Where

ρ = air density (kg/m^3) = 1.225 (kg/m^3)

v = wind speed (m/s)

d = the diameter of the half circle IceWind rotor (m)

μ = air viscosity (kg/ms) = 1.81 x 10^{-5} (kg/ms)

For the present study, a dynamic similarity is prepared between the present turbine model and its real size.

$$Re_{model} = Re_{real} \qquad (3)$$

For the same air properties, if the model diameter of the half circle IceWind rotor is 0.075 m and the actual turbine diameter is 0.75 m, the actual velocity range will be 0.8 to 1.6 m/s.

5. UNCERTAINTY ANALYSIS

Uncertainty analysis [21] is made to calculate the uncertainty values for coefficient of static torque (Cts) at confidence level 95% using equation (1). Uncertainty Analysis of Coefficient of Static Torque for IceWind turbine

$$C_{ts} = \frac{T_s}{T_w} = \frac{T_s}{0.25 * \rho * A_s * D * v^2}$$

T_s = 0.064 $\pm$ 0.005 N.m

ρ = 1.225 $\pm$ 0.001 kg/m³

A_s = 0.008501 $\pm 10^{-6}$ m²

D = 0.16 $\pm$ 0.001 m

$v^2 = (15.8)^2 \pm 0.01$ m/sec

$$U_{Ts} = \frac{error}{reading} = \frac{0.005}{0.064} = 0.078125$$

$$U_{\rho} = \frac{error}{reading} = \frac{0.001}{1.225} = 0.000816$$

$$U_{As} = \frac{error}{reading} = \frac{10^{-6}}{0.008501} = 1.18x10^{-4}$$

$$U_{D} = \frac{error}{reading} = \frac{0.001}{0.16} = 0.00625$$

$$U_{v^2} = \frac{error}{reading} = \frac{0.01}{(15.8)^2} = 6.33x10^{-4}$$

Uncertainty in C_{ts} at confidence level 95% can be obtained from

$$U_{Cts} = \pm[(U_{Ts})^2 + (-U_{\rho})^2 + (-U_{A})^2 + (-U_{D})^2 + (-U_{v^2})^2]^{1/2}$$

$$= \pm[(0.078125)^2 + (0.000816)^2 + (1.18x10^{-4})^2 + (0.00625)^2 + (6.33x10^{-4})^2]^{1/2}$$

$$= \pm 0.078379 \quad = \pm\ 7.84\%$$

Uncertainty of Coefficient of static torque for IceWind turbine

$= \pm\ 7.84\%$

As shown in table 1, case "two blades IceWind turbine 2CW" has a minimum uncertainty value of 5.47. However, case "two blades IceWind turbine RW" has a maximum uncertainty value of 13.17.

Table 1. Uncertainty in (Cts) at confidence level 95%

No	Case title	(%) Cts
1	Two blades IceWind turbine	7.84
2	Two blades Savonius turbine	8.50
3	Three blades IceWind turbine	7.49
4	Two reversed blades IceWind turbine without disk	10.66
5	Two reversed blades IceWind turbine with disk	7.84
6	Two blades IceWind turbine with AR 0.55	7.07
7	Two blades IceWind turbine with arc angle 135	9.28
8	Two blades IceWind turbine 2CW	5.47
9	Two blades IceWind turbine 2CW 90	8.09
10	Two blades IceWind turbine RW	13.17

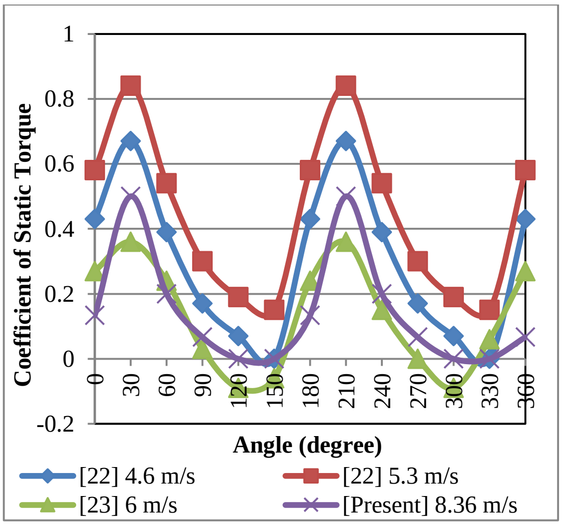


Fig. 40. Relation between coefficient of static torque and rotation angle for Savonius Wind turbine.

6. COMPARISONS WITH PREVIOUS WORK

In order to compare present results with previous results [22 - 23], two blades Savonius turbine arrangement (Figs. 8 and 9) is used. Fig. 40 shows the relation between coefficient of static torque and rotation angle for Savonius turbines at different velocities for the present and previous works. As shown in Fig. 40, a very good agreement is achieved concerning a qualitative analysis. The present coefficients of static torque at a velocity 8.36 m/s has the same trend as those of [22] 4.6 m/s and 5.3 m/s and [23] 6 m/s.

7. CONCLUSIONS

In this work, various arrangements are discussed; number of blades (two, two reversed and three blades), number of stages (single and double stages), existence of end plates (with and without), aspect ratios (0.38 and 0.55) and blade arc angle (112^o and 135^o) are investigated experimentally. IceWind turbine's optimum geometries are determined by obtaining static torque, coefficient of static torque and rotational speed. It can be concluded from the experiments results that:

1. Results of IceWind turbine are slightly better than Savonius wind turbine with the same swept area. Although IceWind turbine isn't simple in manufacturing but its shape has a better looking and less noise.

2. Triple blades rotor gives higher static torque coefficients and rotational speed than double blades and double reversed blades.
3. End plates give better static torque coefficients and rotational speed.
4. For number of stages, CW with the perpendicular orientation arrangement gives higher rotational speed. Whereas, single two blades IceWind turbine has astatic torque coefficient above the others.
5. AR of 0.55 has a higher rotational speed AR of 0.38. The opposite for coefficient of static torque.
6. Blade arc angle of 112º has a higher coefficient of static torque and rotational speed than that of 135º.
7. Calculating uncertainty analysis for coefficient of static torque (Cts) at confidence level 95%, case "two blades IceWind turbine 2CW" has a minimum value and case "two blades IceWind turbine RW" has a maximum value.
8. The present two blades Savonius wind turbine's static torque coefficient is verified with its previous data and a good agreement is achieved.

Finally, from the previous experiments and the parametric study, it can be estimated that single stage three blades IceWind with end plates and aspect ratio (AR) of 0.38 and blade arc angle (ψ) of 112º is recommended to give a superior performance.

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