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CONCEPTS DEVELOPED FOR A MULTIPHASED, VERTICAL AXIS WIND TURBINE SYSTEM WITH AN ADJUSTABLE INLET AIR SCOOP AND EXIT DRAG CURTAIN

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ABSTRACT

A conceptual design is presented of a roof-top type, MULTI-PHASED VERTICAL AXIS WIND TURBINE SYSTEM with an ADJUSTABLE INLET AIR SCOOP and EXIT DRAG CURTAIN at a 100 Watt to 50 kWe commercial scale.

The MULTI-PHASED VERTICAL AXIS WIND TURBINE (MVAWT) SYSTEM is cost effective in an environmentally friendly manner. It is especially useful in areas where it can benefit from the wind velocity increasing and streamlining effects that may occur around small hills, roof tops and tall buildings.

The MVAWT system concentrates, collects and utilizes the available energy in the wind by way of a naturally yawed, downwind seeking, vertical axis orientated flow tube and integrated air turbine assembly with adjustable inlet air scoop and outlet drag sections mounted on the flow tube.

The MVAWT system's air turbine is a combination radial or mixed out-flow and reaction cross-flow type centrifugal fan design as mounted on the discharge end of the flow tube. This air turbine, being more of a radial instead of an axial flow or propeller type design, can potentially exceed the Betz limit of 59.26% energy recovery or effectiveness from the maximum energy available from the wind flowing through the inlet flow tube. A low pressure drop screen can be provided at the inlet and outlet to protect flying birds and mammals from being drawn into the integrated flow tube and air turbine assembly. Additionally, access to the rotating components for inspection and maintenance purposes is much safer, easier and less costly than with conventional propeller type wind turbine systems mounted on tall towers.

No multiple staged wind turbine system as described herein has as yet been researched as to its technical feasibility and developed to the point of a prototype demonstration at a commercial size. Such parameters as overall performance, energy conversion efficiency, costs (installed, operating and maintenance), system reliability, public acceptance and environmental impacts have not yet been truly assessed.

A Phase I - technical feasibility assessment and Phase II - prototype demonstration program for a nominal 10 kWe sized Multi-Phased Vertical Axis Wind Turbine system with an average power output in a 16 mph wind of as much as 2 kWe (kW-hr / hr) and as much as 10 kWe (kW-hr / hr) at a 28 mph wind velocity is suggested to provide this essential information to both the authors and the public at large.

INTRODUCTION

Open propeller (FIGURE No 1) and ducted type axial flow or propeller type wind turbine systems (FIGURE No 2), as well as most other alternative wind turbine system designs of note have been the subject of intensive study and innovative thinking over many years by dedicated scientists and engineers.

WINDGRABBER is an attempt by the authors to explore various possibilities for new ways to implement wind turbine system technology which will have a reduced impact on the public in general from a safety, noise and visibility standpoint with improved systems reliability and availability.

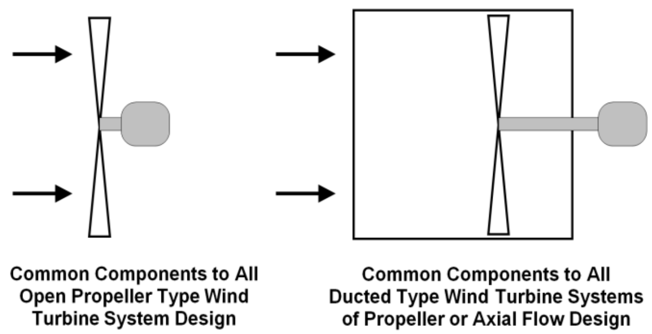


FIGURE No 1 & 2 – EARLY WIND TURBINE CONCEPTS [3] [12]

These improvements in wind turbine systems technology do not come cheaply, however. This paper and the overall WINDGRABBER design in particular builds on the public's ever increasing willingness to pay more for their future energy needs if the result can lead to a reduced negative impact on the world's current environment with an improved quality of life experienced by all.

WINDGRABBER may not be a technology that will be widely implemented in the early decades of the 21st Century, but there is little doubt in the authors' minds that ducted type wind turbine systems of some kind will be a part of the foreseeable future for the human race. This paper is an attempt by the authors to further serious interest and study efforts by future researchers, developers or tinkerers in ducted wind turbine technology. [1] [2]

WINDGRABBER CONCEPTS [18]

WINDGRABBER ™ is a Wind Energy Power Enhancer System, consisting of an adjustable inlet air impact section, a flow tube, an air turbine and an adjustable exit drag section which has been optimally designed for most efficient generation of power from the wind.

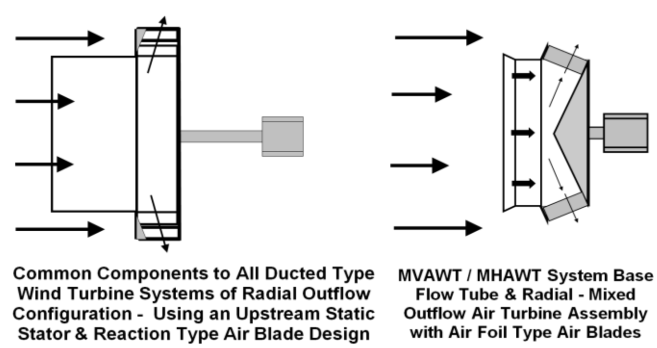


FIGURE No 3 & 4 – EARLY WINDGRABBER CONCEPTS [6] [14]

The WINDGRABBER wind turbine system's overall concept centers around an integrated and aerodynamically optimized inlet flow tube with a radial out-flow type air turbine assembly located immediately downstream of the flow tube outlet (FIGURE No 3). This base WINDGRABBER flow tube and wind turbine assembly is then supplemented with various types of inlet and outlet flow sections which work in combination with the central WINDGRABBER flow tube and air turbine assembly to maximize the differential pressure made available to the WINDGRABBER air turbine assembly for any given locally available prevailing wind's direction and velocity.

The WINDGRABBER radial out-flow type air turbine utilizes a single inlet, centrifugal fan type arrangement, which provides a rather simplistic design approach for development of a highly efficient air foil type air blade design. This design results in a more cost effective fabrication and construction for the overall air turbine assembly. An alternative mixed out-flow type WINDGRABBER design concept (FIGURE No 4), has also been conceived as possibly a more efficient approach for a WINDGRABBER type ducted wind turbine system design range of from approximately 0.1 kWe to 50 kWe in size.

FIGURE No 5 depicts a medium sized WINDGRABBER roof top type ducted wind turbine system of a multi-phased vertical axis (MVAWT) design of approximately 2 to 20 kWe in size, with FIGURE No 6 showing a

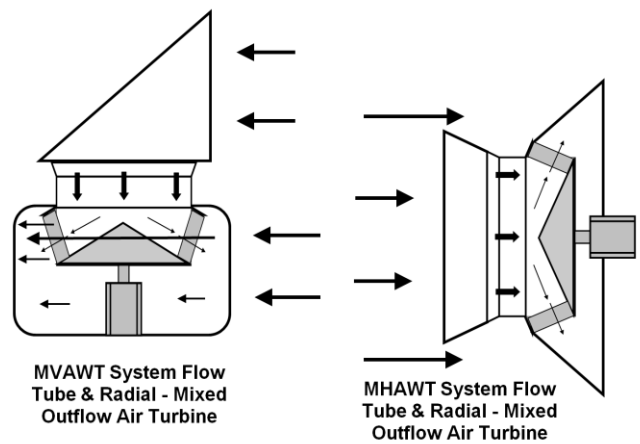


FIGURE No 5 & 6 – ADVANCED WINDGRABBER CONCEPTS

smaller sized multi-phased horizontal axis (MHAWT) design configuration for a WINDGRABBER type system in a 0.1 to 3 kWe range.

FIGURE No 7 & 8 present added details for a radial out-flow and a radial mixed out-flow WINDGRABBER type inlet flow tube and wind turbine assembly. The air foil type air blades are normally optimized for most efficient operation and performance at about 60 % of rated wind speed with blade tip speeds of several times that of the incoming prevailing wind. Also, a second phase of the prevailing wind is injected tangentially to the outer wind turbine circumference in cross flow to assist the wind turbine assembly achieve lower start up speeds in light wind conditions.

FIGURE No 9 & 10 shows larger sized WINDGRABBER systems integrated into larger sized office buildings. These systems use a series of vertical air flow control dampers, located on both the wind ward and lee ward sides of the building, which are then opened and closed, as required, to work in combination with suitable low velocity air supply and exhaust plenums. These two added features use the natural wind impact

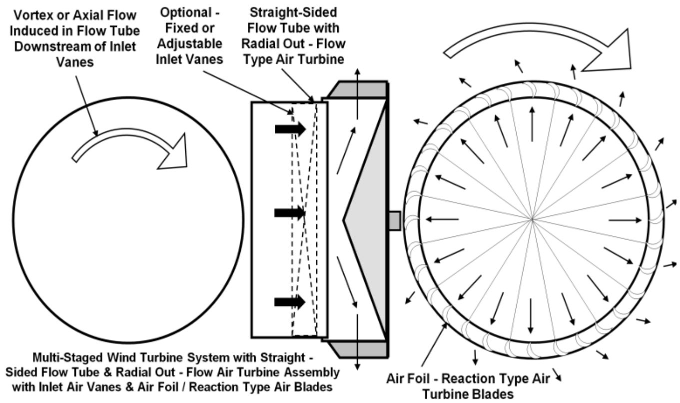


FIGURE No 7 – RADIAL OUT FLOW AIR TURBINE - AIR FOIL BLADE DESIGN

and drag effects of the building itself to simulate the more typical rotating WINDGRABBER inlet air scoop and exit drag curtain.

FIGURE No 9 shows an open type wind turbine discharge system. FIGURE No 10 shows both

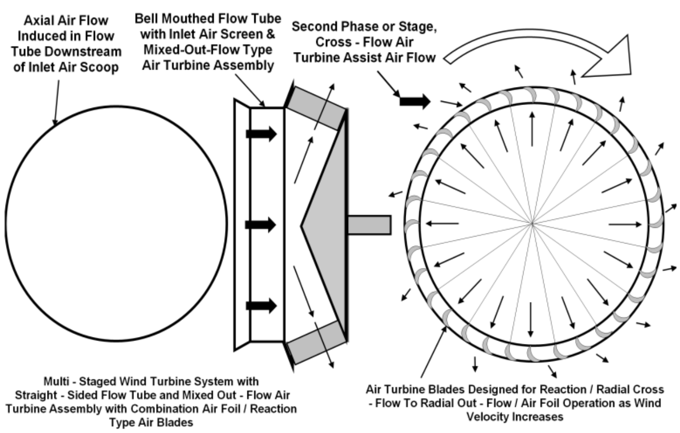


FIGURE No 8 – MIXED FLOW AIR TURBINE - AIR FOIL BLADE DESIGN

common supply and discharge plenums with inlet and outlet control dampers being utilized.

FIGURE No 11 & 12 shows a roof-top WINDGRABBER system design using two different types of rotating cage assemblies. These cage assemblies are assisted in rotation by way of two off center, air foil or vane type stabilizers. FIGURE No. 12 has an additional eccentrically rotated wind turbine assembly feature, which provides additional motive force to the two air foil stabilizer's rotational capability normally utilized with the basic WINDGRABBER system. This overall rotational force maintains WINDGRABBER's inlet facing into the incoming prevailing wind without the need for an auxiliary powered jacking or turning gear.

FIGURE No 13 provides an alternative approach for maintaining the overall WINDGRABBER system in a highly efficient downwind position by means of a centrally supported and eccentrically swiveled inlet air scoop, inlet flow tube, air turbine and exit drag curtain assembly, which has been proven to work by extensive bench scale type physical modeling by the lead author.

FIGURE No 14 is the lead author's latest concept for an ultimate roof top style WINDGRABBER wind turbine

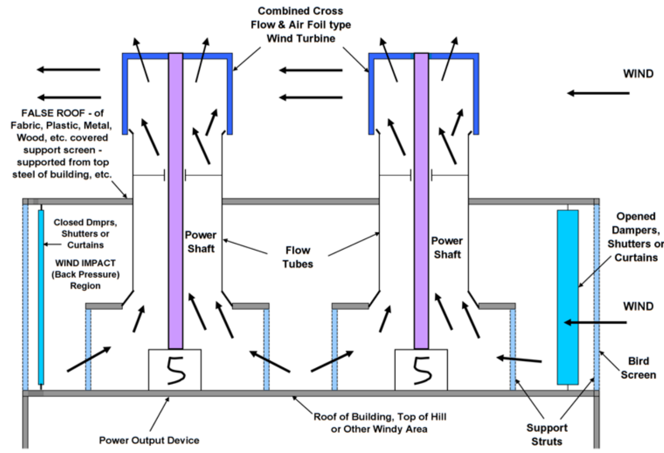


FIGURE No 9 – WINDGRABBER ON A ROOF TOP – NO DRAG CURTAINS [11]

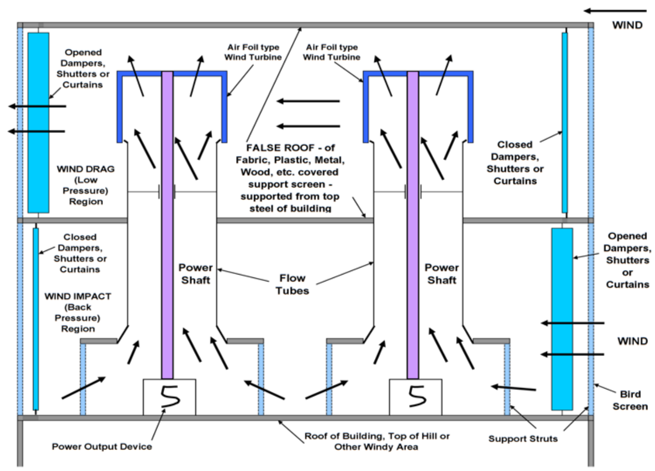


FIGURE No 10 – WINDGRABBER WITH COMMON DRAG CHAMBER [11]

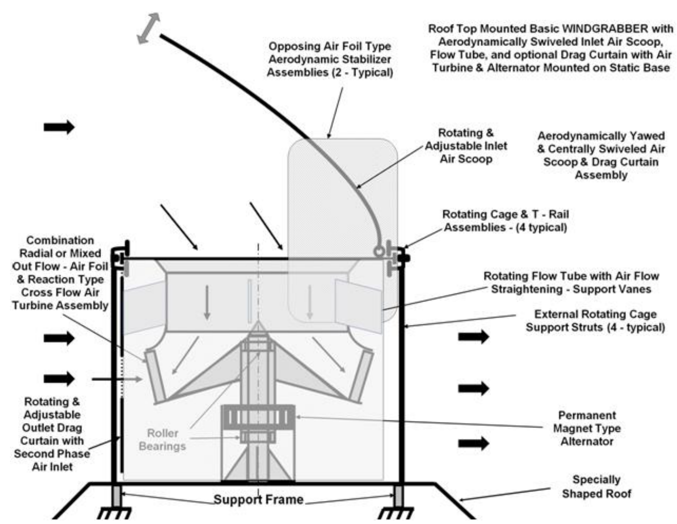


FIGURE No 11 – ROTATING WINDGRABBER & T-TRACK SUPPORT SYSTEM

system of a copula design. This design is projected by the lead author to provide minimal noise and visual distraction to neighbors, while providing the maximum of safety and protection to birds and flying mammals.

WHY WINDGRABBER?

WINDGRABBER is based on a wind turbine system being utilized of a single inlet, centrifugal fan design, with the air flow maintained in the same direction as

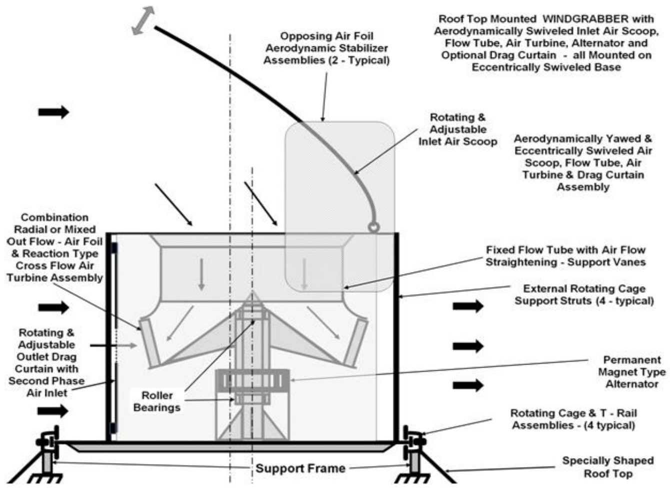


FIGURE No 12 – WINDGRABBER ECCENTRICALLY ROTATED CAGE ASSEMBLY

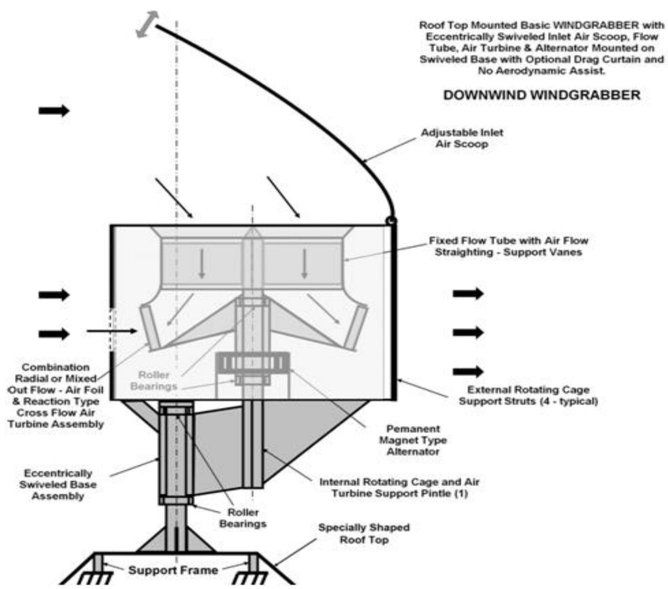


FIGURE No 13 – SINGLE SUPPORT ECCENTRICALLY ROTATED WINDGRABBER

with normal radial fan operation, but with the air flow forces applied on the reverse sides of the highly efficient air foil type air blades.

This type of design allows significantly higher air flows to be realized within the inlet air scoop and flow tube than those achievable with conventional open or ducted propeller or axial flow type wind turbine systems of like diameter. This is because it moves the Betz limit design point from the inlet flow tube to the downstream air turbine system, which can be much more easily increased in throughput cross sectional area for a more cost effective design. FIGURE No 15 shows the performance for a nominally sized 10 kWe WINDGRABBER type wind turbine system using the air power or fan law equations at an 80% air foil type mechanically efficient air turbine design in lieu of the more familiar wind power equations as normally used by wind turbine designers. The primary difference in application of the fan or air power equations as opposed to the wind power equations is that with wind power equations the overall incoming wind's velocity head differential across an open propeller type system is limited to unity. With the fan or air power laws,

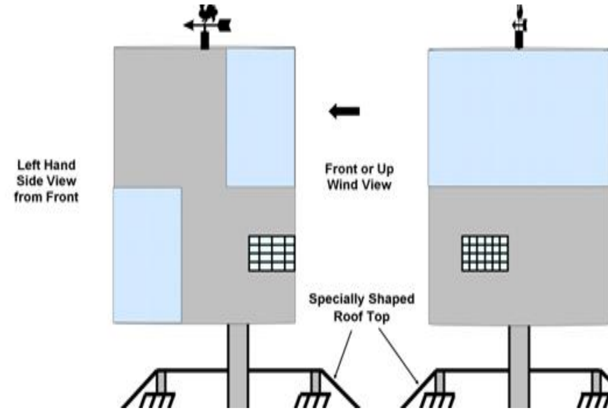


FIGURE No 14 – THE ULTIMATE COPULA TYPE WINDGRABBER SYSTEM

Pressure differentials greater than one velocity head can be applied across the overall WINDGRABBER wind turbine system. This increased pressure differential is accomplished by combining the incoming wind's impact pressure of one velocity head, developed by a first phase of the prevailing wind at the inlet to WINDGRABBER's adjustable inlet air scoop, with the vacuum or negative pressure effect of approximately one half velocity head, created by a second phase of the prevailing wind which flows both around and through WINDGRABBER's adjustable exit drag curtain.

WINDGRABBER TEST BENCH & MODEL WORK

FIGURE No 16 is a plan view of the original test bench configuration assembled and tested by the lead author in late 2005 and during the early part of 2006. These early tests were conducted and photographed with encouraging results, indicating that air velocities equal to or greater than the incoming wind could be consistently achieved in the central portion of both air duct arrangements tested.

A second test bench configuration as shown in FIGURE No 17 & 18 was subsequently constructed and tested with even more favorable results achieved as part of the lead author's efforts to apply for a USPTO non-provisional patent before the end of 2006. [18]

FIGURE No 19 shows a picture of an "Up Flow" type WINDGRABBER physical model, using a 14 inch roof top type turbine ventilator system as the inlet flow tube and air turbine, with an inlet air scoop located below and the exit drag section located above. The primary purpose for this physical model was to make various observations as to the visual effects realized on the turbine ventilator of the wind being admitted from the inside out only, from the outside only, and from a combination of air flows from both the inside and the outside simultaneously. The simultaneous configuration showed best results.

A secondary purpose for the 14 inch roof top ventilator type physical WINDGRABBER model was to explore the various effects of using an eccentrically swiveled support base for the overall WINDGRABBER system in the form of a chair seat swivel base of ball and race design purchased at a local hardware store.

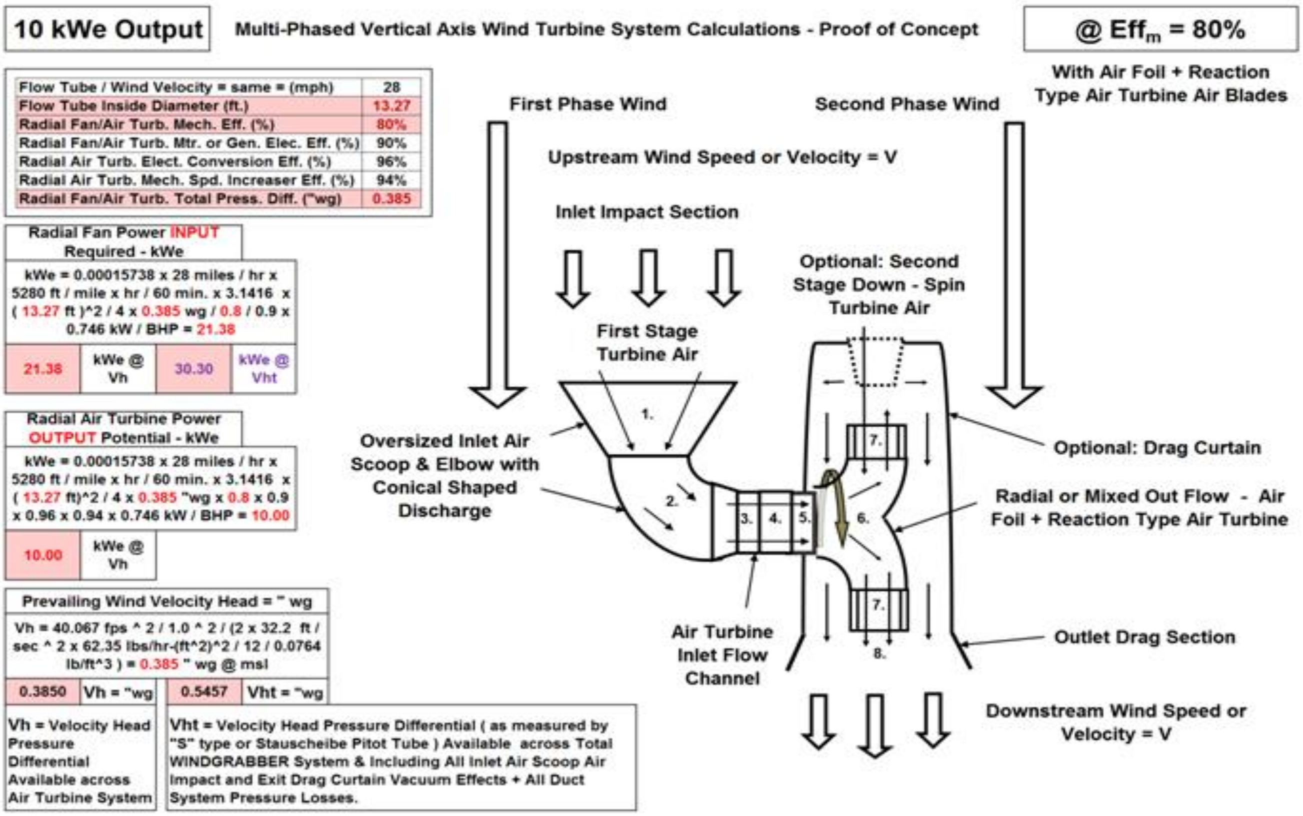


FIGURE No 15 – WINDGRABBER SIZING & PERFORMANCE WITH 80% EFFICIENT AIR FOIL AIR BLADES [4] [5] [6] [10] [12] [13] [14] [16]

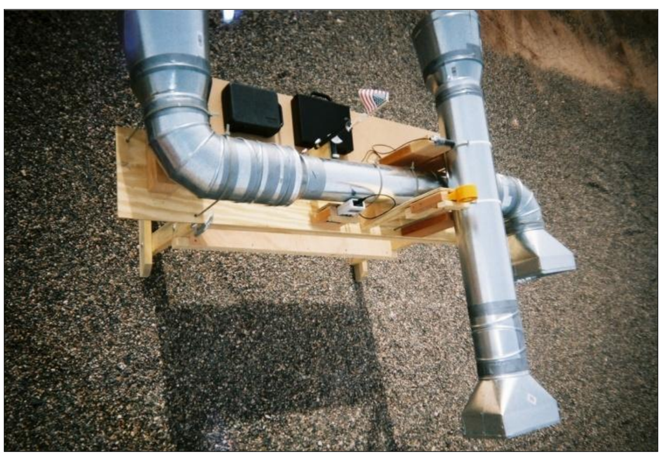


FIGURE No 16 - ORIGINAL 2005 TEST BENCH

FIGURE No 17 - 2006 TEST BENCH - WIND WARD VIEW

Prior to the destruction of the swivel base during a high wind condition one night at the lead author's hilltop home in Rimrock, AZ, it was proven very satisfactorily that a center supported, eccentrically swiveled base for the WINDGRABBER system would be more than adequate to passively rotate the entire WINDGRABBER system into a downwind position, with or without the addition of any stabilization vanes of either a flat plate or an air foil design.

FIGURE No 18 - 2006 TEST BENCH – LEE WARD VIEW

A second, more improved design for an eccentrically swiveled base was also installed and tested with similar results and findings. A third lesson learned during these tests was to acquire a greater respect for the power available in the wind at higher wind speeds.

FIGURE No 19 – 2009 WINDGRABBER WITH ECCENTRICALLY SWIVELED BASE

A general observation concluded by the lead author with the various test bench configurations tested was that the rate of change in air velocity through the various test bench arrays appeared to be slower than that measured in the free or prevailing wind flow.

The lead author's test results as shown in the various photographs taken tried to take these characteristics for the free wind and ducted air flows into account when taking the data. The average of all data taken supported the lead author's general conclusion that significant wind impact and wind drag effects could be achieved in order to increase the overall pressure differential accomplished across the overall WINDGRABBER system to significantly greater than one (1) velocity head from the WINDGRABBER system air scoop inlet to the drag curtain outlet.

WIND POWER VS AIR POWER

FAN or AIR POWER = $P_f = k \wedge Pv / n_f / C$

P_f = Fan shaft power input = BHP (kWe)

^P = static pressure rise across fan, in. wg. (KPa)
v = inlet volume flow rate, ft^3 / min (m^3/sec)
n_f = fan total/mech. efficiency, (100% = 100)
k = compressibility factor, dimensionless, and equals 1 for air or wind power
C = constant of 6354 (1.00 for SI units)
1 / C = 1 / 6354 = 0.0001573811772 for air or wind power equation

Centrifugal fan air blade - air foil type n_f = 80% to 90%. Axial flow fan air blade – n_f = 85% to 90%

WINDGRABBER Power = P_w

$P_w = 0.00015738 \wedge Pvn_t$

EXAMPLE:

P_w = 0.00015738 x 0.385 in. wg x 28 miles / hr x 5280 ft / mile x 1 hr / 60 min x 3.1416 x (13.275 ft) ^ ^{2} / 4 x 0.8 x 0.9 x 0.96 x 0.94 x 0.746 kWe / BHP = 10.0 kWe

10 kWe produced for 1 hour = 10 kW - hr or;
10 kWe = 10 kW - hr / hr of continuous, rated duty

Where:

The flow tube and prevailing upstream wind's air velocity = V = 28 mph (^p = 1 Vh = 0.385 in. wg) and the flow tube inside diameter = D_{ft} = 13.275 ft.

Open flow area of air turbine at air foil type air blades equals ~ open flow area of flow tube with blade obstruction area equaling ~ 50% of air turbine open area (or, ~ 1 / 3 of total air turbine flow area).

E_m = 0.8; $E_{alt.}$ = 0.9; E_{efc} = 0.96; & E_{si} = 0.94;

Thus, the Betz limit = B_L = 16/27 = 59.26%, is also included in the air turbine rotor design and accounted for in the WINDGRABBER air turbine open flow area, which is ~ equal to the inlet flow tube open flow area.

E_m = Total/Mech.; $E_{alt.}$ = Alternator; E_{efc} = Electrical Frequency Converter; E_{si} = Speed Increaser (If required in addition to the Alternator).

n_t = Overall mechanical and electrical efficiency

Or; $n_t = E_m \times E_{alt.} \times E_{efc} \times E_{si}$

The general wind power equation, which assumes an open propeller in axial air or wind flow with only one velocity head (Vh) from the wind available to the wind turbine system, is stated as follows:

WIND Power = $P_P = 0.05472\ V^{\wedge 3} A B_L n_t$

Example:

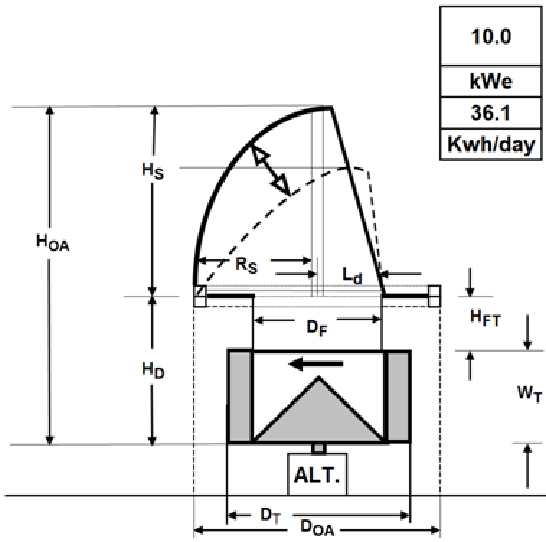
P_P = 0.05472 x (28 miles / hr) ^ ^{3} x (17.24 ft. x 0.3048 meters / ft.) / 2) ^ ^{2} x 3.1416 x 0.5926 x 0.80 x 0.90 x 0.96 x 0.94 / 1000 = 10.0 kWe

Where:

The upstream prevailing wind velocity = V = 28 mph, and the open propeller outer diameter = D_P = 17.24 ft.

FIGURE No 20, 21 & 22 depict the general sizing criteria for a WINDGRABBER system, and show several applications for both a WINDGRABBER and a propeller type wind powered system now under consideration and development by CSU Fresno.

Primary Dimensions for MVAWT System for Preliminary Design Purposes - Rated @ 10.00 kWe



DIM.	Sizing Factor		Component Size (ft.)		Overall Size (ft.)		Des. Area & Vol (ft^2 & ft^3)	Des. Area & Vol (ft^2 & ft^3)	
D_{FT}	1.000		13.280				$3.14 \times D_{FT}^2 / 4$	138.5	
H_S	0.600	1.050	7.968	13.944	MIN.	MAX.		MIN.	MAX.
R_S	0.750		9.960				$2 \times R_S \times H_S$	158.7	277.8
L_d	0.500		6.640						
H_{FT}	0.250		3.320						
H_D	0.950	1.250	12.616	16.600			$2 \times R_S \times H_D$	251.3	330.7
H_{OA}					20.584	30.544			
D_{OA}	1.500		19.920		19.920		$H_{OA} \times D_{OA}$	410.0	608.4
D_T	1.100		14.608		14.608		$2 \times R_S \times H_S$		
W_T	0.4125		5.478		5.478		$2 \times R_S \times H_S$		

FIGURE No 20 – WIND POWER vs. AIR POWER – WINDGRABBER SIZING @ 10 kWe (28 MPH)

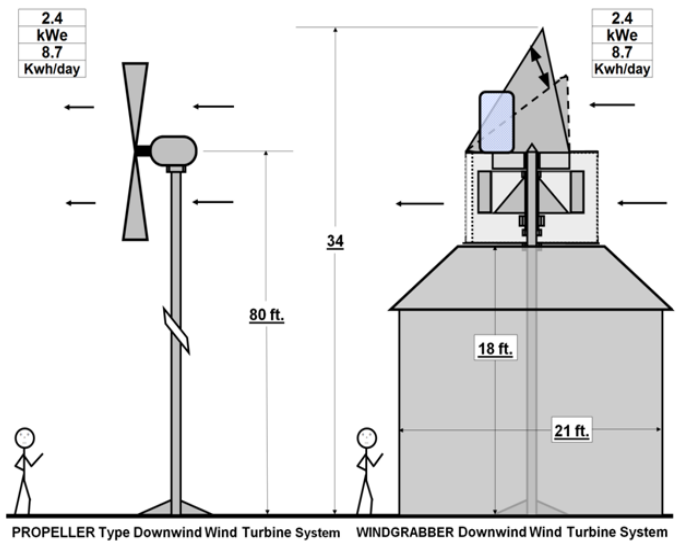


FIGURE No 21 – 2.4 kWe WINDGRABBER - CENTRALLY ROTATED CAGE

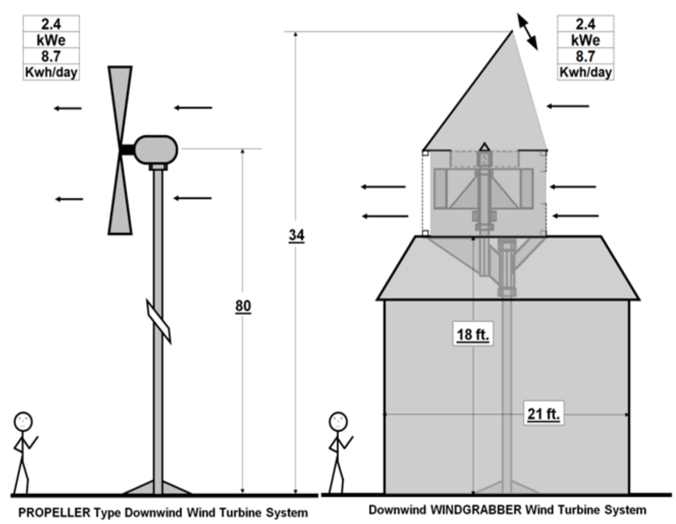


FIGURE No 22 – 2.4 kWe WINDGRABBER - ECCENTRICALLY ROTATED CAGE

WINDGRABBER AND THE BETZ LIMIT

The BETZ Law or limit was originally developed to define both the practical and theoretical limits of the energy that can be extracted from the wind in an open flow field and is limited to one velocity head of pressure drop being available from the prevailing wind as measured from far upstream to far downstream of the wind turbine system being analyzed.

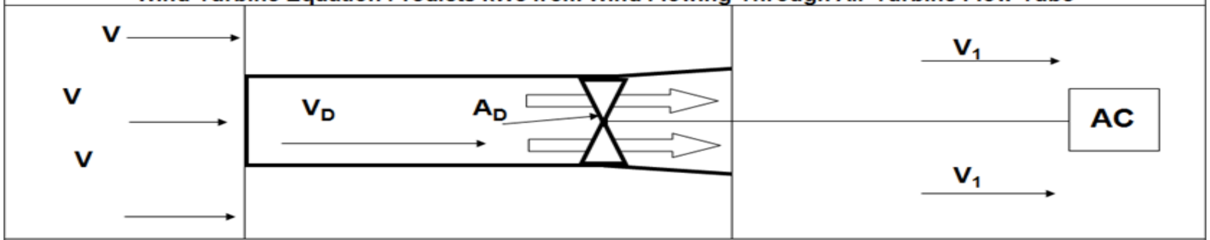
The BETZ Limit is shown applied to both a typical propeller in a flow tube as well as a WINDGRABBER type wind turbine system in FIGURE No 23 & 24.

The BETZ Limit has continued to be the mainstay of wind turbine design engineers as being gospel relative to the limiting of the useful energy recoverable from the wind, even when used in regard to ducted wind turbine systems as developed to date. This limit also applies to WINDGRABBER in an indirect manner.

Since there is no wind turbine, or any other obstruction to free wind or air flow installed within the inlet flow tube for WINDGRABBER (as with the usual propeller in the flow tube approach attempted by many in the past), the BETZ Limit does not apply within the flow tube itself. However, the BETZ Limit does apply to the radial out-flow type WINDGRABBER air turbine assembly, but is easily accommodated in the design by increasing the length of the air blades by around 50% in cross section flow area so that the open flow area within the overall air turbine bladed area is maintained approximately the same as for the inlet flow tube. Additionally, the WINDGRABBER system must account for the overall loss in wind pressure across the overall WINDGRABBER system resulting from shock and resistance to air flow from the ductwork configuration required to both supply and exhaust the wind's air flow to the WINDGRABBER air turbine system and re-entrain it back into the downstream prevailing wind.

kWe = 0.00005472 x (28 miles / hr) ^ 3 x (13.5 ft. x 0.3048/2) ^ 2 x 3.1416 x 59.26% x 80% x 88% x 90% = 6.0 kWe

Wind Turbine Equation Predicts kWe from Wind Flowing Through Air Turbine Flow Tube



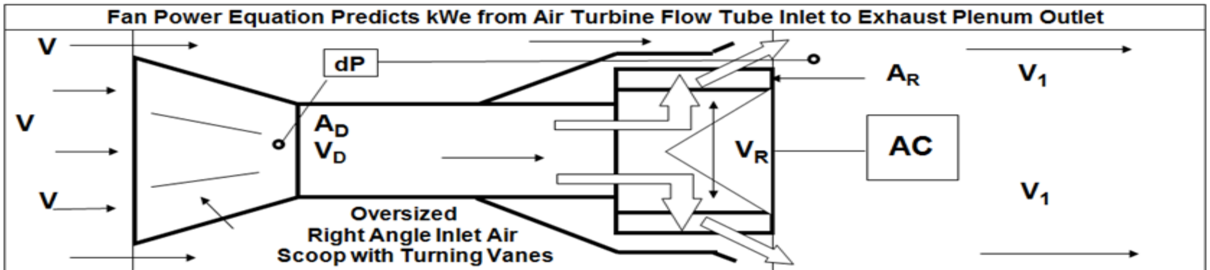
Atmospheric Conditions = 60 °F and 29.92 "Hg Barometric Pressure

Propeller Power from the Wind	kWe	P	0.045	0.132	0.527	2.107	3.292	6.000	10.126
Flow Tube/Propeller Diameter	ft.	D	1.17	2.00	4.00	8.00	10.00	13.50	13.50
Wind Velocity in Undisturbed Flow	mph	V	28.0	28.0	28.0	28.0	28.0	28.0	28.0
Betz Limit Ratio	%	Bz	59.3%	59.3%	59.3%	59.3%	59.3%	59.3%	100.0%

FIGURE No 23 – WINDGRABBER AND THE BETZ LIMIT – BETZ LAW APPLIED TO PROPELLER WITHIN THE FLOW TUBE [7] [8]

kWe = 0.00015738 x 28 miles / hr x 5280 ft / mile x hr / 60 min. x 3.1416 x (13.5 ft.)^2 / 4 x 0.381"wg x 80% x 88% x 90% x 0.746 kW / BHP = 10.0 kWe

Fan Power Equation Predicts kWe from Air Turbine Flow Tube Inlet to Exhaust Plenum Outlet



Atmospheric Conditions = 60 °F and 29.92 "Hg barometric Pressure

WINDGRABBER Power	kWe	P	5.155	6.860	4.686	7.029	10.000	10.000	10.840
Flow Tube Diameter	ft.	D	13.50	13.50	13.50	13.50	13.50	13.50	13.50
Wind Velocity thru Flow Tube	mph	V_R	28.0	28.0	28.0	28.0	28.0	28.0	28.0
Total Wind Turbine System dP	" wg	Hd	0.385	0.450	0.546	0.546	0.546	0.570	0.602
"S" Type Pitot Tube Factor	- / -	Vhs	1.000	0.925	0.840	0.840	0.840	0.822	0.800
Vel. Head Drop thru Air Turbine	Vh	Vht	0.196	0.261	0.357	0.357	0.357	0.381	0.413
Fan Mechanical Efficiency	%	Em	80.0%	80.0%	40.0%	60.0%	85.4%	80.0%	80.0%

FIGURE No 24 – WINDGRABBER AND THE BETZ LIMIT – BETZ LAW AND THE WINDGRABBER FLOW TUBE [4] [16]

The CFD modeling studies that CSU Fresno is currently planning to conduct will help to better define what these losses will be when used in an optimized WINDGRABBER design configuration.

In the final analysis, overall energy conversion efficiency in the low 30% range is projected for the ultimate WINDGRABBER system when the overall WINDGRABBER cross sectional flow area and local wind effects are compared to the far upstream to far downstream prevailing wind's full energy potential.

ECONOMICS FOR WINDGRABBER [9] [15] [17]

The lead author's overall conclusion at this time is that a ducted type wind turbine system such as defined by WINDGRABBER herein will be approximately twice as expensive on an installed $/kWe basis as a large utility sized wind turbine system such as is seen along various rural road sides and freeways.

Small open propeller based wind turbine systems as normally located in the back yards of farms and horse properties fall somewhere in between these numbers. These types of systems are usually designed to use a local utility to provide a means of selling any excess power generated by their wind turbine systems, and are normally supplemented with a battery backup system for those times when the wind is not available.

WINDGRABBER, however, falls into a different economic profile than that normally considered for more conventional wind or solar based green energy systems. That is, due to its simple and rugged design and construction, it can normally be considered for an extended 20 to 30 year economic life as opposed to a 10 to 15 year replacement life used for most others.

This extended WINDGRABBER system design life, when combined with an annual preventive maintenance program as provided by the original equipment manufacturer, allows the WINDGRABBER system to be seriously considered either for inclusion in a conventional 30 year loan package for a new home installation, or, for a 15 to 20 year home equity loan when included as part of a home extension, upgrade, or outbuilding addition to the original homestead.

The current target for a fully commercialized and highly modularized WINDGRABBER system in a 1 to 10 kWe size range would be on the order of magnitude of around $4 per watt on a maximum rated unit output basis in a 28 mph prevailing wind. Of course, those WINDGRABBER air turbine efficiencies as actually achieved in the field by the final design will be a large factor in the ultimate achievement of this objective.

This conclusion applies much more to a WINDGRABBER type ducted wind turbine system design than to a conventional open propeller design as they exist today. For example, going from an approximately 40% mechanical, 32% overall efficient reaction air turbine design to an achievable 80% mechanical, 65% overall efficient WINDGRABBER air foil bladed air turbine design will more than likely reduce the size and cost for the WINDGRABBER system by approximately 50%.

NEED FOR CFD / FEA MODELING AND TESTING

The lead author has made some rough calculations as to the overall potential performance and operation for a WINDGRABBER type ducted wind turbine system.

However, only through state of the art CFD / FEA modeling will the authors really be able to put into proper perspective the future potential for ducted type wind turbine systems such as WINDGRABBER.

CSU Fresno shares this opinion and has thus decided to take up the challenge of modeling and optimizing the WINDGRABBER ductwork configuration and air turbine design with the lead author's input, where needed, in order to help answer these questions.

DESCRIPTION OF CFD MODELING

The primary focus of CFD modeling will be to provide validation of the approximate calculations discussed previously. Assuming the results are favorable, further validation in the form of experimental testing will be warranted. Three different types of turbine will be considered: mixed-flow and radial outflow turbines for use in the ducted system, and an open propeller-type system for comparison purposes. For this study, the duct size and configuration will be the same as in the earlier hand-calculations.

The secondary focus of the modeling effort is to provide more sophisticated models capable of studying various other configurations of ducts, inlet air scoops, outlet drag curtains and air turbine designs. The CFD models developed will be used to optimize the design of a ducted type wind turbine system for maximum performance capability and power output by optimizing the overall WINDGRABBER duct configuration; including the flow tube, inlet air scoop, discharge plenum, drag curtain and air turbine impeller. A nominal "S" type, down-flow configuration will be used as a starting point, using a 14-ft diameter and 7-ft length of straight vertical-axis-orientated flow nozzle immediately preceding a radial out-flow or mixed-flow type vertical-axis air turbine.

The air turbine will be located immediately following the straight-sided flow tube and designed for maximum and most efficient operation at an approaching prevailing wind velocity of 28 mph. The inlet air scoop will be located above the vertical axis orientated flow tube and air turbine assembly with the air discharging from the air turbine and drag curtain in a downwind direction.

Optimization of the overall duct configuration will include optimizing the inlet air scoop, discharge plenum, and drag curtain. The right angle inlet air scoop should be of an optimum configuration so as to minimize the loss in wind energy entering the straight-sided flow tube or nozzle. The entrance to the air scoop should be of such a configuration and should be sufficiently larger in inlet diameter than the flow tube so as to achieve this objective at a minimum of cost.

The right-angle air turbine discharge plenum and second phase wind blocking - drag curtain should also be of an over sized and optimum configuration so as to maximize the wind energy available to the air turbine by way of minimizing the exit losses from the air turbine and discharge plenum, as well as any re-entrainment losses that may be associated with the recombining of the air turbine discharge air back into the prevailing wind in a most cost effective manner.

The overall configuration should also be optimized so as to create the maximum possible vacuum effect at the exit from the optimized drag curtain assembly at its exit plane so as to maximize the total differential pressure available across the air turbine assembly for the production of the maximum possible useful power from the wind for any given size of assembly. The preferred air turbine design should be of a combination cross-flow and radial or mixed out flow configuration. The air blades should be designed to perform primarily as a reaction or cross flow type air turbine at minimum or start up speeds, and as primarily an air foil type air turbine at the maximum design point and throughout as much of the overall operating power output load range as possible. The air foil type air blades should be of a simplistic design configuration, molded onto a bolt and nut type connector for mounting on the air turbine rotor at the optimum orientation. Alternatively, the complete air turbine assembly could be molded in one fiberglass or plastic casting.

One of the primary purposes of this CFD study is to choose whether a mixed flow or a radial outflow type air turbine as described above will provide the best overall efficiency and, thus, the maximum power output available across the design operating range of prevailing winds from minimum to approximately 28 mph at mean sea level, 80 ^{o}F air temperature and 60 percent relative humidity.

The CFD Modeling work is currently intended to be conducted on a PC workstation with a 64-bit, 8-core architecture, with smaller cases being run on a standard quad-core PC. The Software utilized will most likely be COSMOS FloWorks.

CONCLUSIONS & RECOMMENDATIONS

Results of the proposed CSU Fresno CFD modeling, as well as any future trends in public opinion as to the wide spread use of open propeller systems on either roof tops or in the back yards of primarily rural and semi-rural residential homes, will be two of the major factors considered by the authors regarding the continuance of any future R&D efforts with the presently conceived WINDGRABBER technology.

With favorable conclusions reached in these two key areas, the authors' next step will likely be the design, construction, start up and testing of a 5 to 10 kWe rated prototype demonstration unit in a 28 mph prevailing wind at a suitable test site.

As part of this effort, the CFD modeling work that had been conducted up to that time will likely be expanded to include systems and equipment design and performance optimization efforts. Computerized finite elemental analysis (FEA) work would also be undertaken as part of the prototype design work to provide for a most cost effective, reliable and safe installation of the final WINDGRABBER demonstration unit. If future development work should be conducted regarding this WINDGRABBER development program, as defined herein, the authors may present future ASME papers as to the progress and status of this work on an annual or as appropriate basis.

LIST OF REFERENCES

[1] Technology Adoption Lifecycle – Geoffrey A. Moore, Crossing the Chasm (Harper Business, 1991).

[2] Technology Adoption Market Segments – Moving Retail Wind Power Markets to the Mainstream (PowerGen 2009, December 9, 2009, Las Vegas, NV) by Jim Fay; Vice President, Strategic Consulting Services, GKA Research.

[3] Standard Handbook for Mechanical Engineers. - Theodore Baumeister & Lionel S. Marks, 7th Ed., 1967, McGraw-Hill, Inc., Chapter 9, pp 8 -13.

[4] Steam Its Generation and Use – 40th Edition, Babcock & Wilcox Company, 1978. Chapter 3, pp 10-13 & Chapter 23, pp 16-18.

[5] Fan Engineering, - An Engineer's Handbook on Fans and Their Applications, Ninth Edition, Edited by Robert Jorgensen, Howden Buffalo Forge, Inc. 1999. Chapter 2, pp 1-78.

[6] Fundamentals of Turbo machinery, By William W. Peng, Professor of Mechanical Engineering, California State University, Fresno, California. 2008, John Wiley & Sons. Inc., Hoboken, New Jersey. Chapter 6, pp 149-171; Chapter 11, pp 296-314 & Appendix C, pp 356-358.

[7] Homebrew Wind Power, A Hands-On Guide To Harnessing The Wind, First Edition, 2009, By Dan Bartmann and Dan Fink. Buckville Publications LLC, Masonville, CO. Chapter 1, pp 23-26 & Chapter 3, pp 47-66.

[8] WINDPOWER, Renewable Energy for Home, Farm and Business, 2004, By Paul Gipe, Peter Holm, Sterling Hill Productions, Chelsea Green Publishing Company, PO Box 428, White River Junction, VT 05001. Chapter 3, pp 23-54; Chapter 4, pp 55-69 & Chapter 5, pp 71-81.

[9] The Homeowner's Guide to Renewable Energy, 2007, By Dan Chiras, New Society Publishers, PO Box 189, Gabriola Island, BC VOR 1XO, Canada. Chapter 8, pp 207-222.

[10] TRANE Air Conditioning Manual, Forty Ninth Printing by McGill Graphics Arts, St Paul, Minnesota, 1974, Published by the TRANE Company, La Crosse, Wisconsin. Chapter IX, pp 258-304.

[11] National Renewable Energy Laboratory, National Wind Technology Center, 1617 Cole Boulevard, Golden, CO 80401-3393. Section 4.1.3 **Natural Ventilation**: Greening Federal Facilities; DOE/GO-102001-1165, NREL/BK-710-29267, May 2001.

[12] Strategies for the Evaluation of Advanced Wind Energy Concepts, 1983, By Peter South, Richard Mitchell & Eric Jacobs - SERI, Solar Energy Research Institute, A Division of Midwest Research Institute, 617 Cole Boulevard, Golden, CO 80401, Operated by the U.S. Department of Energy. Section 5, pp 71-83.

[13] Elementary Fluid Mechanics, by John K. Vennard, Professor of Fluid Mechanics, Stanford University, Third Edition, John Wiley & Sons, Inc. New York, Seventh Printing, February, 1959.
Chapter 6, pp 126-128;
Chapter 7, pp 162-170;
Chapter 11, pp 288-291;
Chapter 12, pp 338-378.

[14] Chemical Engineer's Handbook – Fifth Edition, by Robert H. Perry & Cecil H. Chilton, McGraw-Hill Book Company, New York, 1973.
Chapter 24, pp 30-31 & pp 38-39.

[15] ENERGY: Principles Problems Alternatives, 1984, by Joseph Priest, Miami University, Third Edition. Addison-Wesley Publishing Company, Reading, Mass. Chapter 10, pp 211-216 & pp 231-234.

[16] COMBUSTION – Fossil Power Systems, 1981, Joseph G. Singer, Editor, Third Edition. Published by COMBUSTION ENGINEERING, INC. 1000 Prospect Hill Rd., Windsor, Connecticut, 06095. Chapter 15, pp 4-20 & Appendix E, pp 1-5.

[17] http://www.solar4power.com/solar-power-sizing.html; General Sizing for Solar Power, Solar Insolation.

[18] WINDGRABBER TM USPTO Trademark applied for 10/28/2009, USPTO Non-Provisional Patent No. 7,488,150 granted 2/10/2009, CIP Application No. 12/355,411 applied for 1/16/2009, USPTO Provisional Patent applied for 12/08/2005.