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Experimental investigations on single stage modified Savonius rotor

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A B S T R A C T

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. To achieve these objectives, the rotors are being studied with and without central shaft between the end plates. Tests in a closed jet wind tunnel on modified form of the conventional Savonius rotor with the central shaft is reported to have a coefficient of power of 0.32. In this study, modified Savonius rotor without central shaft between the two end plates is tested in an open jet wind tunnel. Investigation is undertaken to study the effect of geometrical parameters on the performance of the rotors in terms of coefficient of static torque, coefficient of torque and coefficient of power. The parameters studied are overlap ratio, blade arc angle, aspect ratio and Reynolds number. The modified Savonius rotor with an overlap ratio of 0.0, blade arc angle of 124° and an aspect ratio of 0.7 has a maximum coefficient of power of 0.21 at a Reynolds number of 1,50,000, which is higher than that of conventional Savonius rotor (0.19). Correlation is developed for a single stage modified Savonius rotor for a range of Reynolds numbers studied.

1. Introduction

Savonius rotor is simple in structure, has good starting characteristics, relatively low operating speeds, and an ability to accept wind from any direction. Its aerodynamic efficiency is lower than that of other types of wind turbines, such as Darrieus and propeller rotors. The concept of Savonius rotor is based on the principle developed by Flettner. Savonius [1] claimed a maximum coefficient of power of 0.31. However, field trials done by Savonius on Savonius rotors gave a maximum coefficient of power 0.37. However, the same has not been achieved by subsequent researchers. This means that the main driving force is drag force of wind acting on its blade. However, at low angle of attacks, lift force also contributes to torque production [2]. Hence, Savonius rotor is not a pure drag machine but a compound machine and hence can go beyond the limitation of Cp of a primarily drag type machine ($Cp_{\max} = 0.08$ for plate type turbine, Manwell et al. [3]). Although conventional Savonius rotors have low aerodynamic efficiency, they have a high starting torque or high coefficient of static torque. Due to this they are used at starters for other types of wind turbines that have lower starting torques and for applications which require high starting torque, such as water pumping.

Experiments on conventional Savonius rotors at an overlap ratio of 0.15 and an aspect ratio of 1.0 have been reported to have a maximum coefficient of power at 0.173 by Fujisawa and Gotoh [4] and 0.17 by Kamoji et al. [5] when tested in an open jet wind tunnel. Continual efforts are being made to improve the coefficient of power of conventional Savonius rotor. In an effort to improve the efficiency, minor changes are made in the shape of the conventional Savonius rotors and these rotors have been referred to as modified Savonius rotors. An investigation on modified Savonius rotor with shaft reported by Modi [2] is an effort in that direction. Modified Savonius rotor with shaft is reported to have a maximum coefficient of power of around 0.32. However, these tests are based on closed jet wind tunnel testing and this value of coefficient of power is obtained by a method of extrapolation. There is a need to test this modified Savonius rotor with shaft in an open jet wind tunnel.

Experimental investigations are carried out to study the effect of several geometrical parameters on the performance of modified Savonius rotors (without shaft in between the end plates) in terms of coefficient of static torque, coefficient of torque and coefficient of power. Parameters studied are overlap ratio, aspect ratio, blade arc angle, blade shape factor and Reynolds number. Hence, the objectives of the present work are as follows:

- Conduct experimental investigations on modified Savonius rotor without shaft in an effort to improve the coefficient of power by varying several geometrical parameters.
- Conduct experimental investigations on modified Savonius rotor with shaft in an open jet wind tunnel with the optimum geometrical parameters as reported by Modi and Fernando [2].

Nomenclature

A	aspect ratio (H/D)	Re	reynolds number ($\rho UD/\mu$)
m	overlap distance (m)	r_{rope}	radius of the shaft (mm)
Cp	coefficient of power ($2T\omega/\rho U^3 DH$)	r_{shaft}	diameter of the string (mm)
$Cp_{\max}$	maximum coefficient of power	S	spring balance reading (gms)
Ct	coefficient of torque ($4T/\rho U^2 D^2 H$)	s	end extension (mm)
Cts	coefficient of static torque ($4T_s/\rho U^2 D^2 H$)	T	torque (Nm)
$Cts_{\max}$	maximum coefficient of static torque	Ts	static torque (Nm)
$Cts_{\min}$	minimum coefficient of static torque	TSR	tip speed ratio ($D\omega/2U$)
D	rotor diameter (m)	U	free stream wind velocity (ms^{-1})
Do	end plate diameter (m)		
G	overlap ratio ($m/2R$)	*Greek symbols*	
H	rotor height (m)	ρ	density of air (kg/m^3)
M	mass (g)	ψ	blade arc angle (deg.)
p	straight edge of blade (mm)	θ	reference angle (deg.)
q	radius of circular arc (rad)	μ	absolute viscosity of air (Pa s)
R	blade radius (m)	ω	angular velocity of rotor (rad/s)

- Comparison of the performance of the modified Savonius rotor (with shaft), modified Savonius rotor (without shaft) and conventional Savonius rotor.
- To develop correlation for single stage modified Savonius rotor for the range of Reynolds numbers tested.

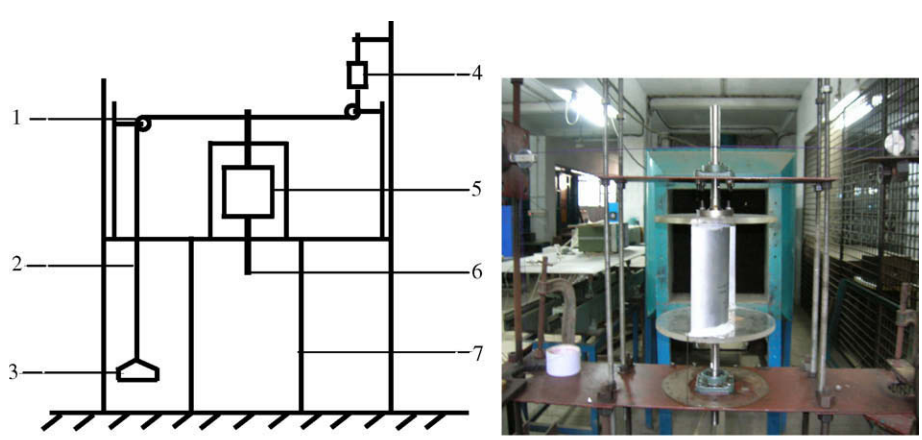
2. Experimental set-up and procedure

Uniform main flow is produced by an open-jet-type wind tunnel driven by a two 10 H.P. contra rotating fans. Air exits from a square contraction nozzle with a wind tunnel outlet of 400 mm × 400 mm. Experimental set-up for housing and conducting experiments on rotating rotor is shown in Fig. 1. The set-up is placed at a distance of 750 mm downstream of the wind tunnel nozzle exit such that the centre of the rotating rotor is in line with the centre of the wind tunnel exit. The measured velocity distribution at the rotor position is uniform within ±1% in the central area of 250 mm × 250 mm. The turbulence intensity at the rotor position is estimated to be 1%.

Experimental set-up for conducting rotational experiments consists of a structure housing the modified Savonius rotor fabricated using studs and mild steel plates [6]. The mild steel plates are held in place by means of washers and nuts. Two bearings (UC 204, NTN make) bolted to the mild steel plates support the modified Savonius rotor. The usage of studs, nuts and bolts facilitated easy replacement of rotors of different diameters and positioning of rotor centre at the centre of the wind tunnel.

Friction is an important parameter that affects the measurement of torque of the rotating Savonius rotor. Friction in the bearings and the 1 mm inelastic fishing nylon wire wound on the rotor shaft must be minimized. The seals are removed from the bearings and bearings are washed in petrol to remove the grease before mounting resulting in the reduction of friction. Wind velocity is measured with help of Pitot tube connected to a micro-manometer (make: Furness Controls Ltd., UK, model FC012). Calibrated accuracy of micro-manometer is ±0.01 mm of water column. Wind velocity is adjusted corresponding to a given Reynolds number and the rotor is allowed to rotate from no load speed. Rotational speed of the rotor is recorded by a non-contact type tachometer. Each bearing is sprayed with W-D 40 (a commercially available spray) lubricant before each reading [7]. The rotor is loaded gradually to record spring balance reading, weights and rotational speed of the rotor.

A set of experiments is carried to calculate the static torque of the rotor at a given rotor angle using the brake drum measuring system. The static torque of the rotor is measured at every 15° of the rotor angle. At a given wind velocity, the rotor is loaded to pre-



1. Pulley 2. Nylon string 3. Weighing pan 4. Spring balance 5. Savonius rotor
6. Shaft 7. Structure

Fig. 1. Schematic diagram of the rotational set-up.

vent it from rotation at a given rotor angle. The values of load and spring balance reading are recorded to calculate the static torque at a given rotor angle. The reference angle for measurement of coefficient of static torque is in clock wise direction for modified Savonius rotors (with and without shaft) as shown in Figs. 4 and 13b, respectively.

3. Rotors covered in this study

Fig. 2 shows the basic modified Savonius rotor without shaft. The basic geometrical parameters considered in the present study are aspect ratio (*H/D*), overlap ratio (*m/D*), blade arc angle (ψ) and blade shape factor (*p/q*). Modified Savonius rotors are fabricated from aluminium pipe whose thickness is 2 mm. Rotors are covered at the top and bottom by an acrylic plate of 10 mm thickness. Modified Savonius rotor without shaft is not having any shaft between the two end acrylic plates. Stainless steel flanges housing the two end shafts are bolted to the two acrylic sheets.

Main objective of the present work is to study the influence of overlap ratio (*m/D*), aspect ratio (*H/D*), blade arc angle (ψ), blade shape factor (*p/q*) and Reynolds number (*Re*) on the performance of basic modified Savonius rotor as shown in Fig. 2. Table 1 gives the matrix of experiments carried out to study the effect of the above geometrical parameters. Experiments are carried out keeping the end plate parameter (*Do/D*) at a constant value of 1.1 for Reynolds numbers of 120,000 and 150,000.

Figs. 3 and 4 show the basic and optimum modified Savonius rotor (with shaft in between the end plates) subjected to optimization by Modi and Fernando [2]. The optimum configuration of the blade geometry is as follows:

Overlap ratio (*m/D*) = 0.0; aspect ratio (*H/D*) = 0.77; blade arc angle (ψ) = 135°; blade shape factor (*p/q*) = 0.2; end plate parameter (*Do/D*) = 1.33.

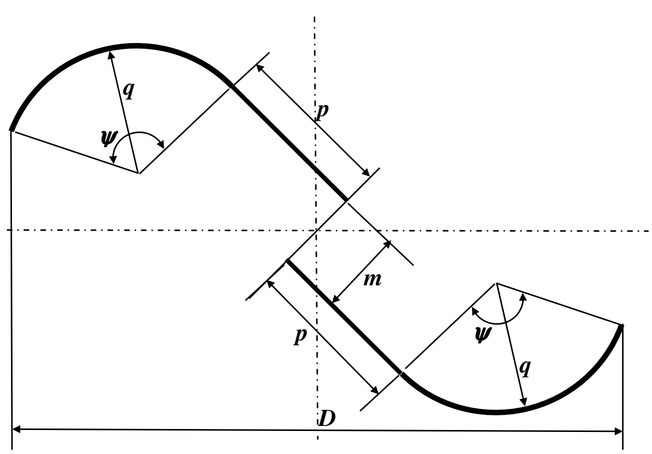


Fig. 2. Basic modified Savonius rotor without shaft (present study).

Table 1
Configurations of rotors of the modified Savonius rotor (without shaft) covered in the present study

Overlap ratio (*m/D*)	Aspect ratio (*H/D*)	Blade arc angle (ψ)	Blade shape factor (*p/q*)
0.0, 0.10, 0.16	0.77	124°	0.2
0.0	0.6, 0.7, 0.77, 1.0	124°	0.2
0.0	0.7	110°,124°,135°,150°	0.2
0.0	0.7	124°	0.2, 0.4, 0.6

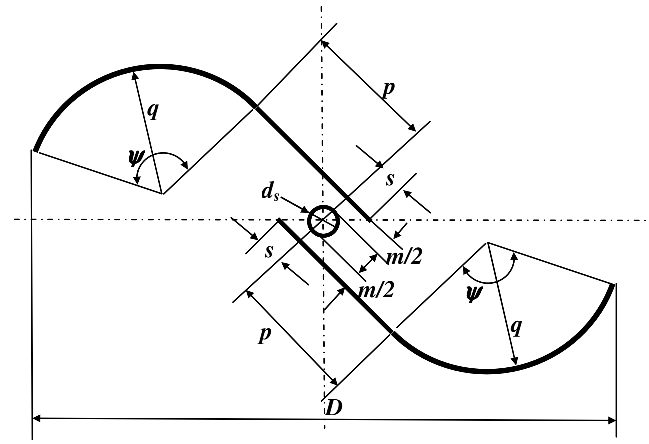


Fig. 3. Basic modified Savonius rotor with shaft [2].

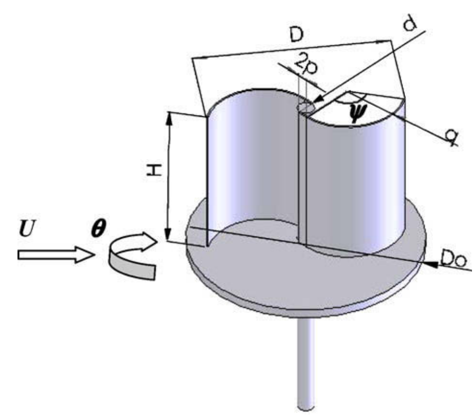


Fig. 4. Geometrical parameters of optimized modified Savonius rotor with shaft [2].

Literature [4] suggests that the conventional Savonius rotor with the following geometrical parameters has high coefficient of power.

Overlap ratio (*m/D*) = 0.15; Aspect ratio (*H/D*) = 1.0; end plate parameter (*Do/D*) = 1.1; blade arc angle (ψ) = 180°.

Experiments with the above geometrical parameters for conventional Savonius rotor with the present set-up are conducted. The performance of the modified Savonius rotor (with and without shaft) is compared with the performance of the conventional Savonius rotor (without shaft). The size of the rotors tested had diameters varying from 180 mm to 230 mm.

4. Data reduction

Reynolds number based on the rotor diameter is given by

$$Re = \frac{\rho U D}{\mu} \tag{1}$$

where *Re* is Reynolds number, ρ is the density of air, *U* is the free stream velocity, *D* is the rotor diameter and μ is the absolute viscosity of air.Tip speed ratio is given by

$$\mathrm{TSR} = \frac{\omega D}{2U} \tag{2}$$

where ω is the angular velocity.

Torque calculated from the measured load and spring balance load is given by

Table 2
Uncertainties of various parameters

Parameter	Uncertainty (%)
Tip speed ratio	2.5
Coefficient of static torque	4.5
Coefficient of power	4.8

$$T = \frac{(M - S)(r_{\text{shaft}} + r_{\text{rope}})g}{1000} \tag{3}$$

where M is the load, S is spring balance load, r_{shaft} is the radius of the shaft, r_{rope} is the radius of the nylon string.Coefficient of torque (Ct), coefficient of static torque (Cts) and coefficient of power (Cp) are given by

$$Ct = \frac{4T}{\rho U^2 D^2 H} \tag{4}$$

$$Cts = \frac{4T_s}{\rho U^2 D^2 H} \tag{5}$$

$$Cp = \text{TSR} \times Ct \tag{6}$$

Uncertainties in various basic parameters, coefficient of static torque and coefficient of power are presented in Table 2. The uncertainties in the coefficient of static torque and coefficient of power at the maximum coefficient of power are around 4.5% and 4.8%, respectively. Uncertainty calculations are carried out based on Moffat [8].

5. Results and discussion

Coefficient of power of modified Savonius rotor is a function of the shape of the rotor and Reynolds number. This is expressed in dimensionless form as in Eq. (7).

$$Cp = f(m/D, H/D, \psi, p/q, Do/D, Re) \tag{7}$$

First five parameters depend on the geometry of the rotor and the Reynolds number depends on the wind velocity and the rotor diameter. Fabricated rotors are tested for the above parameters to obtain the optimum configuration of the modified Savonius rotor without shaft in between the end plates. The first four parameters are tested for the different values in the following order (Table 1) to obtain a better configuration of the rotor in terms of power performance. Experiments are conducted in an open jet wind tunnel for two Reynolds numbers namely 120,000 and 150,000. The end plate parameter (Do/D) is kept constant at 1.1.

5.1. Effect of overlap ratio (m/D)

The rotors are fabricated to study the effect of overlap ratio (m/D) choosing the blade shape factor (p/q) of 0.2, aspect ratio of (H/D) of 0.77, blade arc angle (ψ) of 124° and an end plate parameter (Do/D) of 1.1. Overlap ratios tested are 0.0, 0.10 and 0.16. Rotors are tested at two Reynolds numbers at 120,000 and 150,000 for coefficient of static torque, coefficient of torque and coefficient of power.

The effect of overlap ratio on coefficient of power, coefficient of torque and coefficient of static torque is shown in Figs. 5 and 6 for Reynolds numbers of 120,000 and 150,000. Rotor with a zero overlap ratio is having higher coefficient of power at both the Reynolds numbers. Increasing the overlap ratio (from 0.0 to 0.1 and 0.16) for modified Savonius rotor (blade arc angle of 124°) increases the losses due to vorticities. These increase in the vorticity losses decrease the aerodynamic performance of the rotors. However, for a conventional Savonius rotor (blade arc angle of 180°) the vorticity loss increases above overlap ratio of 0.15. Thus, conventional Savonius rotors show better performance at overlap ratios of

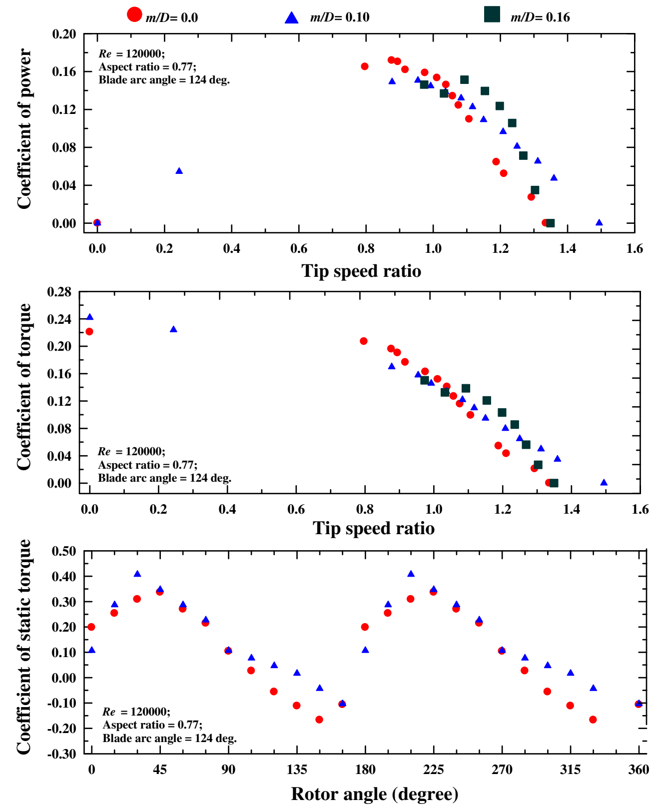


Fig. 5. Effect of overlap ratio on the coefficient of power, coefficient of torque and coefficient of static torque at a Reynolds number of 120,000.

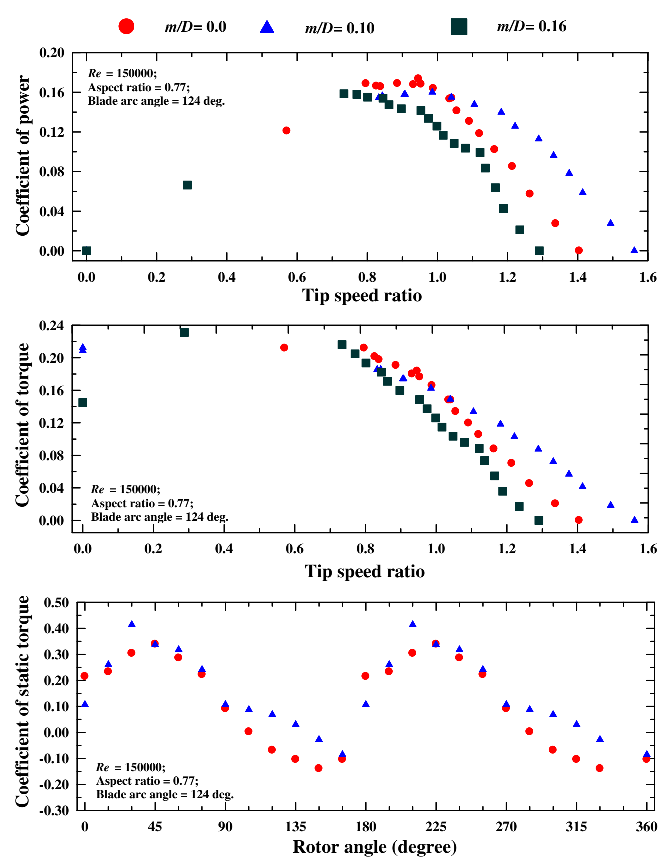


Fig. 6. Effect of overlap ratio on the coefficient of power, coefficient of torque and coefficient of static torque at a Reynolds number of 150,000.

0.15, whereas modified Savonius rotors show better performance at overlap ratio of 0.0.

The coefficient of torque decreases with decrease in the tip speed ratio and reaches a value of around 0.20 at a tip speed ratio of 0.8. Rotors have negative coefficient of static torque between the rotor angles of 120°–165°. The maximum coefficient of power occurs at an overlap ratio of zero which is 0.17.

5.2. Effect of aspect ratio (H/D)

Experiments are conducted on rotors with an overlap ratio of zero and varying the aspect ratio (*H/D*). Aspect ratios studied are 0.6, 0.7, 0.77 and 1.0. In these set of experiments, blade arc angle (ψ) of 124°, blade shape factor (*p/q*) of 0.2 and end plate parameter (*Do/D*) of 1.1 are fixed.

Figs. 7 and 8 show the variation of coefficient of power, coefficient of torque and coefficient of static torque for aspect ratios of 0.6, 0.7, 0.77 and 1.0 at Reynolds numbers of 120,000 and 150,000 respectively. Table 3 gives the maximum value of the coefficient of power and corresponding tip speed ratio and the coefficient of torque at a Reynolds number of 120,000 and 150,000. The rotor with an aspect ratio of 0.7 is having a maximum coefficient of power. All the rotors have negative coefficient of static torque between rotor angles of 120° and 165° and between rotor angles of 300° and 345°.

5.3. Effect of blade arc angle ()

Experiments are conducted on rotors with an overlap ratio of zero and an aspect ratio (*H/D*) of 0.7. Different blade arc angles (ψ) studied are 110°, 124°, 135° and 150° for a fixed blade shape factor (*p/q*) of 0.2. Figs. 9 and 10 show the variation of coefficient

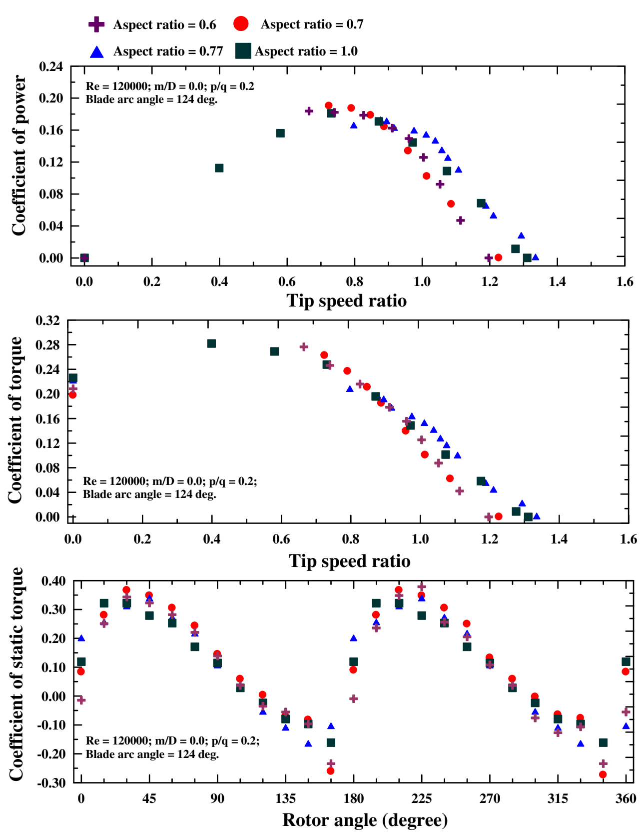


Fig. 7. Effect of aspect ratio on the coefficient of power, coefficient of torque and coefficient of static torque at a Reynolds number of 120,000.

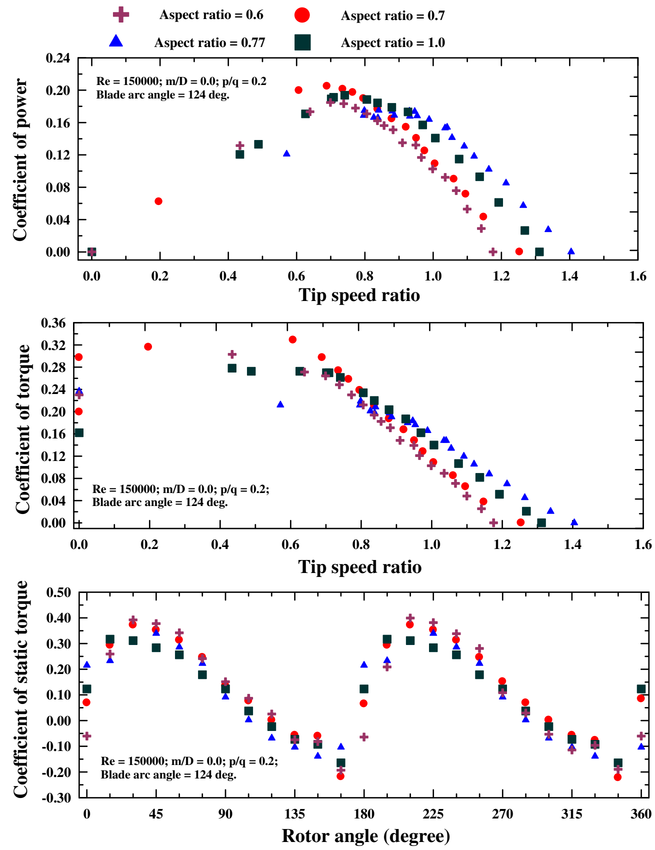


Fig. 8. Effect of aspect ratio on the coefficient of power, coefficient of torque and coefficient of static torque at a Reynolds number of 150,000.

Table 3
Maximum coefficient of power and the corresponding tip speed ratio and coefficient of torque for aspect ratios of 0.7, 0.77 and 1.0 at Reynolds numbers of 120,000 and 150,000

Aspect ratio (*H/D*)	Reynolds number (*Re*)	Maximum coefficient of power (Cp_{max})	Tip speed ratio corresponding to Cp_{max}	Coefficient of torque corresponding to Cp_{max}
0.6	120,000	0.18	0.66	0.28
	150,000	0.19	0.7	0.26
0.7	120,000	0.19	0.72	0.26
	150,000	0.21	0.69	0.30
0.77	120,000	0.17	0.87	0.20
	150,000	0.18	084	0.21
1.0	120,000	0.18	0.73	0.25
	150,000	0.19	0.74	0.26

of power, coefficient of torque and coefficient of static torque for blade arc angles of 110°, 124°, 135° and 150° with Reynolds number of 120,000 and 150,000. Table 4 gives the maximum value of the coefficient of power and corresponding tip speed ratio and the coefficient of torque at a Reynolds number of 120,000 and 150,000. Rotor with a blade arc angle of 124° is having the higher coefficient of power compared to rotors with other blade arc angles of 110°, 135° and 150°. Coefficient of static torque is maximum for all the rotors at the same rotor blade angle of 30° and minimum at a rotor angle of 165°.

5.4. Effect of blade shape factor (p/q)

Experiments are conducted on rotors with an overlap ratio of zero, aspect ratio (*H/D*) of 0.7 and blade arc angle (ψ) of 124°.

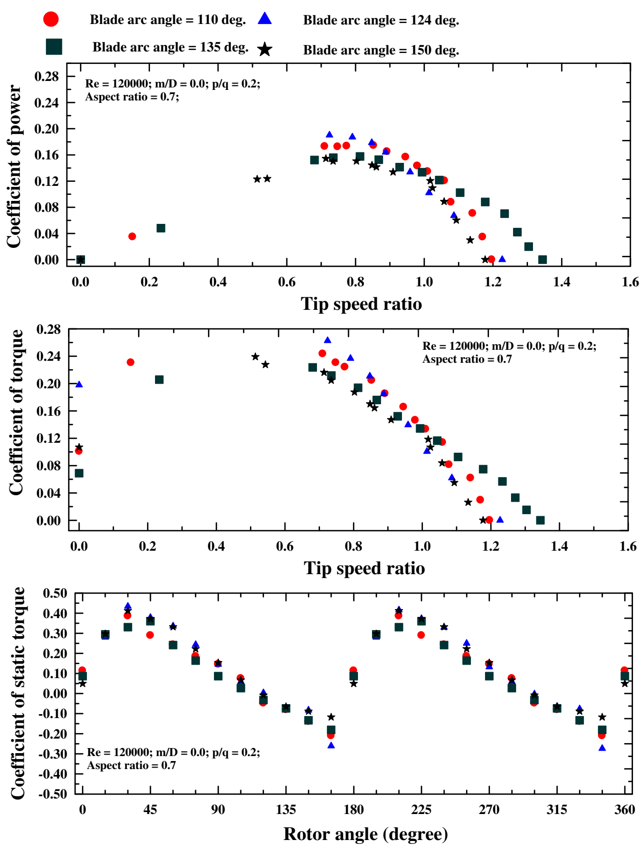


Fig. 9. Effect of blade arc angle on the coefficient of power, coefficient of torque and coefficient of static torque at a Reynolds number of 120,000.

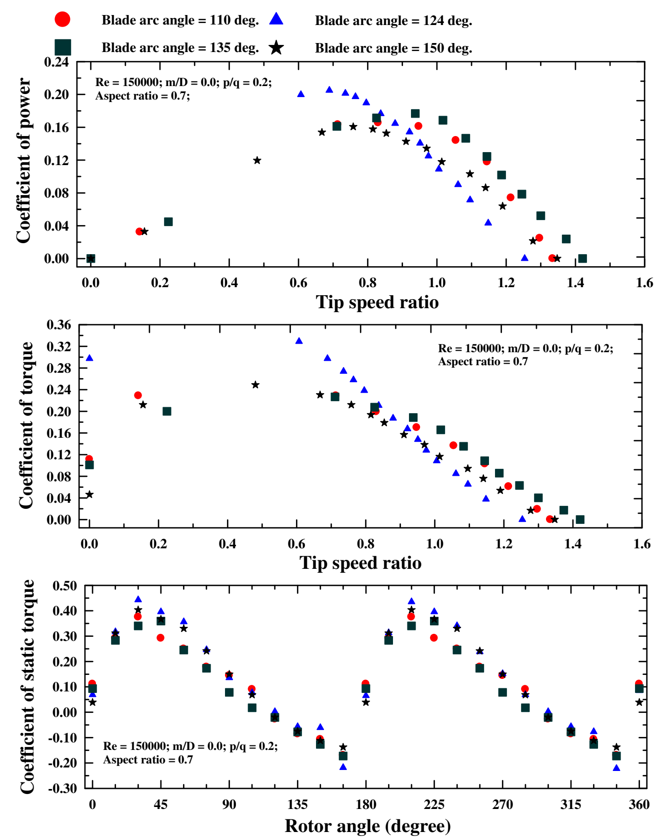


Fig. 10. Effect of blade arc angle on the coefficient of power, coefficient of torque and coefficient of static torque at a Reynolds number of 150,000.

The blade shape factors (*p/q*) considered is 0.2, 0.4 and 0.6 for a fixed end plate parameter (*Do/D*) of 1.1. Figs. 11 and 12 show the variation of coefficient of power, coefficient of torque and coefficient of static torque for a rotor with blade shape factors of 0.2, 0.4 and 0.6 at Reynolds numbers of 120,000 and 150,000. The rotor with a blade shape factor of 0.2 is having slightly higher coefficient of power compared to the rotors with blade shape factors of 0.4 and 0.6.

Based on the experiments, it may be concluded that the rotor with an overlap ratio of zero, aspect ratio (*H/D*) of 0.7, blade arc angle (ψ) of 124°, blade shape factor (*p/q*) of 0.2 and end plate parameter (*Do/D*) of 1.1 results in highest coefficient of power of 0.21. Fig. 13 shows modified Savonius rotor without shaft with the geometrical parameters resulting in maximum coefficient of power.

5.5. Effect of Reynolds number

Influence of Reynolds number is investigated for a modified Savonius rotor (without shaft) for an overlap ratio (*m/D*) of zero, aspect ratio (*H/D*) of 0.7, blade arc angle (ψ) of 124°, blade shape factor (*p/q*) of 0.2 and end plate parameter (*Do/D*) of 1.1. Fig. 14 shows the variation of coefficient of power, coefficient of torque and coefficient of static torque for Reynolds numbers ranging from 80,000 (5.57 m/s) to 150,000 (10.44 m/s). Table 5 gives the maximum coefficient of power along with the corresponding tip speed ratio and coefficient of static torque. Coefficient of power increases by 19% as Reynolds number increases from 80,000 to 150,000. Maximum coefficient of power increases with the increase in the Reynolds number. Sheldahl et al. [9] report that for conventional Savonius rotor (at a given rotor diameter) the delayed separation around the blades at higher wind velocities may be responsible for the increase in the maximum coefficient of power with the increase in the Reynolds number. This increase in the Cp_{max} with increase in *Re* was also reported by Sheldahl et al. [9] and Shankar [10] and for conventional Savonius rotors. Coefficient of torque increases linearly with the decrease in the tip speed ratio and it reaches its maximum value for tip speed ratios ranging from 0.6 to 0.7. Variation in coefficient of static torque with rotor angle is almost independent of the Reynolds number in the range of 80,000 to 150,000. Coefficient of static torque reaches its maximum value at a rotor angle of 30° and it decreases with the further increase in the rotor angle to 165°. The coefficient of static torque is negative in between the rotor angles of 120° to 165° and from 300° to 345°.

Table 4
Maximum coefficient of power and the corresponding tip speed ratio and coefficient of torque for different blade arc angles

Blade arc angle (ψ)	Reynolds number (*Re*)	Maximum coefficient of power (Cp_{max})	Tip speed ratio corresponding to Cp_{max}	Coefficient of torque corresponding to Cp_{max}
100°	120,000	0.17	0.85	0.21
	150,000	0.16	0.83	0.20
124°	120,000	0.19	0.72	0.27
	150,000	0.21	0.69	0.3
135°	120,000	0.16	0.81	0.19
	150,000	0.18	0.94	0.19
150°	120,000	0.15	0.71	0.22
	150,000	0.16	0.76	0.21

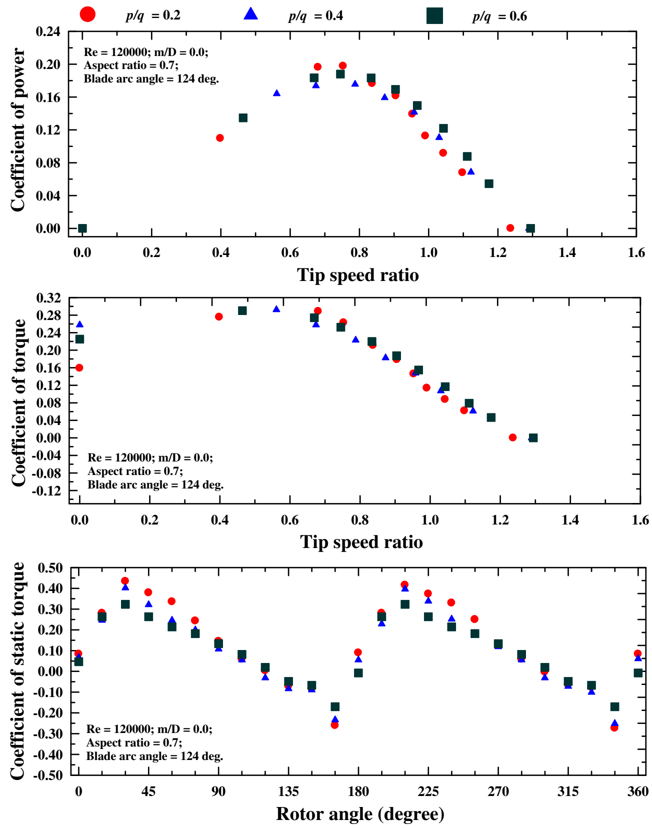


Fig. 11. Effect of blade shape factor on the coefficient of power, coefficient of torque and coefficient of static torque at a Reynolds number of 120,000.

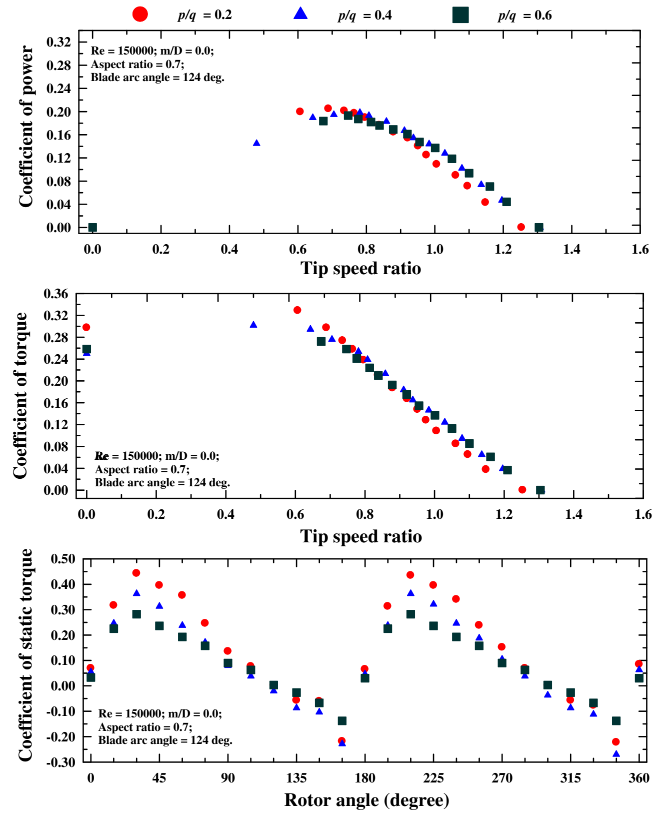


Fig. 12. Effect of blade shape factor on the coefficient of power, coefficient of torque and coefficient of static torque at a Reynolds number of 150,000.

5.6. Comparison of single stage Savonius rotor with the modified Savonius rotor (with and without shaft between the end plates)

Tests for the optimization of the basic modified Savonius rotor was carried out by Modi and Fernando [2] in a closed jet wind tunnel for a range of Reynolds numbers from 170,000 to 400,000. It was inferred that the optimum geometry had a peak coefficient of power of 0.32 at a tip speed ratio of 0.79 in unconfined conditions. The optimum configuration of the Savonius rotor with shaft (Fig. 4) is as follows:

Dimensionless overlap size (m/D) = 0; dimensionless end extension (s/D) = 0; blade aspect ratio (H/D) = 0.77; blade shape parameter (p/q) = 0.2; blade arc angle (ψ) = 135°; end plate parameter (Do/D) = 1.33.

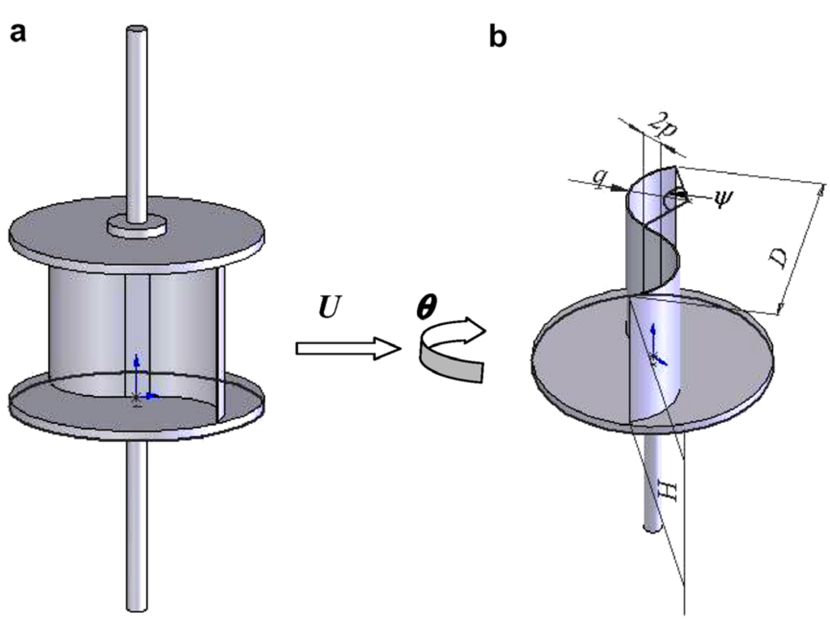


Fig. 13. (a) Modified Savonius rotor without shaft in between the end plates (present study) and (b) Geometrical parameters of modified Savonius rotor.

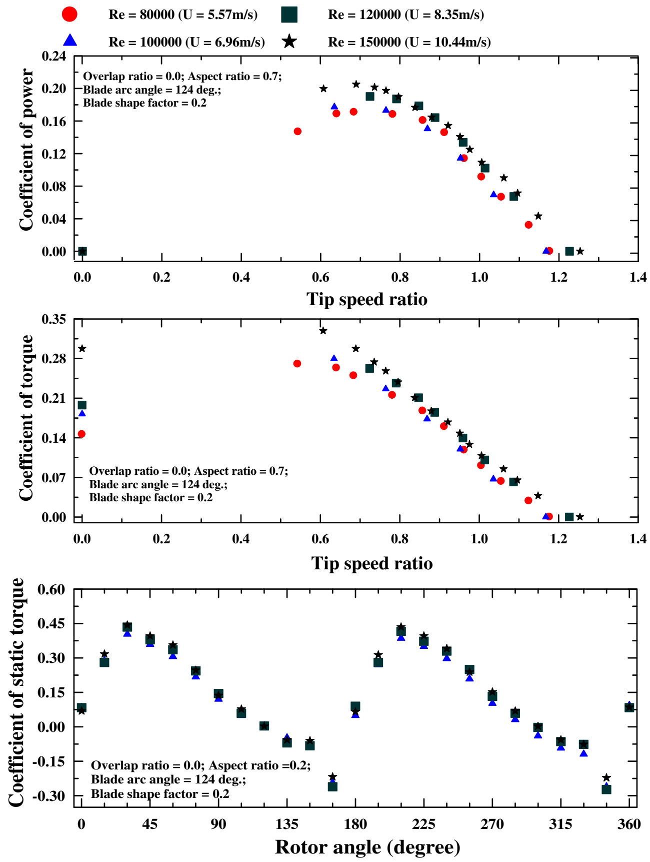


Fig. 14. Effect of Reynolds number (wind velocities) on the coefficient of power, coefficient of torque and coefficient of static torque for the modified Savonius rotor.

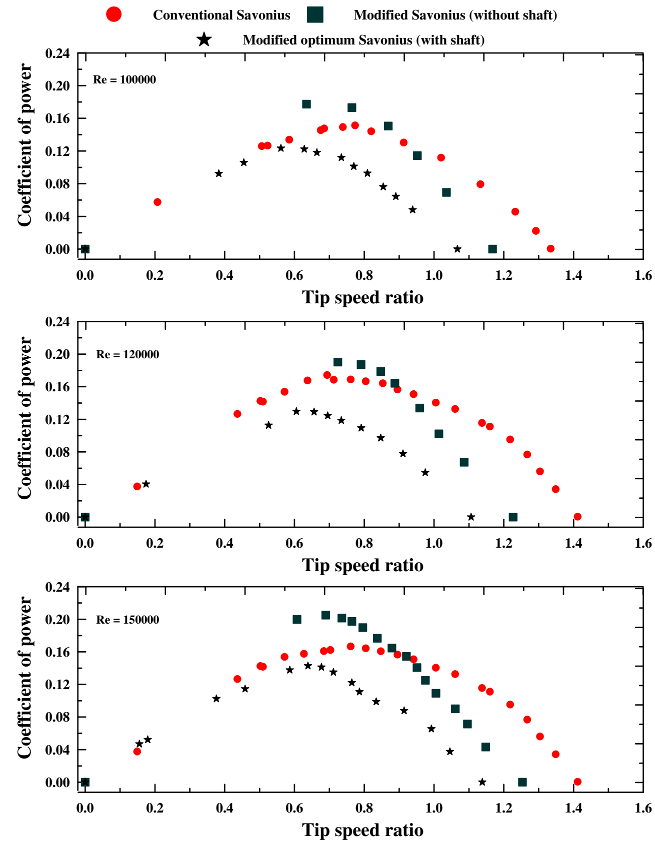


Fig. 15. Variation of coefficient of power with the tip speed ratio for the conventional Savonius, modified Savonius (without shaft) and modified optimum Savonius (with shaft) at Reynolds numbers of 100,000, 120,000 and 150,000.

Table 5
Maximum coefficient of power, corresponding tip speed ratio and coefficient of torque at different wind velocities for modified Savonius rotor (without shaft)

Reynolds number (*Re*) (wind velocity)	Maximum coefficient of power (Cp_{max})	Tip speed ratio corresponding to Cp_{max}	Coefficient of torque corresponding to Cp_{max}
80,000 (5.57 m/s)	17.1	0.68	0.25
100,000 (6.96 m/s)	17.7	0.63	0.27
120,000 (8.35 m/s)	19.0	0.72	0.26
150,000 (10.44 m/s)	20.5	0.69	0.29

A rotor (with shaft) is fabricated and tested with the above optimum parameters for the performance in an open jet wind tunnel. Experimental results for conventional Savonius rotor without shaft tested in the present study are used for comparison with modified Savonius rotor (with and without shaft).

The performance of optimum modified Savonius rotor (with shaft), modified Savonius rotor (without shaft) and the optimum conventional Savonius rotor (without shaft) are compared. Figs. 15 and 16 show the comparison of coefficient of power and coefficient of torque for the three rotors at Reynolds numbers of 100,000, 120,000, and 150,000, respectively. Table 6 gives the maximum coefficient of power along with the corresponding tip speed ratio and coefficient of torque for conventional Savonius, optimum modified Savonius (with shaft) and modified Savonius (without shaft) at Reynolds numbers of 100,000, 120,000, and 150,000. Maximum coefficient of power and the corresponding coefficient of torque of the modified Savonius rotor (without shaft) are higher than the conventional Savonius and modified optimum Savonius rotor (with shaft). Maximum coefficient of power of modified Savonius rotor (without shaft) increases by 17%, 11% and 18% when compared with the conventional Savonius rotor (without shaft) at Reynolds numbers of 100,000, 120,000 and 150,000, respectively. Modified Savonius rotor (without shaft) requires lesser material than conventional Savonius rotor. Maximum coefficient of power of modified Savonius rotor (without shaft) is higher in comparison with modified Savonius rotor (with shaft) by 44%, 46% and 43% at Reynolds numbers of 100,000, 120,000 and 150,000, respectively. The tip speed ratio at no load is higher for conventional Savonius followed by modified Savonius (without shaft) and modified optimum Savonius (with shaft).

Fig. 17 shows the variation of coefficient of static torque with the rotor angle for the three rotors. Three rotors have maximum coefficient of static torque at a rotor angle of 30° and a minimum coefficient of static torque at a rotor angle of 165°. The maximum coefficient of static torque for the modified Savonius rotor (without shaft) and modified Savonius rotor (with shaft) is marginally higher than the conventional Savonius rotor. The minimum coefficient of static torque at rotor angle of 165° for the modified Savonius (without shaft) is marginally lower than the modified optimum Savonius (with shaft) and conventional Savonius rotor.

5.7. Correlations for performance of single stage modified Savonius rotors (without shaft in between the end plates)

Single stage modified Savonius rotors are experimentally tested for performance at different Reynolds numbers. Variation of coefficient of torque for a single stage modified Savonius rotor at different Reynolds numbers (77,600, 103,000, 129,000 and 155,000) is

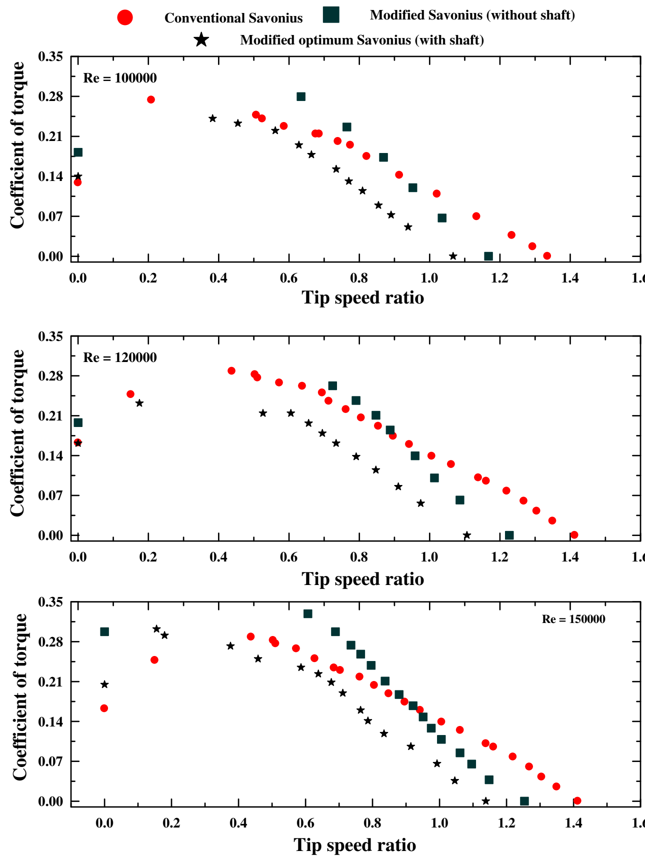


Fig. 16. Variation of coefficient of torque with the tip speed ratio for the conventional Savonius, modified Savonius (without shaft) and modified optimum Savonius (with shaft) at Reynolds numbers of 100,000, 120,000 and 150,000.

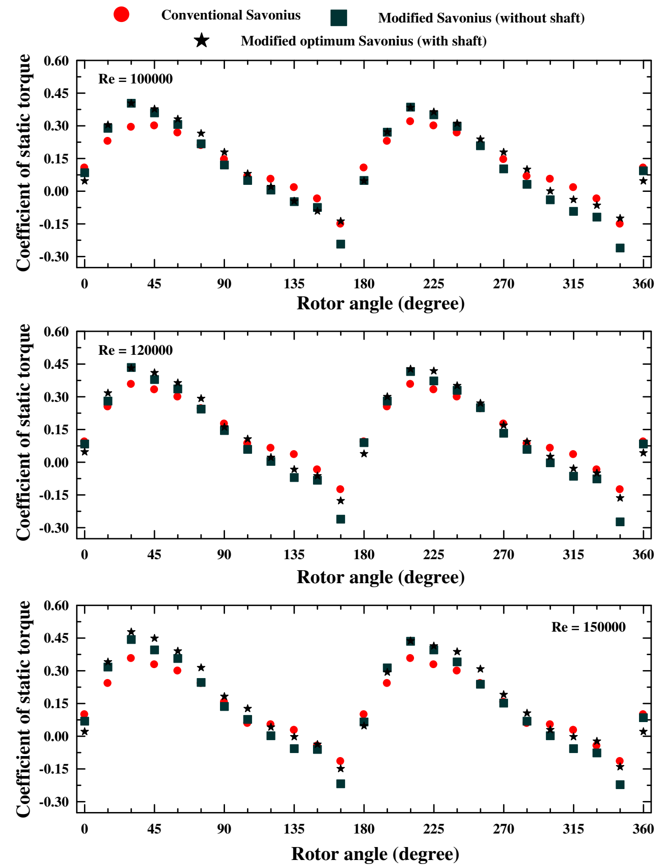


Fig. 17. Variation of coefficient of static torque with the rotor angle for the conventional Savonius, modified Savonius (without shaft) and modified optimum Savonius (with shaft) at Reynolds numbers of 100,000, 120,000 and 150,000.

shown in Fig. 18. These curves almost merge into a single curve for $Ct/Re^{0.3}$ as shown in Fig. 19. Correlation equation is linear and is fitted for tip speed ratios of 0.6. The parameter $Ct/Re^{0.3}$ computed using the correlation compares with the experimental results within ±5% for tip speed ratios below 1.0. Correlation for single stage modified Savonius rotor with the overlap ratio of zero, aspect ratio (H/D) of 0.7, blade arc angle (ψ) of 124°, blade shape factor (p/q) of 0.2 and end plate parameter (Do/D) of 1.1 is given by

$$\frac{Ct}{Re^{0.3}} = -0.0107 \times \text{TSR} + 0.0149 \quad 77600 \geq Re \leq 155000; \text{TSR} \geq 0.6 \tag{8}$$

Comparison of the computed coefficient of power and torque from the correlation and the experimental values for single stage modified Savonius rotor is shown in Figs. 20 and 21 for Reynolds numbers of 120,000 and 150,000. Computed coefficient of power and coefficient of torque compare with the experimental results within ±5%.

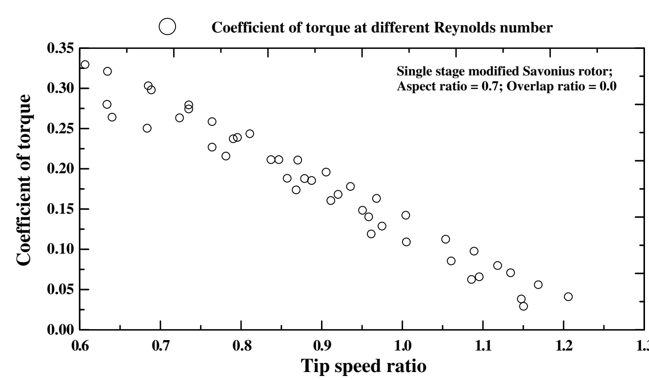


Fig. 18. Variation of Ct with TSR at different Reynolds numbers from 77,600 to 150,000 for single stage modified Savonius rotor.

Table 6
Comparison of maximum coefficient of power and the corresponding tip speed ratio and coefficient of torque for conventional Savonius rotor, modified optimum Savonius rotor (with shaft) and modified optimum Savonius rotor (without shaft)

Rotor	Re = 100,000			Re = 120,000			Re = 150,000		
	Cp_{max}	TSR at Cp_{max}	Ct at Cp_{max}	Cp_{max}	TSR at Cp_{max}	Ct at Cp_{max}	Cp_{max}	TSR at Cp_{max}	Ct at Cp_{max}
Conventional Savonius	0.15	0.77	0.20	0.17	0.78	0.22	0.175	0.69	0.25
Modified optimum Savonius (with shaft)	0.12	0.56	0.22	0.13	0.61	0.21	0.14	0.64	0.22
Modified optimum Savonius (without shaft)	0.18	0.63	0.27	0.19	0.72	0.26	0.21	0.69	0.30

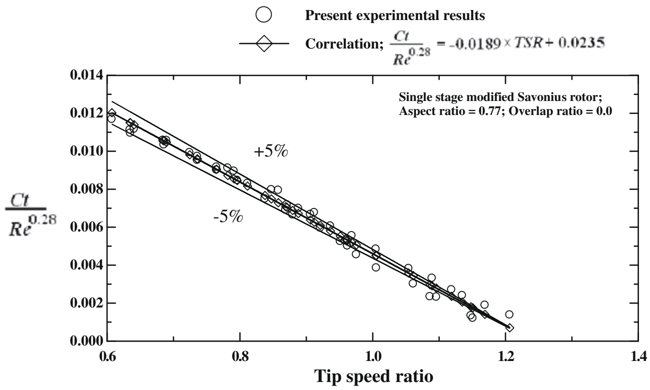


Fig. 19. Correlation curve for single stage modified Savonius rotor for different Reynolds numbers from 77,600 to 150,000.

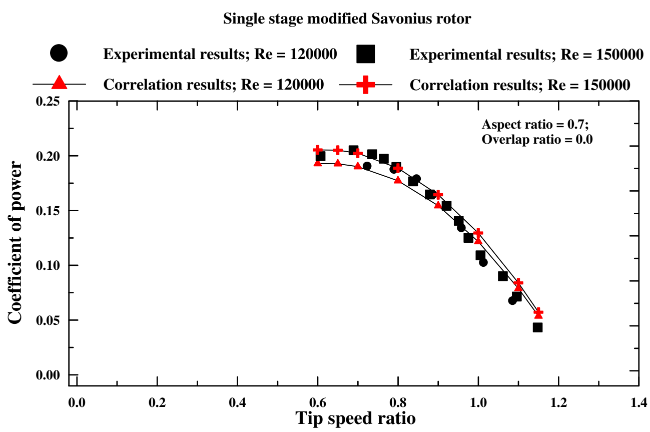


Fig. 20. Comparison of coefficient of power for experimental and correlation results for single stage modified Savonious rotor at Reynolds numbers of 120,000 and 150,000.

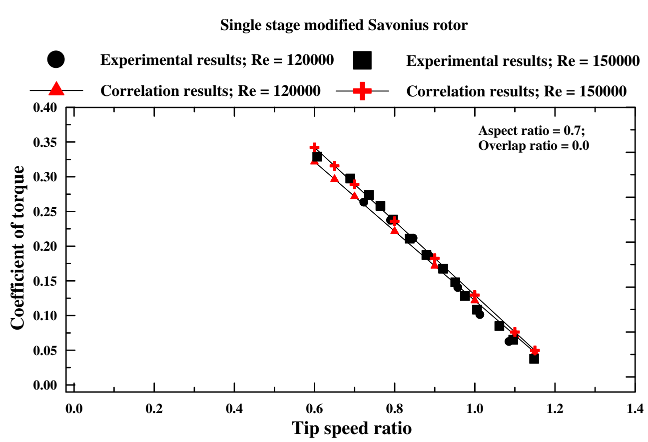


Fig. 21. Comparison of coefficient of torque for experimental and correlation results for single stage modified Savonious rotor at Reynolds numbers of 120,000 and 150,000.

6. Conclusions

Modified Savonius rotor (without shaft in between the end plates) is tested in an open jet wind tunnel by varying the overlap ratio (*m/D*), aspect ratio (*H/D*), blade arc angle (ψ) and blade shape factor (*p/q*) with a constant endplate parameter (*Do/D*) of 1.1. A modified Savonius rotor with shaft in between the end plates with the optimum geometrical parameters as given by Modi and Fernando [2] is fabricated and tested in an open jet wind tunnel. The modified Savonius rotor (without shaft) and the modified Savonius rotor (with shaft) are compared with the conventional Savonius rotor in terms of coefficient of power, coefficient of torque and coefficient of static torque. Experiments are carried out for three Reynolds numbers in an open jet wind tunnel. The conclusions that may be drawn from this study are as follows:

1. Modified Savonius rotor (without shaft) with an overlap ratio of zero, aspect ratio (*H/D*) of 0.7, blade arc angle (ψ) of 124°, blade shape factor (*p/q*) of 0.2 and end plate parameter (*Do/D*) of 1.1 results in high coefficient of power of 0.21 at a tip speed ratio of 0.69 for a Reynolds number of 150,000.
2. Modified Savonius rotor without shaft is having the highest coefficient of power followed by conventional Savonius rotor (without shaft between the end plates) and modified Savonius rotor with shaft. Maximum coefficient of power at a Reynolds number of 150,000 is as follows:
   Cp_{max} of modified Savonius (without shaft) = 0.21; tip speed ratio = 0.69.
   Cp_{max} of conventional Savonius = 0.175; tip speed ratio = 0.69.
   Cp_{max} of modified Savonius (with shaft) = 0.143; tip speed ratio = 0.64.
3. Three different types of rotors have maximum coefficient of static torque at a rotor angle of 30° and a minimum coefficient of static torque at a rotor angle of 165°. Negative coefficient of static torque is observed for all the three rotors from a rotor angle of 135° to 165° and from 315° to 345°. Thus, for almost a 1/6th (60°) of a cycle, rotor would not start at wind velocities corresponding to Reynolds numbers up to 150,000, with no load on the rotor.
4. A correlation is developed for coefficient of torque and power for modified Savonius rotor (without shaft in between the end plates) for Reynolds numbers in the range of 80,000–150,000.

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