Improvement of Performance of Slow-Running, Vertical-Axis Wind Rotors

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ABSTRACT

The paper sums up recent work aimed at improving the performance of slow-running, vertical-axis wind rotors. Attempts to improve the sectional geometry of rotors of this class, studies of secondary design parameters, and work on augmenting power output from the rotor by using products and vanes for concentrating and/or deflecting wind are dealt with. It is seen that rotors with two blades give the best performance and that with augmentation the power output from a rotor of improved sectional geometry can well exceed 2.5 times the output of the Savonius rotor, the best known member of this class of rotors, with similar overall dimensions and operating at the same wind speed. The implications of these improvements to the design and development of wind-rotors of this class and to the efficient extraction of wind power are also commented on.

INTRODUCTION

Although it is common practice to assess the performance of wind rotors on the basis of the power coefficient, C_p, power generation (or, preferably, total estimated energy output) per unit capital investment would be a more relevant and realistic measure of the suitability of a wind rotor design for the generation of power. It is in view of this that considerable attention has been paid to developing wind rotors of simple design, and to the possibility of increasing the power output from wind rotors by using simple augmentation systems. Given the diffuse nature of wind energy and the generally low power-to-mass-ratio of wind rotors, and given the fact that most medium and small wind power systems have rotors whose structural strength is adequate for the generation of a far greater amount of wind power than the rated value for the system, it is reasonable to expect that the system could be rendered more economical by the installation of simple power augmentation facilities. This, however, does not rule out the need for simple modifications to the aerodynamic design of the rotor, which could result in a considerable increase in the rotor power coefficient, C_p.

Several augmentation systems, such as the vortex augmentation systems of refs. 1-3, the tip-vane augmentation system of ref. 4, and the concentrator/diffuser systems of refs. 5 and 6, have been developed for use with horizontal-axis wind rotors. Of these systems, only the one involving a concentrator/diffuser duct can suitably be adopted for the vertical-axis wind rotor. The use of concentrator ducts and wind deflecting vanes for augmenting power in vertical-axis wind rotors dates back several centuries. Some of the early designs of vertical-axis wind rotors (see Fig. 1) could not have operated without the aid of wind deflecting devices. Others depended on the use of mechanisms to move the rotor vanes while the rotor was in operation, in order that the resistance to motion was minimized. The performance of rotors of this class, however, remained poor, despite the use of power augmenting devices, mainly because of the fact that these rotors were all panemones. The Savonius rotor [7, 8], introduced in the late 1920's, was the first slow-running,

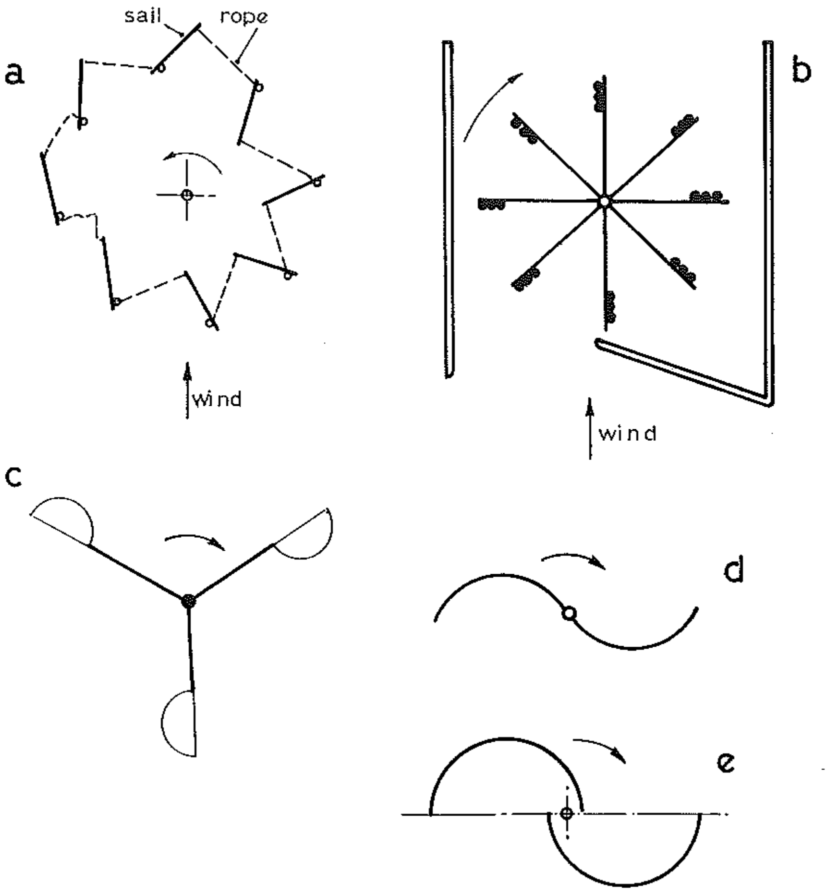


Fig. 1 Slow-running vertical wind turbines: a. Chinese sail-type rotor; b. Ancient Persian windmill; c. A cup anemometer; d. The S-rotor; e. The Savonius rotor.

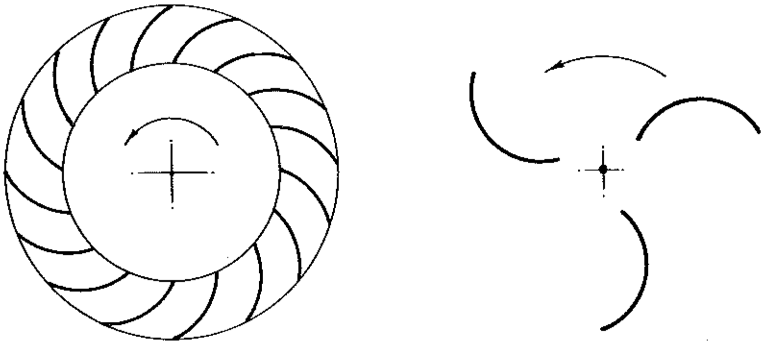
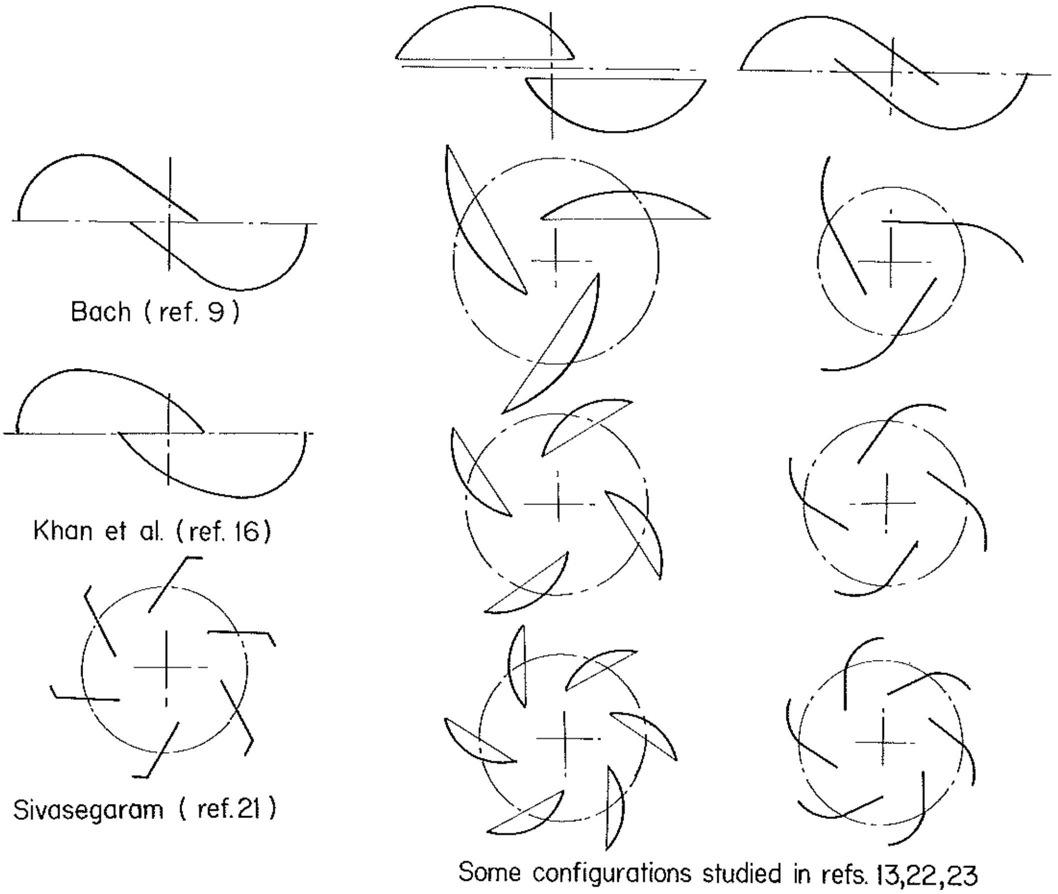


Fig. 2: Vertical-axis wind turbines: a three-bladed rotor and a turbine-type rotor.



Bach (ref. 9)

Khan et al. (ref. 16)

Sivasegaram (ref. 21)

Some configurations studied in refs. 13,22,23

Fig. 3. Rotor designs investigated in recent years.

vertical-axis wind rotor to have a power coefficient comparable with horizontal-axis wind rotors of the traditional type and proved to be simple in structure, economical to produce, stable in operation and easy to maintain. Although the original two-bladed Savonius rotor was followed by other designs such as the three-bladed version of the Savonius rotor, "turbine-type" rotors with several blades and other designs (see Fig. 2), none of these designs surpassed the Savonius rotor in performance. Bach [9] who made a systematic study of the Savonius rotor in a series of wind-tunnel tests concluded that a simple modification to the geometry of the rotor section would result in a cosiderable improvement in performance (see Fig. 3). The quantititative estimate of this improvement was rather uncertain because of wind-tunnel blockage effects which could not be reliably estimated. However, no major attempt was made to improve the performance of the Savonius rotor, or any other rotor of the present class, until the "energy crisis" of the 1970's.

Several detailed investigations of the conventional Savonius rotor [10-14] were undertaken, and rotors with a wide range of sectional geometries were investigated [15-23] with the aim of improving the performance of the rotors of this class. Attempts were also made to study the effects of parameters other than those relating to sectional geometry in order to optimise the overall design of the rotor [10, 11, 24, 25]. These studies led to a considerable improvement in rotor performance compared to that of the conventional Savonius rotor. However, despite this improvement in performance, the power to mass ratio for the rotor remained low compared to fast-running rotors operating at similar wind speeds. Perhaps as an obvious consequence, attempts were made to improve rotor performance by using power augmenting systems. The use of ducts and air-deflecting vanes for augmenting power output from wind rotors have been investigated with some thoroughness [26 – 30].

This paper reviews recent work on improving the performance of slow-running, vertical-axis wind rotors. Given the poor performance of panemone wind rotors, the review will mainly concern Savonius-type rotors and rotors of related geometry. Some comments on experimental uncertainties are considered necessary in view of large disparities among reported measurements on rotors of very similar geometry, and these comments will precede the discussion of the work on improving the sectional geometry and that of the work on power augmenting systems. The concluding section of the paper contains a summary of the achievements so far and some suggestions for future work.

The Rotors and Their Performance

The early designs of slow-running, vertical-axis wind rotors consist mainly of panemones and rotors with moveable vanes. The power coefficients of these rotors have always been low and often considerably below 0.1. Recent attempts at improving the designs of panemones [31] and of moveable vane rotors [32, 33] have failed to produce rotors with power coefficients noticeably larger than 0.1. The "turbine-type" rotor, the Savonius rotor and related designs of rotors, have a definite aerodynamic design advantage over panemones and over rotors with moveable vanes developed so far. With improvements in the sectional geometry of the Savonius rotor and other related types of rotors, their performance proved far superior to that of other types of slow-running, vertical-axis rotors. These improvements not only made it possible to tap wind power with greater efficiency for agricultural purposes but also made it feasible to use Savonius-type rotors for the development of electrical power on a small scale [34]. Before proceeding to comment on the modifications and the resulting improvement in performance of the rotors, it will be useful to recognize certain difficulties in comparing the reported measurements of performances of different designs of rotors.

The difficulty of making a theoretical assessment of the performance of Savonius-type rotors is not hard to recognize. Theoretical analyses of the fast-running, vertical-axis Darrieus rotor with thin blades of aerofoil section have proved successful in predicting rotor behaviour and performance [35, 36]. No such analysis has been shown to be possible for the Savonius rotor, except for a qualitative assessment of the influence of Reynolds number and of the wake aspect ratio (r_a) of the rotor [24].

Field investigations on full-scale rotors, which are necessarily restricted to a limited range of rotor geometries, suffered the disadvantages associated with the unsteady behaviour of the wind. Model tests conducted in wind tunnels were, generally, subject to large errors arising from tunnel blockage effects. Testing of models placed outside wind tunnels in the jet issuing from the wind tunnel exit were also subject to blockage effects, but opposite in sign to that for models placed inside wind tunnels and significantly smaller in magnitude. While tests on models placed inside wind tunnels tended to severely overestimate the power coefficient of the rotor, tests on models placed outside wind tunnels tended to underestimate the rotor power coefficient. It is interesting to note that Jansen [37] who tested horizontal-axis rotor models placed in the jet issuing from a wind tunnel observed the blockage effects to be negligible, provided that the model was placed in the core of the jet and the lateral dimensions of the rotor were less than half the width of the jet. Under these circumstances, the most reliable course was to test the models outside the wind tunnel and ensure that the overall dimensions of the models were more or less the same: this ensures that the blockage error is small and of comparable magnitude in all rotors.

The influence of Reynolds number on rotor performance is an important factor in interpreting results from tests on models. Experimental studies of the effect of Reynolds number on the performance of rotors revealed that the influence of Reynolds number was most significant at low Reynolds numbers ($Re_c < 100{,}000$). This can be seen from Fig. 4. Note that the results of refs. 9 and 10 are subject to a large, positive, tunnel-blockage effect, and that those of ref. 25 to a small, negative, blockage effect.

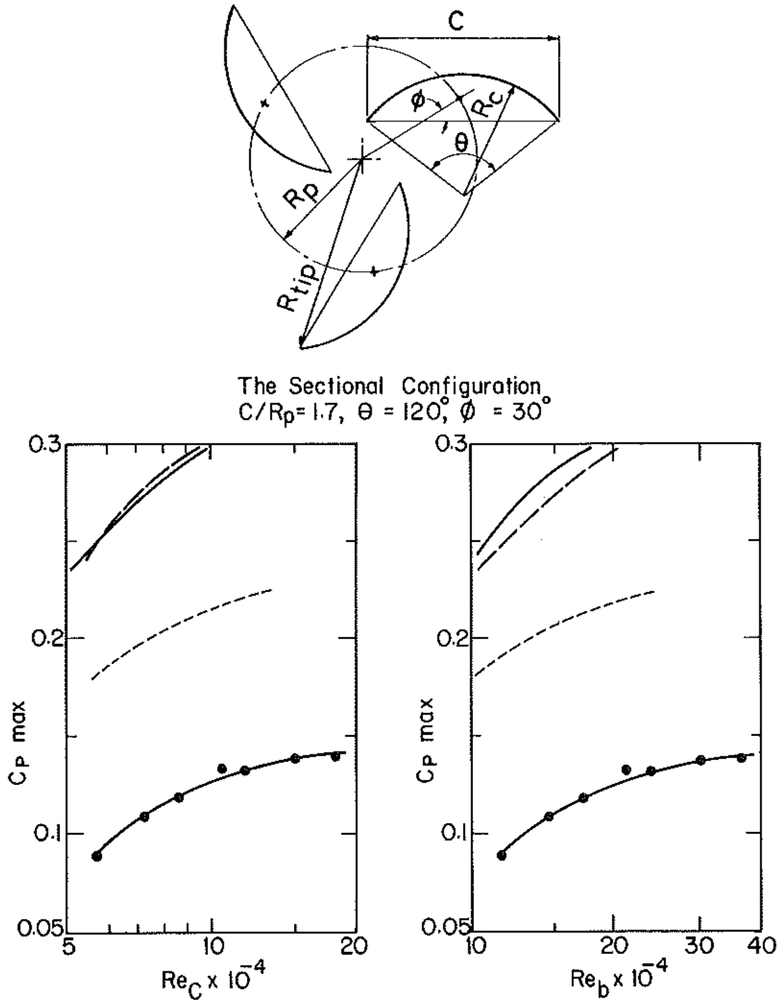


Fig. 4 Influence of Reynolds number on rotor performance
———————— 2-bladed rotor [10]
— — — — 2-bladed rotor [10]
- - - - - - - - - - 2-bladed rotor [9]
—•—•—•— 3-bladed rotor [25].
(Sectional configuration of 3-bladed rotor of ref. 23 is shown)

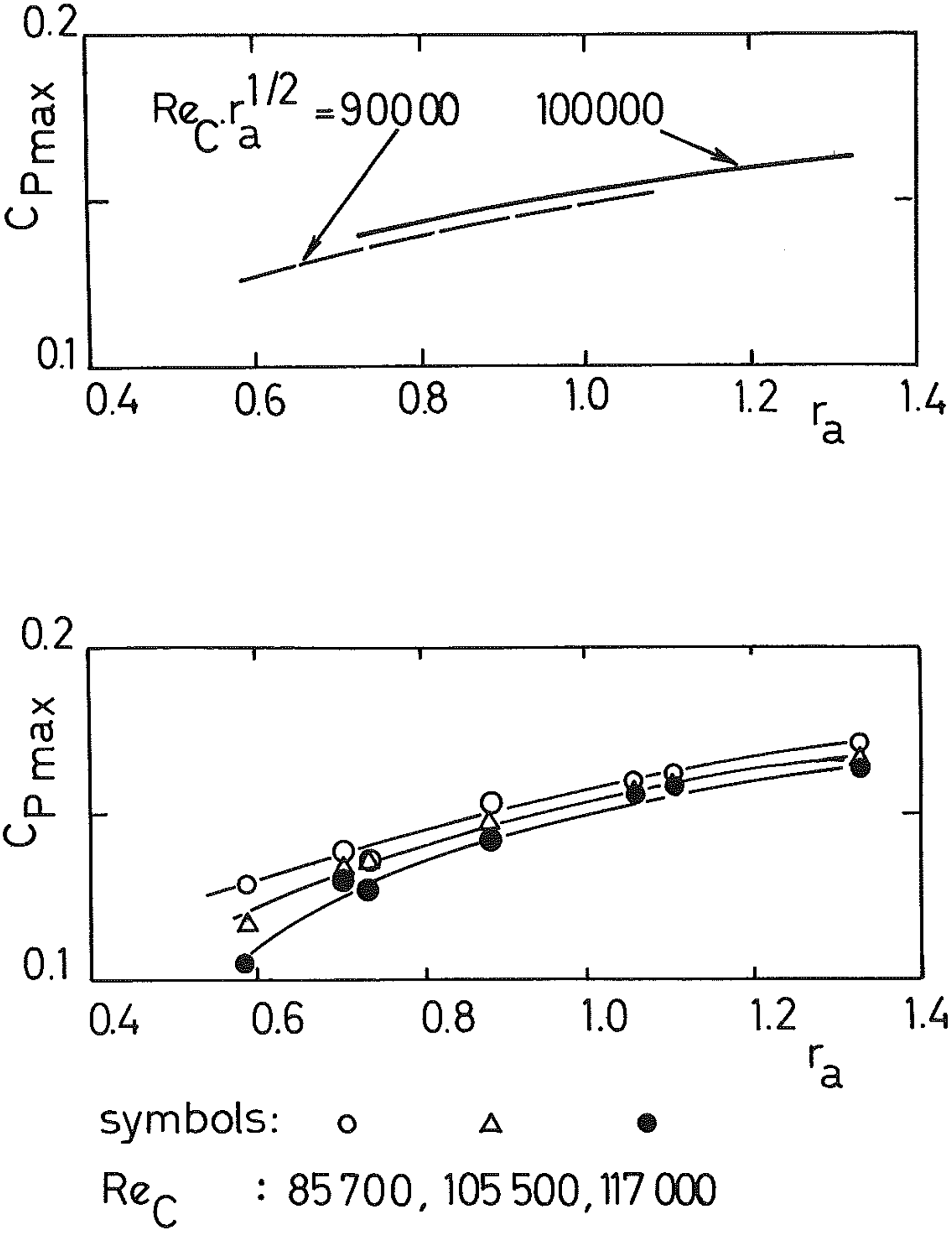


Fig. 5 Influence of wake aspect ratio on rotor performance. (Sectional configuration of rotor as for ref. 25, Fig. 4).

Ref. 25 also reported the influence of the wake aspect ratio (Fig. 5),. which was found to be in agreement with the qualitative estimate of Lissaman [24], the influence of the rotor shaft diameter, and the influence of the diameter of the rotor end-plates. The rotor diameter did not appear to have any influence except when it was large enough to cause serious blockage of air flow through the rotor and the optimum end-plate diameter was just in excess of the overall width (i.e., the wake width) of the rotor.

On the basis of these findings and the findings of the investigations of studies of rotors with a wide range of sectional geometries, optimum sectional geometries were selected for rotors with a number of blades ranging from 2 to 6, and with two types of blade sections (Fig. 6). Models made to a wake aspect ratio, r_a, of 1.5 were tested at comparable air flow conditions. The results as reported in ref. 38 are given in Table 1. The overall improvement achieved as a result of the investigations undertaken by workers in this field is demonstrated by the power-coefficient – tip-speed-ratio curves shown in Fig. 7 for the conventional Savonius rotor of optimum sectional geometry and for the optimum rotor section determined by Sivasegaram [23] (see Fig. 8). The possibility of improving on this performance by using 'aerofoil' type of blades (Fig. 8), or blades of section comprising arcs of two different radii or of a 'spiral' section, does exist. However, the possible improvement is likely to be marginal and may not justify the sacrifice of the simplicity of design.

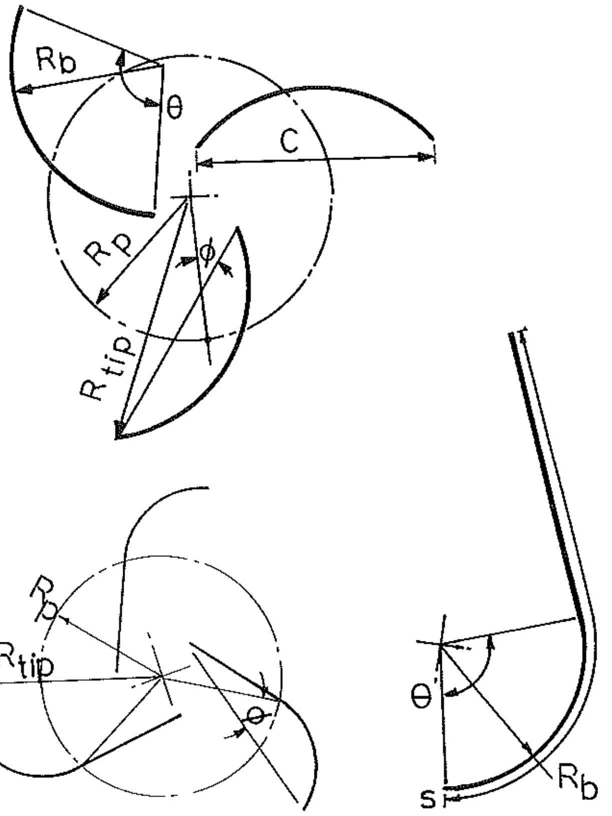


Fig. 6 Geometric parameters of rotors of ref. 22 (top) and ref. 23 (bottom).

Table 1
Maximum achievable power coefficients (from ref. 39)

Blade Section	Maximum achievable power coefficient for rotor / Maximum power coefficient for Savonius rotor — Number of Blades 2	3	4	6
Ref. 22 (See Fig. 6)	1.25	1.1	1.1	1.1
Ref. 23 (See Fig. 6)	1.45	1.15	1.1	1.1

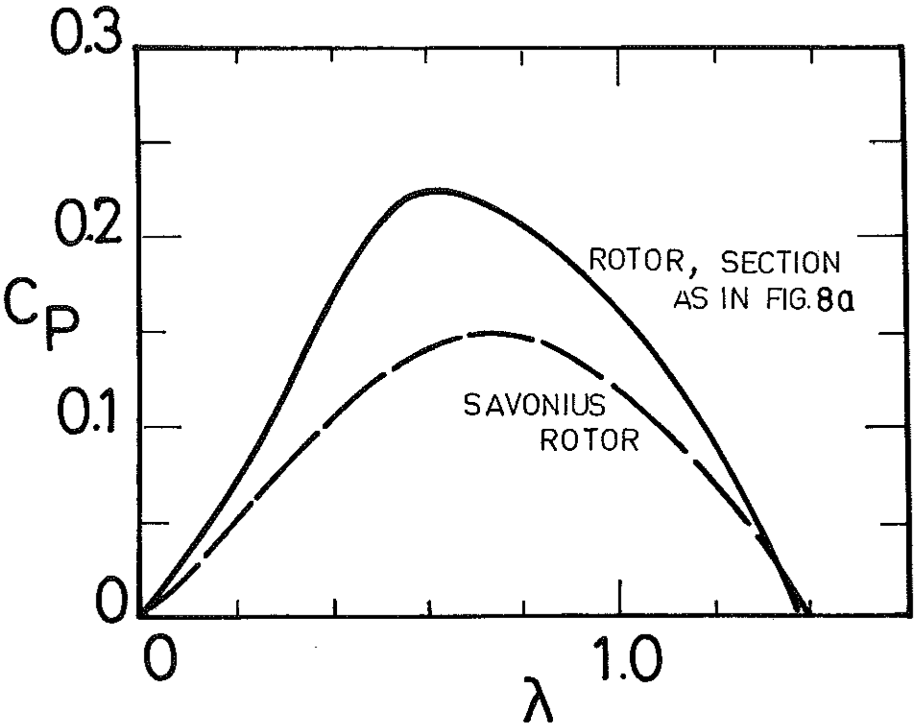


Fig. 7 Performance of Savonius rotor compared with that of rotor of section as in Fig. 8a.

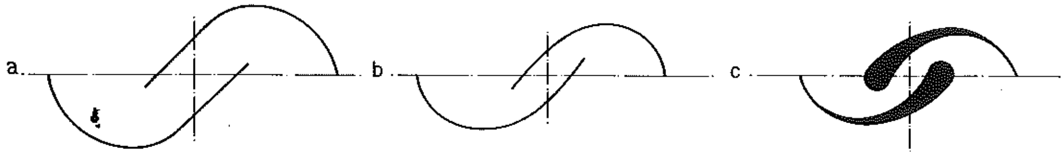


Fig. 8 Sectional geometries for high performance rotors: a. Sivasegaram [23], $n = 2$; $\theta = 127^{\circ}$; $s/R_b = 3.11$, $ns/R_p = 1.4$, $\phi = 10^{\circ}$; b. Rotor with spiral – section blades; c. Rotor with aerofoil-section.

Power Augmentation Systems

Sabzevari [26] investigated the possibility of augmenting power output from a Savonius rotor by enclosing the rotor in a chamber with a concentrator duct (see Fig. 9). Although Sabze-

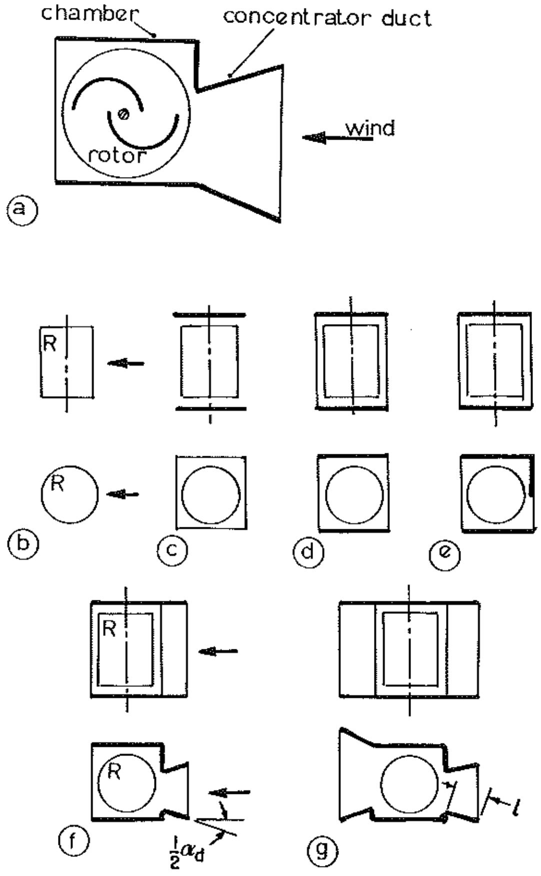


Fig. 9 Concentrator augmentation systems: a. Sabzevari [26]; b. Rotor without augmentation; c. Rotor with chamber roof and floor only; d. Rotor with chamber, front fully open; e. Rotor with front chamber partly blocked; f. Rotor with concentrator; g. Rotor with concentrator and diffuser. (b – g tested in ref. 27).

vari observed a considerable augmentation of output, the extent of the augmentation was, perhaps, severely overestimated. [39]. The effects of tunnel blockage, although uncertain, appeared to be large. However, Sabzevari's observation of a noticeable improvement in power output was confirmed by Sivasegaram [27], who investigated a wide range of concentrator duct geometries (Fig. 9). The investigations of Sivasegaram indicated the possibility of power augmentation by a factor of 1.5 using ducts of realistic dimensions. It should, however, be noted that the concentrator systems suggested by refs. 26 and 27 necessarily imply that the rotor is rendered direction-dependent and is thus deprived of what could be considered its principal advantage over horizontal-axis rotors. It may, however, be noted that the rotor performance did not show much sensitivity to small variations in wind direction (± 10° about the direction of the duct axis) although the rotor performance was poor when the wind direction deviated significantly (say by 30° or more) from that of the duct axis.

The concentrator augmentation system nevertheless offered another advantage besides the increase in power output: the rotor speed and the starting torque showed a considerable increase over that of the rotor without augmentation (see Fig. 10). This was perhaps one factor that prompted Tachi [34], who developed a concentrator system somewhat less dependent on wind direction than that of refs. 26 and 27, to use Savonius-type rotors for generating electricity. It is also worth noting that the concentrator system of refs. 26 and 27 was somewhat bulky and one section of the chamber housing the rotor contributed to an increase in air resistance to the motion of the rotor.

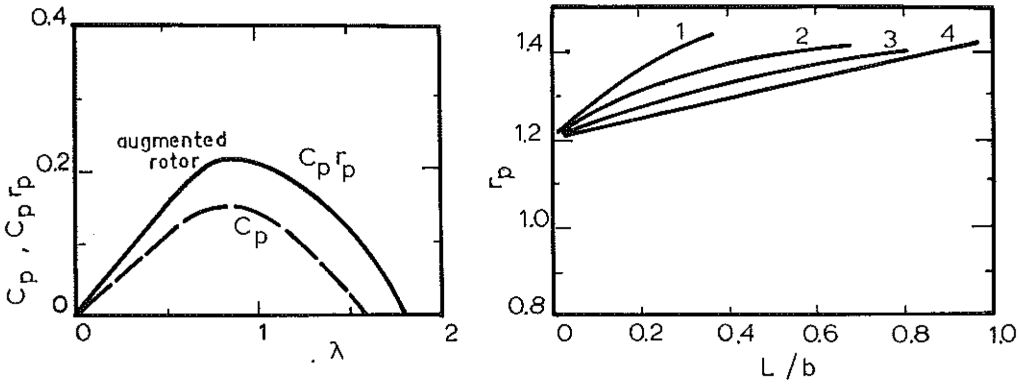


Fig. 10 Comparative performance of Savonius rotor with and without augmentation; and dependence of augmentation ratio (r_p) on duct length (L) and duct angle (1:120°; 2:90°; 3:60°; 4:40°).

Sivapalan and Sivasegaram [28] investigated the possibility of concentration augmentation systems independent of wind direction. Their study covered a wide range of concentration systems with the number of vanes ranging from 1 to 8 (see Fig. 11). The rotor used in the investigation was a six-bladed rotor of optimum sectional geometry as prescribed in ref. 22. It was found that a system with several vanes failed to produce a significantly large improvement in output, while two- and three-vane systems with vanes of moderate dimensions yielded an increase in power output of over 50%. But, of course, the performance of the system was highly dependent on wind direction and a diminished power output was possible over a limited range of wind directions (see Fig. 12). The power augmentation possible with the three-vane system compared favourably

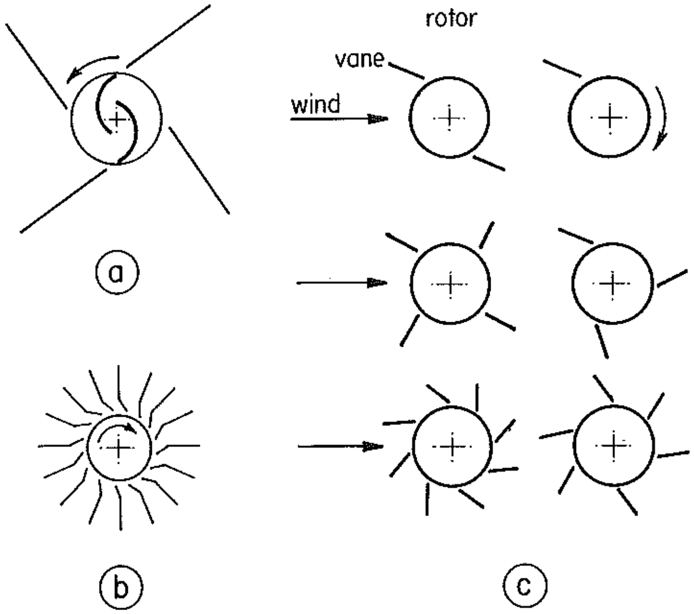


Fig. 11 Director-independent concentration-augmentation systems: a. Tachi [34]; b. Brown [40]; c. Sivapalan [28].

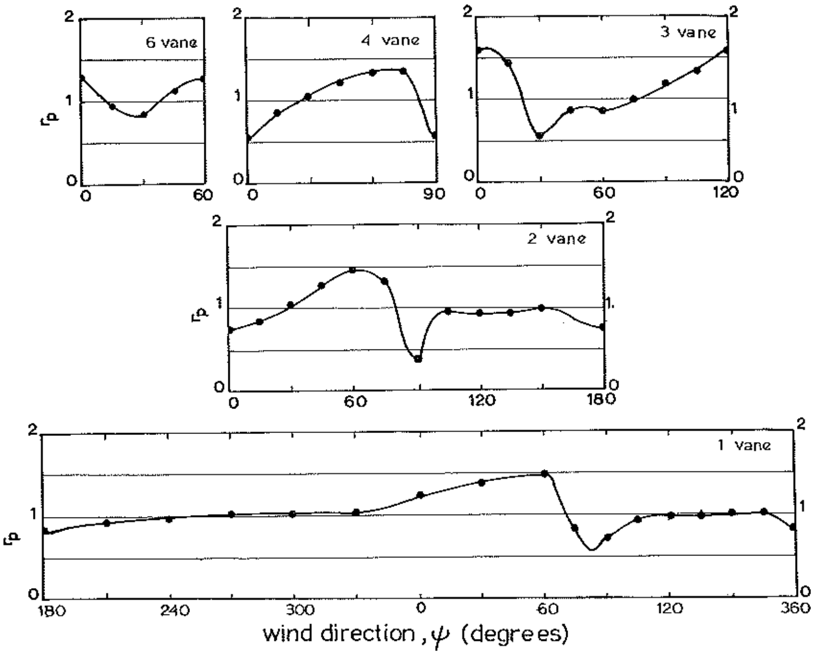
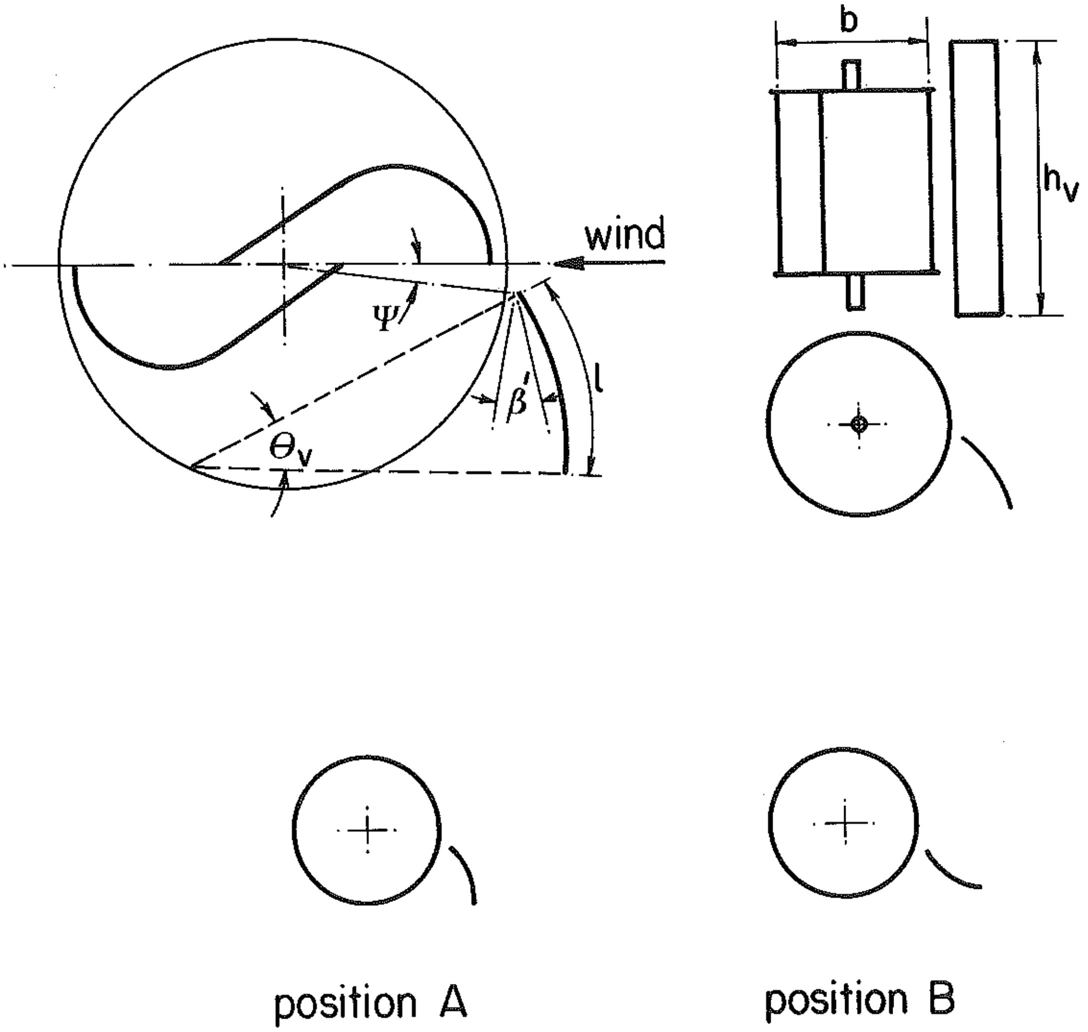


Fig. 12 Performance of direction-independant augmentation system of ref. 28: influence of wind direction on performance.

with the concentrator system of ref. 27 with comparable duct dimensions (60% increase in output compared to 42% for the corresponding duct geometry of ref. 27).

On the basis of the findings of ref. 28, Sivasegaram and Sivapalan [29] undertook an investigation of a single vane air-deflecting system for the augmentation of power output from a Savonius rotor. They found that a single vane of moderate width caused an increase in power output of over 50%, and that the use of curved vanes instead of flat vanes resulted in a marginally better performance. Increasing the vane width beyond a given value did not appear to produce any significant improvement in performance (see Figs. 13 and 14). It was also observed that the use of the vane contributed more to the increase in output when the vane was used to shield from the wind the section of the rotor moving against the wind than when it was used to deflect the wind towards the section of the rotor moving in the direction of the wind.



position A

position B

Fig. 13 Single-vane augmentation system of ref. 29. Rotor wake width, b = 140 mm, vane sectional arc length, l = 25, 50, 75 mm.

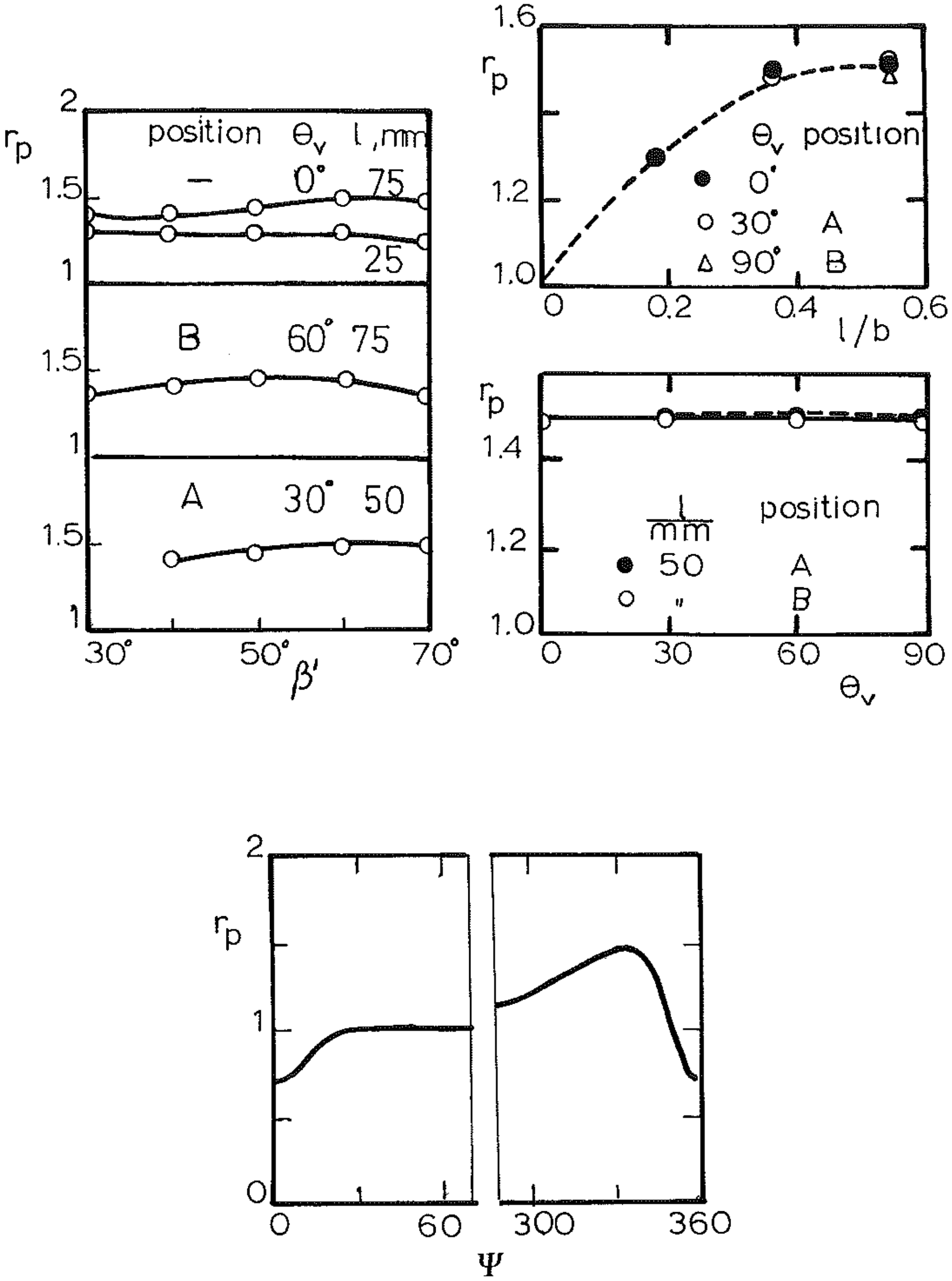


Fig. 14 Dependence of performance of augmentation system of ref. 29 on vane geometric parameters and on wind direction.

The possibility of combining the two functions of the vane, namely the local acceleration of the air flow and the reduction of air resistance to the motion of the rotor, was explored by Sivapalan and Sivasegaram [30] in a subsequent study. The investigations were confined to flat vanes and it was found that power augmentation by a factor of 1.8 was possible using vanes of moderate size (see Figs. 15 and 16).

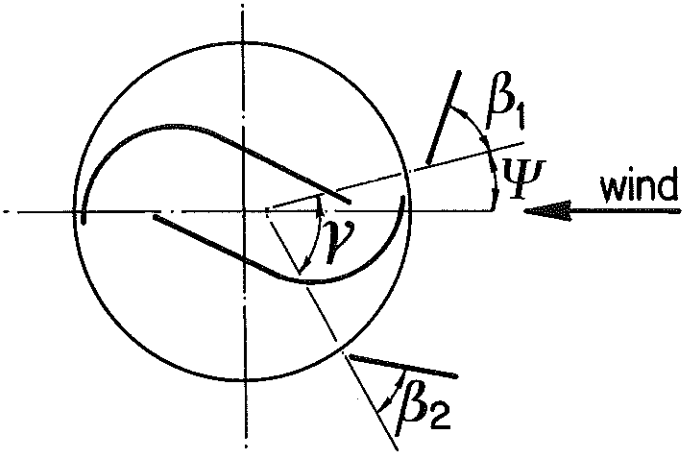


Fig. 15 Two-vane augmentation system of ref. 30.

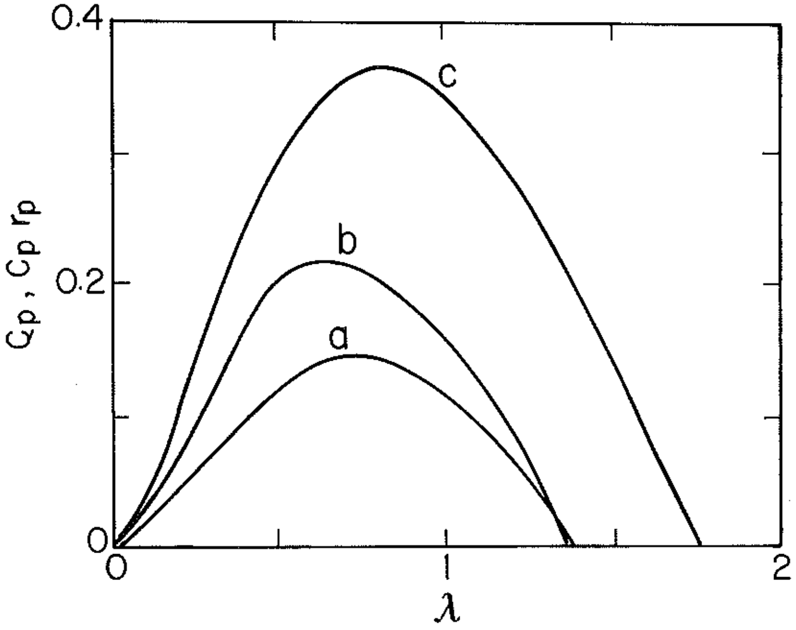


Fig. 16 Performance of rotor with and without augmentation: a. Savonius rotor (conventional); b. Rotor of improved sectional geometry (Fig. 8a); c. Augmented rotor (rotor: as for (b), augmentation system as in Fig. 15 with $l/b = 0.5$, $\beta_1 = 60°$; $\beta_2 = 120°$; $\gamma = 90°$).

Although the augmentation systems studied in refs. 29 and 30 suffer a considerable degree of direction-dependence, the relatively compact vanes make it possible to orient the systems to suit the main wind direction. However provision of facilities to self-align the system is likely to add considerably to the cost of the system.

Concluding Comments

The improvements to the geometry of the rotor and related studies have made it possible to achieve a rotor power coefficient at least 45% more than that for the conventional rotor, without any increase in the constructional cost of the rotor.

The use of simple power augmenting systems comprising two flat plates of modest size could increase the output by 80%, thus making it possible to achieve a power output 2.6 times larger than that of the conventional Savonius rotor. This improvement, however, is achieved at the expense of direction-independence of the rotor. Direction-independent augmentation systems do not appear to be capable of giving a significantly large improvement in performance for all wind directions.

Further improvements to the augmentation system by using curved vanes is possible. The possible extent of the improvement deserves to be investigated.

Although the use of aerofoil-type blades for the Savonius rotor may not yield a significantly large improvement in rotor power output, it may be useful to determine the optimum sectional geometry and explore the possibility of augmenting the power output of the rotor with optimum sectional geometry.

NOMENCLATURE

b	rotor wake width = $2\,R_{tip}$
C	blade chord (Fig. 4)
CP	power coefficient = $P/(\frac{1}{2}\,b\,h\rho V^3)$
h	rotor height
h_v	vane height (Fig. 13)
L, l	vane sectional length (Figs. 9, 13)
n	number of rotor blades
P	power output
r_a	wake aspect ratio = h/b
R_b, R_c	radius of curvature of blade (Fig. 4)
R_p	pitch circle radius (Fig. 4)
R_{tip}	rotor tip radius (Fig. 4)
Re	Reynolds number
r_p	power augmentation = power output with augmentation/power output without angmentation
s	sectional arc length of rotor blade (Fig. 6)
V	wind velocity
α	duct angle
β_1, β_2, β'	vane angle of setting (Figs. 13 and 15)
ϕ	angle of setting of blade (Fig. 4)
θ	arc angle of blade (Figs. 4 and 6)

ψ	wind direction (Fig. 13)
λ	tip speed ratio = rotor tip speed/wind speed

Subscripts

b	wake width
C	blade chord
max	maximum

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