

# Novel developments towards efficient and cost effective wind energy generation and utilization for sustainable environment

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**Abstract**. This keynote paper dwells on innovative approaches towards the development of cost effective and sustainable environment and living using renewable energy sources. The works described are based essentially on the author's work at the University of New South Wales in Australia during the past decade. Power generation and their utilization with minimum carbon footprint are two themes around which the content of this paper has been organised.

The first theme deals with the methodologies associated with the design of rotors for small horizontal axis wind turbines to operate in low to high gust wind conditions for direct electricity generation.

However, for sustainable living with minimum carbon foot print, efficient and effective use of available power is also of paramount importance. The second theme is built towards achieving this objective. It comprises of the design and developments activities towards the minimisation of electricity use by employing wind driven turbine ventilator and providing air quality and comfort for occupants inside buildings.

Finally, the author outlines his vision of future possibilities. The concept of a novel small hybrid wind turbine to generate mechanical power or electricity and operate with greater safety and lower noise level is also outlined. The author also foresees application of flow control technologies towards novel, efficient and cost effective wind energy generation and utilization for sustainable environment.

### Key words

Wind turbine, roof top turbine ventilator, active flow control

### Nomenclature

Α	rotor disk area $(=\pi r^2)$
$A_0$	wake cross sectional area
В	number of rotor blades
$C_P$	power co-efficient
$C_T$	thrust co-efficient
$C_{PO}$	power coefficient based on wake area
$C_{TO}$	thrust coefficient based on wake area
с	local blade chord length
$c_d$	local form drag coefficient
$c_l$	local lift coefficient
d	local form drag
l	local lift drag
F	tip loss factor
f	sheet spacing parameter
G(x)	dimensionless circulation function
Р	power
R	blade radius (radius of rotor disk)
$R_e$	Reynolds number
$R_O$	wake radius
r	local blade radius
S	slipstream distortion
Т	thrust
V	free stream velocity
<i>v</i> <sub>i</sub>	induced velocity of the vortex sheet
W	velocity relative to the blade section
W	displacement velocity
$\overline{w}$	dimensionless displacement

	velocity, $(=\frac{w}{V})$
χ	dimensionless radius (= $\frac{r}{R}$ )
α	angle of attack of blade section
β	blade angle (= $\phi - \alpha$ )
$\Gamma(x)$	circulation at radial station, x
$\frac{\varepsilon}{\chi}$	axial loss factor
λ	free stream advance ratio (= $\frac{V}{\omega R}$ )
$\lambda_o$	wake advance ratio
$\sigma$	solidity
$\phi$	relative wind angle
χ	mass coefficient
ω	angular velocity of the rotor

### 1. Introduction

The Tsunami induced nuclear disaster of Japan in 2011, the Gulf of Mexico oil spill disaster in 2010, the Exxon Valdez disaster in1989 or the Chernobyl Disaster in the former USSR in 1986 are wake-up calls for developing clean, hazard free and renewable energy sources. The havoc such oil spills or radiation wreak on the environment will pale in comparison to the havoc that continued dependence on fossil fuel or nuclear power can wreak on the world's economy and security and even mankind's existence.

The existence of wind turbine as a provider of useful natural source of power for the last thousand years is well documented [1-4]. The windmill, which once flourished along with the water wheel as one of the two prime movers based on the kinetic energy of natural sources, peaked in the 18<sup>th</sup> century and began to decline, as primary movers based on thermal energy from the combustion of fuel took precedence. In recent times, however, with increasing cost of thermal energy and a greater emphasis on sustainable environment, the wind turbine is experiencing a revival. And the new millennium has commenced with the knowledge that wind represents a rapidly increasingly economically viable solution to a major problem of our time the provision of electricity without pollution.

It is estimated that with the doubling of wind power plant capacity, which is currently happening every two and a half years, comes a 15% drop in wind's cost, that is 6% a year [5]. Wind power plants today contribute less than 1% to electricity production in the world. This figure is slightly higher in the USA which is encouraging since the USA is by far the largest consumer of electricity in the world. According to the estimates of the Department of Energy, USA [6], it consumed about 3400 billion kilo-Watt-hours in 1998, which is roughly 45% of the total world electricity consumption. Thus by observing the growth of wind power plants in California which is the largest state in terms of size, population and economy in the USA, the relevant increase in the significance of electricity production using wind can be ascertained. Since 1980, the installed capacity of wind power plants in California has grown dramatically from 10 MW to 1,600 MW in 1992 [7] and according to the study conducted jointly by the five National laboratories of the Department of Energy [8], the installed power capacity of California is projected to be 200,000 MW by the year 2030 making wind a leading renewable energy source comparable to hydropower. A similar study also predicts that by 2030, as much as one-third of the electricity in Europe could technically be produced from wind energy [9].

However, the fact remains that wind power plants are not yet as cost-effective and reliable as conventional means of electricity production.

The full exploitation of a wind turbine as a source of clean, non-polluting and renewable energy depends not only on more huge multi-Mega Watt wind parks that can be found in Denmark, Germany or the USA, but also on small wind turbine that can generate power to meet the demand of electricity need of average households. The present paper, however, will deal only with small wind driven device for power generation and power extraction, in other words devices that can be used to produce electricity directly and ones that uses wind directly for its operation. The materials presented are based on the author's experience on working on these devices over the past decade at the University of New South Wales in Australia. More specifically, the work relates to horizontal axis wind turbines and wind driven rotating ventilators.

# 2. Small wind turbines for power generation

The current state-of-the art technology and public perceptions of wind power can be aptly described in a humorous way using the following cartoon that appeared in Sunday Telegraph of Australia recently [10].

Small horizontal axis wind turbines for power generation considered here are the ones that can produce power between 1kW to 10kW. The applications sought are primarily for domestic electricity generation in residential buildings or boats or yatchs. Although the ideas have been around for a long time, it appears that, it is only recently that the issue is taken up seriously by various governments around the world.

In Australia, for example, householders in the state of New South Wales will be allowed to build wind turbines on the roofs of suburban homes to generate green electricity under a sweeping overhaul of New South of Wales planning laws. Linda Silmalis [11] reported that the state is proposing to allow windmills with a generating capacity of 10kW or less to be erected in residential areas, adding to solar panels as an option for domestic power generation.



Figure 1: Cartoonist Lobbecke's view of roof wind turbine [10]

A height limit of 3m above the roof line will be imposed and turbines will have to be at least 25m from neighbouring properties. As with solar panels, home owners will be able to sell surplus power they generate to the electricity grid, protecting them from skyrocketing power prices. Under the plan, families intending to install a wind turbine would lodge a 10-day complying development application with the local council. Strict noise and location controls would ensure neighbourhoods were not turned into turbine jungles. "Making it easier for property owners to install wind and solar systems would turn suburbs and rural areas into renewable energy harvesting areas with no, or minimal environmental and local amenity impacts", said NSW Planning minister Tony Kelly. The amendments to the law went on public exhibition on 18 April, 2010.

Under the plan wind turbines would be restricted to 10kW in residential zones and 60kW in rural and industrial areas. The solar energy feed-in system, introduced in January, 2010, allows households to earn 60c for each kilowatt hour of electricity produced. The government estimates that individual households could earn an average of \$1500 by selling surplus energy to the feed-in system. A formal review of the effectiveness of the scheme will be undertaken in July, 2010.

In the USA, small scale residential wind turbines are allowed in parts of New York. For example, a five storey affordable housing apartment building in the South Bronx, in New York, has deployed 10kW wind turbines to supplement the facility's conventional power usage in the building's hall ways, elevators and other common areas, the paper states.

Full exploitation of wind turbine technology will be possible when wind turbines will have the capacity to run without shut-down irrespective of wind conditions which in turn may depend on the optimum design of turbine blades that can operate efficiently under moderate to extreme variations in wind conditions. To be more effective, it may also mean identifying low wind areas and high wind areas and design optimum rotors accordingly to suit the different wind conditions. The following section is presented to provide a simple methodology for possible optimum rotor design, or the use of the light loaded or highly loaded theories, both of them based on vortex theory. The vortex sheet inherent in the formulation itself is considered to be an infinite number of vortex filaments each of infinitesimal strength extending to the boundary of the flow. The lightly loaded theory can be applied to low free stream velocities and small wind gusts and operate with advance ratios of  $\lambda$ , of less than half. The point of note is that a rotor designed for light wind load applications will not be efficient in heavy wind areas.

# 2.1 The light loaded and highly loaded theories for HAWT Rotor Design

### 2.1.1 Basic consideration

The vortex theory applicable to aircraft propellers has generally been used to model the behaviour of horizontal-axis wind turbines (HAWT). The theory developed by Glauert [12], Betz-Prandtl [13] and Goldstein [14] has been adopted by Larrabee [15] in the design of manpowered aircraft propellers and wind mill rotors. Larrabee used what may be called the light loading theory, where an assumption is made that the change in the cross sectional area of the stream tube of the rotor is negligible implying thereby that the blades are widely spaced and suffer no distortion. This assumption cannot be considered appropriate for heavily loaded horizontal axis wind turbine, because the retardation of the flow through the rotor causes the vortex sheet spacing and stream tube cross section to change continuously downstream (Figure 2).

The works [16-18] at the University of New South Wales combine the computational simplicity of the Betz-Prandtl relations [13] with the vortex theory of heavily loaded airscrews of Theodorsen [19] to yield a simple method of maximizing power co-efficient, the and consequently predicting the ideal blade geometry of optimum HAWT rotors at their design advance ratio (wind speed/tip speed).

What follows next are based on the salient features of this approach.



Figure 2: Vortex sheet Geometry

#### 2.1.2 Load distribution along the blade

Betz-Prandtl [13] theorem of the 'rigid screw' predicts the circulation distribution along a (airscrew) rotor blade for minimum induced energy loss. The condition is analogous to the minimum induced drag (elliptic lift distribution) on a finite wing. The theorem states that the ideal circulation distribution is achieved when the helical vortex sheets, shed by the advancing blades, are displaced rearward by a radially constant displacement velocity,  $\overline{w}$  (Figure 2). The displacement velocity is an 'apparent' velocity, since the induced velocity  $v_i$  of a vortex element on the vortex sheet is directed normal to the free vortex sheet. Hence the displacement is given by:

$$\overline{w} = \frac{v_i}{v\cos\phi} = \frac{w}{V} \tag{1}$$

where  $\phi$  is the angle between the induced velocity on the vortex sheet and a parallel to the axis of rotation (Figure 2).

An approximate solution to the potential flow problem appropriate to this condition was provided by Betz and Prandtl [13]. Their solution offered a simple set of relationships for predicting the ideal circulation distribution along the blade. The solution was obtained by assuming the rotor to be lightly loaded and consequently, the shed vortex sheets to be regularly spaced in a constant area wake ( $A=A_0$ ). For light loading condition, Goldstein [14] showed that the Betz-Prandtl approximations were sufficiently accurate to predict the ideal circulation distribution along the (propeller) blade at low advance ratios,  $\lambda < 0.5$ .

There is considerable distortion of the slipstream caused by the horizontal axis wind turbine rotor as it extracts energy from the wind. The ratio of the rotor disk to the area of the wake behind the wake,  $A/A_0$  may be used to quantify the wake expansion. Sanderson and Archer suggests [16] that the HAWT rotor be treated as heavily loaded if  $A/A_0 \le 0.9$  or  $A_0/A \ge 1.1$ .

Provided that reference is made to the helix surface far behind the rotor, Theodorsen [19] has demonstrated that the predicted circulation distribution of a lightly loaded rotor was directly applicable to a heavily loaded rotor. The dimensionless circulation distribution is often referred to as the 'Goldstein function [14] and can be determined by the Betz-Prandtl relationships as expressed below:

$$G(x) = \frac{B\Gamma(x)\omega}{2\pi V^2 (1+\overline{w})\overline{w}} = \frac{Fx^2}{\lambda_0^2 + x^2}$$
(2)

Where the tip loss factor F is evaluated by:

$$F = \frac{2}{\pi} \cos^{-1}(\exp - f)$$
 (3)

and the sheet spacing parameter, f, by:

$$f = \frac{B}{2} \frac{\sqrt{\lambda_0^2 + 1}}{{\lambda_0^2}^2} (1 - x)$$
(4)

The advance ratio  $\lambda_0$  is defined for the wake (figure 1), as:

$$\lambda_0 = \frac{V(1+\overline{w})}{\omega R_0} \tag{5}$$

and is related to the free stream advance ratio by:

$$\lambda = \frac{\lambda_0}{(1 + w_d)\sqrt{A/A_0}} \tag{6}$$

For the assumptions of the light-loading theory,  $A/A_0 = 1$  and  $\lambda = \lambda_0$ . However, in the heavily loaded theory,  $\lambda_0$  is adopted instead of  $\lambda$  as the independent variable describing the action of the rotor. Evaluation of  $\lambda$  is performed in the final stages of computation by equation (6).

#### 2.1.3 Maximizing the power coefficient

The maximization of the power coefficient is expected to be carried out at the initial steps in the design of an HAWT rotor. By neglecting the form drag, the power produced by the rotor may be assumed to be dependent on the circulation distribution and displacement velocity.

Expressing the power in the form

$$P = C_{P0} \frac{1}{2} \rho V^3 A_0 \tag{7}$$

where  $C_{P0}$  is the power co-efficient based on the wake area, consideration of the momentum changes to the flow behind the rotor shows that  $C_{P0}$  is determined from Theodorsen [19]:

$$C_{P0} = 2\chi w_d (1 + \overline{w})(1 + \frac{\varepsilon}{\chi}\overline{w})$$
(8)

The mass co-efficient is the dimensionless momentum resulting from the induced velocities in the wake between successive vortex sheets and is evaluated by:

$$\chi = 2\int_{0}^{1} G(x)xdx = O(1)$$
(9)

It can be regarded as the mean radially weighted Goldstein function G(x).

The axial loss factor relates the proportion of momentum change in the axial direction to the momentum changes in the wake. With decreasing advance ratio, the components of induced velocity,  $v_i$  in the radial and tangential directions decrease and, hence, the axial loss factor increases with decreasing advance ratio

(Figure 3). This parameter is given by Theodorsen [19]:

$$\frac{\varepsilon}{\chi} = 1 + \frac{1}{2} \frac{d(\ln \chi)}{d(\ln \lambda_o)} = O(1)$$
(10)

The condition for maximum power:

$$P_{max} = C_{P0max} \frac{1}{2} \rho V^3 A_0$$
(11)

Is achieved when  $C_{P0}$  in eq (8) is maximized.

If  $\chi$  and  $\frac{\varepsilon}{\chi}$ , which are functions of the wake advance ratio only are treated as constants, the equation (8) becomes a simple cubic of  $\overline{w}$ . Consequently, the optimum condition can be derived from equation 8 and corresponds to the solution of the quadratic equation:

$$3(\frac{\varepsilon}{\chi})\overline{w}^{-2} + 2(1 + \frac{\varepsilon}{\chi})\overline{w} + 1 = 0$$
(12)

The negative root of  $\overline{w}$  is applicable to horizontal axis wind turbine rotor. It is noted that that the limit as  $\lambda \to 0$ , of both  $\chi$  and  $\frac{\varepsilon}{\chi}$ , has a unit value and, hence, the non-trivial root of equation 12 is  $\overline{w} = -1/3$  at  $\lambda_0 = 0$ . Henceforth, the subscript max will be omitted and it will be assumed that the value of  $C_{p0}$  is that obtained by equation (8), subject to the solution of equation (12).

#### 2.1.4 Geometric relationships

The blade geometry in its non-dimensional form,  $\frac{c}{R}$ , can be derived in the following manner. For an assumed value of  $\lambda_0$ , equations (2)-(4) are used to obtain an expression for the circulation  $\Gamma(\mathbf{x})$  at a radial station  $\mathbf{x}$ :

$$\Gamma(x) = \frac{2\pi V(1+\overline{w})wG(x)}{Bw}$$
(13)

Also from airfoil theory:

$$\Gamma(x) = \frac{1}{2} WC_l c \tag{14}$$

Using from velocity diagram (Figure 4):

$$W = \frac{V}{\sin\phi} (1 + a\cos^2\phi) \tag{15}$$

where, *a* is the interference factor, similar to the displacement velocity  $\overline{w}$  and is negative for a windmill.

Finally combining equations (13)-(15):

$$\Gamma(x) = \frac{1}{2} \frac{V}{\sin \phi} (1 + a \cos^2 \phi) C_l c \tag{16}$$

is obtained. By introducing the local solidity defined by:

$$\sigma = \frac{Bc}{2\pi r} \tag{17}$$

From equations (13), (16) and (17):

$$\sigma C_l = \frac{2(1+w)wG(x)\sin\phi}{\gamma(1+a\cos^2\phi)w}$$
(18)

From equation (5):

$$\frac{w}{\omega} = \frac{w}{(1+w)} (\lambda_0 R_0)$$
(19)

equation (18) reduces to:

$$\sigma C_l = \frac{2\overline{w\lambda_0}G(x)\sin\phi}{(\chi R/R_0)(1+a\cos^2\phi)}$$
(20)

From figure 3:

$$\tan\phi = \frac{(1+a)\lambda}{\chi} \tag{21}$$

And from equation (5):

$$\lambda = \frac{\lambda_0}{(1+\overline{w})R/R_0} \tag{22}$$

Equation (20) reduces to:

$$\sigma C_l = \frac{2(1+\overline{w})\overline{w}G(x)\sin^2\phi}{(1+a)(1+a\cos^2\phi)\cos\phi}$$
(23)

Using the following expression given by Theodorsen [19] for interference factor,

$$a = \frac{0.5\overline{w} + (\varepsilon/\chi)\overline{w}^2}{1 + \overline{w}(1 + \varepsilon/\chi)}$$
(24)

And the incident angle  $\phi$  along the blade is obtained combining equations (21) and (22) to give:

$$\tan\phi = \frac{(1+a)\lambda_0}{(1+w)\chi R/R_0}$$
(25)

This in turn requires the evaluation of the wake expansion parameter  $A/A_0$ . Archer and Sanderson [16] proposes a method that neglects form drag and equates the thrust developed by the circulation distribution in the wake to that at the rotor. Adopting the convention that the displacement velocity is negative for HAWT rotors, equation (23) is rewritten as:

$$\sigma C_{l} = \frac{-2(1+\bar{w})\bar{w}G(x)\sin^{2}\phi}{(1+a)(1+a\cos^{2}\phi)\cos\phi}$$
(26)

Combining with equation (17), the expression of the dimensionless chord is finally obtained as:

$$\frac{c}{R} = \frac{-4\pi (1+w)wG(x)\sin^2 \phi}{C_l(1+a)(1+a\cos^2 \phi)\cos\phi}$$
(27)

# 2.1.5 Determination of Slipstream expansion, *A*/*A*<sub>0</sub>

Neglecting form drag, the thrust developed at the rotor is expressed as (see Figure 4):

$$T = \frac{1}{2} BR \int_{0}^{1} W^{2} C_{l} \cos \phi dx$$
 (28)

Using equations (14), (15) and (25) and (28):

$$T = 2\rho V^2 A \frac{\overline{w}(1+\overline{w})}{(1+a)} \int_0^1 (1+a\cos^2\phi) G(x) dx \quad (29)$$

Using the thrust co-efficient,  $C_{T0}$ , based on wake area:

$$T = C_{T0} \frac{1}{2} \rho V^2 A_0 \tag{30}$$

and following the same principle s as the power coefficient  $C_{p0}$  (see ref 5, p28):

$$C_{T0} = 2\chi \overline{w} \left[ 1 + \overline{w} \left( \frac{1}{2} + \frac{\varepsilon}{\chi} \right) \right]$$
(31)

Combining equations (29)-(31), the slipstream expansion expression is obtained:

$$\frac{A}{A_0} = (1+a)\chi [1+\frac{-}{w}(\frac{1}{2}+\frac{\varepsilon}{\chi})]/$$

$$[2(1+\frac{-}{w})\int_{0}^{1} (1+a\cos^2\phi)G(x)xdx]$$
(32)

Using the slipstream distortion parameter, S as :

$$S = \frac{2}{\chi} \int_{0}^{1} \cos^2 \phi G(x) dx$$
(33)

equation (32) is expressed as:

$$\frac{A}{A_0} = (1+a)[1+\overline{w}(\frac{1}{2}+\frac{\varepsilon}{\chi})]/[(1+\overline{w})(1+aS)] (34)$$

The evaluation of the slipstream expansion requires the simultaneous solution of equations (25), (33) and (34). These equations are found to converge rapidly, from an initial assumption of light loading  $A/A_0 = 1$ , using a simple convergence criterion on  $A/A_0$ . For a given  $A/A_0$ , the incident angle  $\phi$ , along the blade can be found and the integration in equation (34) performed, thus providing a new value of the slip stream expansion of  $A/A_0$  by equation (33).

### 2.1.6 Estimation of profile drag

Using figure 4, the contribution to the thrust caused by the profile drag can be accounted for by rewriting equation (28):

$$T = \frac{1}{2} \rho B R \int_{0}^{1} W^{2} c(C_{l} \cos \phi + C_{d} \sin \phi) dx \qquad (35)$$

Substituting  $C_l$ ,  $\Gamma(x)$  and W from equations (13-15),

$$T = \frac{1}{2} \rho BR \int_{0}^{1} \frac{V(1 + w)w}{B\omega} G(x) \frac{V}{\sin \phi} (1 + a\cos^{2}\phi)(\cos \phi + (36))$$

Using equations (5) and (21):

$$C_{T} = \frac{2T}{\rho V^{2} \pi R^{2}}$$
  
=  $-4\lambda \int_{0}^{1} (1+\overline{w}) \overline{w} G(x) \frac{V}{\sin \phi} (1+a\cos^{2}\phi) (\frac{1}{\tan \phi} + \frac{1}{l/d}) dx$   
(37)

Note the change of sign was made to comply with the negative convention of the displacement velocity.

Similarly, the corrected expression for power produced for form drag becomes:

$$P = \frac{1}{2} \rho R^2 \int_{0}^{1} W^2 c (C_1 \cos \phi - C_d \sin \phi) \omega x dx \quad (38)$$

In a manner similar  $C_T$ ,

$$C_{p} = -4 \int_{0}^{1} (1+\overline{w})\overline{w}(1+a\cos^{2}\phi)(1-\frac{1}{l/d}\tan\phi})G(x)xdx$$
(39)







Figure 4: Velocity diagram for radial station, x

The equivalent results from light loading theory assuming

$$a = \frac{\overline{w}}{2} \text{ are:}$$

$$C_{T} = -4\lambda \int_{0}^{1} (1 + \frac{\overline{w}}{2}\cos^{2}\phi) \overline{w} (\frac{1}{\tan\phi} + \frac{1}{l/d}) G(x) dx$$
(40)

and

$$C_{p} = -4 \int_{0}^{1} (1 + \frac{w}{2} \cos^{2} \phi) \overline{w} (1 - \frac{1}{l/d \tan \phi}) G(x) x dx$$
(41)

Using the methodology described above, Sanderson and Archer [16] obtained the optimum rotor blade angle distribution and its plan form for a two rotor blade horizontal axis wind turbine for light loading and heavy loading as shown in Figures 5 and 6 respectively.



### Figure 5: Theoretical optimum rotor, for light loading and heavy loading blade angle distribution



# Figure 6: Theoretical shapes of optimum rotor for light loading and heavy loading blade planform

### 2.2 Experimental validation

For validation of the theories expounded earlier and to adapt a horizontal axis wind turbine for high gust wind environment, it was decided to continue with the initial work that began in the early 1980's at the University of New South Wales to produce an optimized horizontal axis wind turbine for use at the Australian Mawson Station in the Antarctica. Meteorological conditions at the Mawson Antarctic base are characterized by strong morning winds blowing from the south east away from the high polar plateau, a high average speed of above 14 m/s, a small period of calm (5%) per year, and hurricane strength storms with gusts exceeding 50 m/s [20]. Another impetus to this work is the scarcity of water supply at Mawson and a natural solution to this problem was to use wind energy as a heat source to melt snow. During these initial studies, however, it was realized that lightly loaded theory advanced by workers such as Glauert [12], Betz [13], Goldstein [14] or Larrabee [15] often used for propeller type windmill rotors, was not suitable to produce an optimum rotor design for a horizontal axis wind turbine in such circumstances.

The unusual nature of Mawson wind frequency distribution also favours a rotor design with rated speed to mean wind speed ratio approaching unity instead of the ratio of approximately 2 for the more usual Weibull distribution [20] and consequently the analysis of Sanderson and Archer [16] could be explored.

Work was, therefore, initiated to reinforce with test results the effectiveness of the highly loaded theory for the design of a Horizontal Axis Wind Turbine for optimum power production over a wide range of advance ratios. Initial tests [17] on two small rotors of 0.3 m and 0.6 m diameters revealed problems with low  $R_e$  or scale effect, high g-loading, strength, stiffness and vibration. Although the theory [16] accurately predicts the blade chord and constant  $R_e$  radially, laminar separation took place at subcritical  $R_e$  with consequent loss in performance. Furthermore, the changing effect of higher  $R_e$  on l/d produced rapid changes in performance. To overcome these problems, two further 3-bladed rotors of 1.2 m blade diameter were designed and a direct means of measuring torque and speed of the rotor shaft was devised. The maximum efficiency obtained in these tests was, however, only 85% of the theoretical value. The test facility has been modified to obtain more accurate results and further tests have been carried out. The maximum efficiency thus obtained was corrected for the mechanical power loss associated with the transmission system of the test rig and close agreement with theory was obtained.

### 2.2.1 Design and manufacture of rotor

The basis of rotor design is briefly explained here. The theoretical analysis [16], suggests that the peak performance, for example, of a two bladed rotor as expressed by the power coefficient, C<sub>p</sub>, is approximately 0.4 and occurs at low advance ratios,  $\lambda$ , of approximately 0.14. In the high average winds of Mawson, this implies a tip speed ratio, TSR, of 7.4 and a high tip speed of approximately 100 m/s. If a 1.2 m diameter rotor were designed to generate 1kW in an average speed of 14 m/s, it would have to rotate at approximately 1600 r.p.m. with a centrifugal g-loading of approximately 17,000. In the extreme condition, that is, at gust speeds of 50 m/s, the rotor would have to rotate at approximately 6,000 r.p.m with a centrifugal gapproximately 200,000 loading of and supersonic tip speed. If no furling or braking is to be provided then it would be necessary to adopt a higher design advance ratio or lower tip speed ratio. With this consideration, rotor design was carried out for a lower C<sub>p</sub> than the peak optimum value of 0.4.

Because of damage to the rotors used in the study reported above, a new test rotor was produced. It was a 3-bladed, 1.2m in diameter with a 0.4m diameter hub, Clark Y blade section and designed for an advance ratio of 0.333. The rotor was made of wood (Queensland Maple) and manufactured using a numerically controlled machine as outlined in ref [17].

### 2.2.2 Modifications to Turbine Test Rig and Wind Tunnel Testing

Several modifications were also carried out to the turbine test rig. These included a 3:1 gearing

system between the rotor and alternator to obtain peak performance results at a higher free stream speed of 10m/s.

Also, to improve the measurement error margin, a new turbine stand was designed to ensure that the rotor was positioned centrally in the wind tunnel test cross section. A dual shaft arrangement as opposed to single shaft to minimize errors arising from misalignment during assembly and disassembly of the rig and a more accurate shaft speed tachometer were also incorporated. The total error in  $C_p$ , therefore, improved to within  $\pm$  0.0025 or approximately  $\pm$  1% at a  $C_p$  of 0.25.

To absorb the power produced by the rotor, a DC electric motor was used. By loading the Horizontal Axis Wind Turbine test rig via an alternator, the corresponding amount of power required by the motor to achieve predetermined speed could be measured. By comparing the value of the power produced by the alternator, the power loss was determined for a range of alternator loads and motor speed which is shown in Figure 7. On this graph, the calibration equation which was used to correct the wind tunnel testing data is also given.



# Figure 7: Power loss in the system as a function of alternator shaft speed

Testing was carried out using the largest available test section, 3.05 m x 3.05 m (10 ft x 10 ft), of the large subsonic wind tunnel of the Aerodynamic laboratory [21] of the University of New South Wales. A schematic of the modified Horizontal Axis Wind Turbine test rig is given in Figure 8.



Figure 8: Schematic of the horizontal axis wind turbine test set up

### 2.2.3 Results and Discussion

Rotor performance curves obtained using the old and the new arrangements are given in Figure 9 for comparison with highly loaded theory. For ease of viewing, the correction due to mechanical power loss is applied to the results of the new arrangement for the free stream velocity of 10 m/s only. In interpreting the results of this graph, it should be realized that the theory under consideration provides a curve which is essentially a locus of peak performance of different rotors. Thus the results for C<sub>p</sub> can only be compared with theory at the design point. There is also a shortfall depending on the  $R_e$  and the findings of the earlier work on smaller rotors are instructive in this respect [17]. It was confirmed that the theory is expected to give an over-estimation of performance peaks for small rotors operating in the subcritical  $R_e$ regime where airfoils undergo non linear changes and that the accuracy of prediction can be expected to improve for larger rotors operating above the critical  $R_e$  range.

Results with the old rig produced a peak test value nearer to 85% of the theoretical design

value with improvements as  $R_e$  increased. Results obtained using the new test rig also shows a similar trend. The peak performance at 10 m/s was found to be around 90% of the theoretical prediction. The power loss correction added approximately a further 3% to the uncorrected value. It should be pointed out that further improvements to the test rig, such as streamlining, need to be carried out to obtain the performance curve for much higher free stream velocities to replicate the 14 m/s of Mawson Base.



# Figure 9: Comparison of predicted power coefficient with experiment for a 3-blade rotor

Based on the results presented in this study, it can be concluded that the Sanderson and Archer optimum loss theory offers a rational basis for the design of propeller wind turbines for peak performance. The main attraction of the theory is its simplicity and the ease with which design curves can be set up. The design process can become rapid since required calculations can be carried out using only hand held calculators.

# 3. Small roof top wind driven ventilators to reduce household power consumption

A distinction is made in this section between wind-driven devices that do not produce electricity but use wind energy directly, thereby saving electricity usage. The device considered here is wind-driven rotating roof top ventilator.

Proper ventilation in building requires that there be a movement or circulation of air within a space and that the temperature and humidity be maintained within a range that allows adequate evaporation of perspiration from the skin. It was formerly believed that the discomfort, headache, and lethargy were caused entirely by the increase in the amount of carbon dioxide and the decrease in the oxygen content of the air. There is now evidence to show [21] that the deleterious effects may also result largely from interference with the heat-regulating mechanism of the body. Lack of air currents and the increase in relative humidity and temperature, especially noticeable in crowded or poorly ventilated places, prevent normal evaporation of perspiration and loss of heat from the surface of the skin.

Also, despite the wide distribution of air pollutant sources, the concentration of indoor pollutants may be the dominant risk factor in relation to personal exposure, as most people spend an average of 87% and 6% of their time within enclosed rooms and vehicles. respectively [22]. Indoor exposure may pose more harmful health effects, as the indoor concentrations of many pollutants are often higher than those typically encountered outside [23]. Under requirements to maintain a safe working environment, many dwellings and factories now need adequate fresh air exchange to remove gaseous, process emissions and/or heat build up. The high priority placed on indoor air quality from health considerations has prompted New York in the USA to pass legislation effective from December, 2008 to require landlords to notify tenants and building occupants of indoor air test results [24].

Modern day building's air conditioning system is typically responsible for around 50% of the base building energy consumption [25]. The other 50% typically includes other services such as common area lighting, domestic hot water, lifts, etc. As such, any reduction in air consumption or efficient use of energy utilisation will offer significant savings in total building energy consumption and carbon emissions. Under these circumstances, wind driven rotating ventilators, which use wind as a natural energy source are cheap to manufacture, install and maintain, and has, therefore, found widespread use in most parts of the world.

The rotating wind driven ventilator is environmental friendly, and costs nothing to operate. It can be installed either on the roof of a dwelling or moving vehicle or side-mounted on their windows. It is simple in structure, light in weight and cheap to install. This type of ventilator is generally manufactured from corrosion resistant aluminium. Some common forms of roof top wind driven ventilators are shown in Figure 10. A series of cylindrical ventilators operating on the Red Centre building of the University of New South Wales can also be seen in Figure 11.



# Figure 10: Some common forms of roof top wind driven ventilator (Image:taken with permission, <u>www.edmonds.com.au</u>)

The simplicity of the rotating wind driven ventilator belies the fact, that the actual mechanism associated with its operation is very complex. A rotating roof top ventilator can be likened in part to a vertical axis wind turbine in its rotor configuration and in the sense that it also uses wind energy directly for its rotation. However, in terms of operational details, it behaves more like a centrifugal compressor. There is, however, a major difference. A centrifugal compressor accepts air in an axial direction and expels the same air in a radial direction. A rotating ventilator, in contrast, works with air from two sources: it accepts from the free stream of the atmosphere in the axial direction, but expels air from a different source, namely the contaminated air from inside a building into the atmosphere.



# Figure 11: Cylindrical centrifugal ventilator at the University of New South Wales

Most wind riven rotating ventilators have evolved through a process of trial and error in the past as long as they met the regulatory requirements of being able to withstand wind speeds of 220 km/hr without blowing off from a rooftop and not posing any hazards to the population. Works [26-30] carried out at the University of New South Wales were probably the first systematic investigations of the aerodynamic performance of these ventilators. The initial works were mainly experimental in nature using simple physical models in a wind tunnel. The models consisted of a stationary cylinder and a spinning cylinder. Such models were useful in understanding some of the aspects of aerodynamic force acting on a wind ventilator. The flow visualization experiments were limited in scope but still provided useful qualitative information about the nature of the flow, particularly, in relation to force component associated with drag that were later confirmed in force/torque transducer measurements. The size of the ventilator wake was found not to increase in size appreciably downstream of the ventilator.

The rapid decay of the ventilator wake also emphasized the importance of flow mixing by the blades of the rotor.

Recent works have involved the investigation on internal flows within rotating vanes of these ventilators using computational fluid dynamics [31]. An objective this study was to explore the effect of inclined roof on the performance of these ventilators.

First some wind tunnel experiments were performed. The turbine ventilator used in this investigation is a Hurricane H100 produced by CSR Edmonds Australia Ltd. It consists of a rotating portion (Rotor) with 8 curved blades and a stationary portion in the form of a cylindrical base. The dimensions of the various components of this ventilator are shown in Figure 12.

The physical experimentation were conducted in a 76mm diameter open return, 0.2% turbulence intensity open test section wind tunnel [1, 32] of the Aerodynamics Laboratory of the University of New South Wales. The experimental setup is shown in Figure 13.

The wind tunnel measurements were obtained at three different cut planes of h = 270mm, 370mm, 420mm, respectively (see Figure 13) with free stream velocity kept at 10 m/s. The mean value of static pressure at each pressure ports at a measurement location were obtained from data recorded over a 10 second sampling period.



Figure 12: Modelling of turbine ventilator

The velocity vectors and static pressure distributions thus obtained from this experiment were used to serve as the bench mark data to validate the initial aspects of the CFD simulation. The schematic diagram of the wind tunnel test set up is given in figure 13.





(a) Free Stream Velocity = 5 m/s

(b) Free Stream Velocity = 10 m/s



(c) Free Stream Velocity = 15 m/s

Figure 16 (a)-(c): 3D velocity vector distribution inside the ventilator

Figure 13: Schematic of experimental setup



Figure 14: Modelling domain and dimension



Figure 15: Three dimensional path line of the flow associated with the rotating ventilator at 10m/s.

The CFD validation offered further scope to investigate both external and internal flows around and within a rotating ventilator [Figures 15-16]. The results were encouraging as they showed trends that were in good agreement with those observed by other experimental studies [29, 33-35]. Performance studies of rooftop ventilator operating with different blade sizes were also conducted. With increases of 50% and 100% in the ventilator blade height, the improvements of between 15% and 25% in exhaust mass flow rate were achieved, respectively. The exhaust mass flow rate was found to have a linear relationship with the oncoming wind speed and blade heights, similar to those reported in the published literature [33-35]. The results of such modelling successfully simulated the complex flow field associated with a rotating ventilator. Thus a promising conclusion that can be drawn from this study is that CFD analysis could be used as a cost effective aid to future design and development of rooftop turbine ventilators with enhanced performance.

The ventilation research at the University of New South Wales with which the author is actively involved, have benefitted substantially in the recent past from two industry collaboration programs funded by the Australian Research Council that have resulted in novel aerodynamic techniques for highly three-dimensional measurement flow and analysis [36-39] and used in ventilation studies, a simple conceptual model [28] for wind driven turbine ventilator design, and a more efficient blade design which has been incorporated in the 'Hurricane' ventilator with nearly 15% increase in air extraction and is currently commercially manufactured and marketed by CSR Edmonds. The works have also provided engineering solutions for enhanced safety and performance of wind driven ventilator in rain and operation at low speed and produced novel techniques for skin friction measurement [40] on roof surface, and formed the basis for the concept of a hybrid ventilator [30, 41-43] to overcome the dependence of conventional roof top ventilators on the availability of wind. This resulted in the 2008 AIRAH Excellence award winning hybrid ventilator, the 'ECPOWER' in the HVAC-Achiever category as a distinguished Australian

product, invention or innovation in heating, ventilation/air conditioning. The 'ECOPOWER' (see Figure 17) is currently marketed worldwide by CSR Edmonds. Stories about these outcomes have featured in Australian Research Council report to Australian parliament [42].



### Figure 17: A Computer aided image of Wind-Electric ECO-POWER

### 4. Future possibilities

# 4.1 Novel Hybrid Wind Turbines for Power Generation

A new low noise, high efficient safe operating wind turbine that combines some of the features of the horizontal axis and vertical wind turbines for an efficient (a patent application has been filed), is described briefly.

With reference to Figure 18, the proposed wind turbine is akin more to a vertical axis wind turbine, 1, imounted on the turbine support structure, 2, with direction vanes, 3, to direct the wind towards the turbine blades, 4. The turbine blades can be of fixed or variable pitch. A second row of counter rotating blades can also be used to improve efficiency. The surrounding structure, 5, conditions the air flow such as to provide improved conversion of the wind energy through the turbine blades to mechanical energy which can be also converted to electrical energy. Mechanical or electrical devices can be mounted at the base of the structure, 6, which allows easy maintenance and lighter support structures for the turbine. The speed of the turbine can be controlled by rotating the surrounding structure,

5, varying the turbine blade pitch, 4, or varying the direction vanes, 3. Flow conditioning structures attached to, 5, also can also be varied to control turbine speed. The shape of the surrounding structure, 5, of the turbine conditions the flow which decreases the impact of sudden gusts on the turbine blades and increases the air velocity at the turbine. This would result in improved low wind speed starting and overall efficiency. A protective screen,7, can be included to protect the turbine from bird strikes. Part or all of the surrounding structure, 5, could be rotated to face the direction of the wind by any external motor and direction system including any mechanical wind vane. The vertical wind turbine, 1, combined with the surrounding structure, 5, decreases noise levels by acting as a noise absorbing chamber.



Figure 18: Schematic of a Novel Wind Turbine

# 4.2 Incorporation of flow control technologies

The performance of horizontal axis wind turbines and wind driven ventilators can be substantially improved by incorporating passive or active flow control technologies. However, with the unit cost of each rotating ventilator presently ranging from \$50-\$200, incorporation of such technologies may be more appropriate to horizontal axis wind turbine purely from present economic realities.

Gyatt and Lissaman [45] carried out a theoretical and field experimental program to investigate the use of tip devices on horizontal axis wind turbine rotors. The objective was to improve performance by the reduction of tip losses. While power output can always be increased by a simple radial tip extension, such a modification also results in an increased gale load both because of the extra projected area and longer moment arm. Tip devices have the potential to increase power output without such a structural penalty. The types considered were a change in tip plan form, and a single-element and double-element non planar tip extension (winglets). Results for each of the three new tip devices, compared with the original tip, showed a small decrease (of the order of 1 kW) in power output over the measured range of wind speeds from cut-in at about 4 m/s to over 20 m/s, well into the stall limiting region. Changes in orientation and angle-of-attack of the winglets were not made. For aircraft wing tip devices, favorable tip shapes have been reported and it is likely that the tip devices tested in this program did not improve rotor performance because they were not optimally adjusted. Gyatt [46] also tested the effectiveness of vortex generators (VGs) for a small horizontal axis wind turbine, Arrays of VGs in a counter-rotating arrangement were tested on the inbound half-span, outboard half-span, and on the entire blade. Field test data showed that VGs increased power output up to 20 at wind speeds above 10 m/s with only a small (less than 4) performance penalty at lower speeds. The VGs on the outboard span of the blade were more effective than those on inner sections. For the case of full span coverage, the energy yearly output increased almost 6 at a site with a mean wind speed of 16 mph. The VGs did reduce the performance loss caused by leading edge roughness. An increase in blade pitch angle has an effect on the power curve similar to the addition of VGs. VGs alleviate the sensitivity of wind turbine rotors to leading edge roughness caused by bugs and drift.

At the University of New South Wales, the active flow control research team headed by the autor have been exploring to develop various techniques [47-62] to manipulate flow features for practical applications in diverse areas ranging from power generation to hypersonic heat dissipation, from aircraft flight to ventilation within buildings and so forth. Some limited work conducted at the University of New South Wales suggests application of Coanda jet as a circulation control technique may provide a useful means to improve the performance of Horizontal axis wind turbines. Figure 19 shows the experimental set up used at the aerodynamics laboratory of the University of New South Wales. The results are promising. An important lesson learnt from this experiment is that there is a need to have an efficient air delivery system. This has lead to exploring the use of an orbital pump, a concept first proposed by Day [63]. A possible adaptation of the proposed compressor to wind turbine for performance enhancement is shown in Figure 20. However, to be effective to small horizontal axis wind turbine, will entail substantial miniaturization of the compressor. This would be a major engineering undertaking which will be highly dependent on the size of the hub of the wind turbine in adapting the air delivery system.



# Figure 19 : Experimental set-up for active flow control application on Horizontal Axis Wind Turbine

An excellent example of application of small wind turbine alongside solar panels for power generation can be seen from the picture of the 'Pink Lady', the boat that Jessica Watson used for her historic round the world voyage, see Figure 21. This may be a pointer for future with combined use of wind and solar renewable power sources, one complementing the other in the times of no-wind or no-sun conditions.



Figure 20: A schematic diagram of possible arrangements of miniaturized compressor in the hub of a wind turbine.



Figure 20: Jessica Watson, the youngest person ever to sail around the world in 210 days (completed on 16 May, 2010)

# 5 Conclusions

A primary concern with any wind driven device is the availability of wind, in other words, the ability to operate these devices at zero and low wind conditions. If continuous power is to be achieved, adequate means of storing of the electricity generated efficiently and economically by batteries or other means have to be ensured. Alternatively, some form of hybrid systems incorporating wind, solar and other power sources have to be devised to reduce usage of electricity produced by fossil fuel sources.

Finally the presentation is ended on a positive message. Greater awareness in people about environmental issues is forcing governments around the world to formulate policies towards greener power sources. This will give boost to more directed and intense research and rapid technological developments and breakthroughs. In the words of the Nobel Peace-laureate and conservation icon Al Gore, 'the time will soon come for 21st-century technologies that use fuel that is free forever: the sun, the wind and the natural heat of the earth.'

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