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Design and Wind Tunnel Testing of Funnel Based Wind Energy Harvesting System

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Abstract

Modern wind energy systems are of giant structures having a turbine generator on the top of tower at a height of 80 metres with control mechanisms like yaw control and pitch control. With this modern wind energy systems, exploitation of wind energy at low wind speeds is not possible, operation and maintenance and yaw control are difficult. In other fact, environmental problems related to disturbance in signals and birds life are considerably high. Considering all the difficulties that are faced with modern wind energy systems, a new approach for extracting wind energy is studied here. In this paper, design and experimental setup of funnel based wind energy harvesting system (FBWEHS) is explained in detail. For studying the feasibility of this new approach, a subsonic wind tunnel testing is carried out. Further smoke test in the wind tunnel is also carried out for visualizing the flow of air into the nested funnel. The results of wind tunnel testing showed the performance of the FBWEHS, in which the velocities at the turbine section is increased by a venturi speed ratio of 1.80 to 3.22 than the inlet velocities at nested funnel. Power availability at the turbine section is also increased with increase in velocity than the power available at the nested funnel. Experimental setup of FBWEHS with a propeller blade of diameter 7cm coupled with a small size generator is used for generating power. Generated power is in the range of 0.0001 W to 9.93 W over a range of wind velocities at funnel inlet as 0.5 m/s to 7.89 m/s. With this, FBWEHS is feasible to generate more power than modern wind turbines under similar conditions of wind turbine swept area and the wind velocities by eliminating the yaw control.

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Keywords: Wind energy; nested funnel; venturi speed ratio; FBWHES; wind tunnel testing

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1. Introduction

Wind energy systems have been harvesting energy from the wind for centuries, from early wind mills used for grinding grains and pumping water to the present day large scale electricity generating wind turbines. Early use of wind energy for sailing ships in the Nile River was dated to 5000 B.C.Recorded history, the pneumatics of Hero of Alexandria by (Marie Boas Hall, 1971) explains the first use of wind energy [1](Manwell et al., 2009)clearly described the existence of first wind mill from Hero of Alexandria [2]. Wind mills were in the use by Persians between 500 and 900 B.C., [3] later this was spread to surrounding areas in the Middle East and to the European nations. European wind mills made their first recorded appearance with advanced design incorporating top rotor blades and yaw mechanism that is seen in modern wind turbines. Initially in the 18th century, wind mills were meant for mechanical power, later the development of electrical generators in 19thcentury gave a great approach in using wind for electricity generation. In the 20th century, technological advancement in wind power conversion led to the development of modern wind turbine systems used primarily on large scale for generating electricity [2]. Today's most common design of wind turbine systems is horizontal axis wind turbine (HAWT) having a turbine generator on the top of tower of height 80 m. The present day HAWT was incorporated with highly proven technology, but still there were challenges related to exploiting wind energy at low wind speeds, operation and maintenance, changing of rotor direction as per wind direction, transportation of massive structures and installation at specific site. [4] describes few innovative concepts in wind power generation like diffuser augmented wind turbine (DAWT) to address the above mentioned challenges. The concept of DAWT is accelerating the flow of air inside the duct by inducing the mass flow rate through an intake. This will improve the output power of wind turbine that is placed optimally inside the duct. An experimental study by [5] shows the effect of diffuser length on the performance of bare and nozzle diffuser augmented turbines. However the nozzle diffuser augmentation shows the better response. An integrated ducted wind turbine with solar system was implemented by [6] for reliable power generation in Bangladesh. This system has a conical shaped duct in front of the traditional wind turbines, which allowed to extract the wind energy even at low wind speeds [6]. Even though these ducted turbines performs better than traditional HAWT, but still there are challenges of tower mounting turbine-generator and operation and maintenance. A new concept called INVELOX by Daryoush Allaei et al. [7-9]gave better performance than other traditional wind turbines as well as ducted wind turbines. In fact INVELOX is also another ducted turbine having five different parts: Intake, Pipe carrying and accelerating wind, Boosting wind speed by venturi, Wind energy conversions and Diffuser. This is having few special features: tower elimination, ground level based turbine-generator and elimination of yaw mechanism. This newly emerged INVELOX technology offered a solution to all the challenges in wind energy that we are facing today.

In this paper, the concept of INVELOX and its outer look is taken for implementing an experimental setup for demonstrating the performance based on the resources available in Karunya University. The main objective of this paper is to design a Solid Works 3-D model and to fabricate FBWEHS, to test its feasibility in wind tunnel and a comparison of power availability in wind at turbine section of FBWEHS to the power availability in wind before the wind turbine that is mounted on conventional tower is shown.

2. Design of FBWEHS

FBWEHS has three major parts: Nested funnel, Bent section and Convergent-Divergent duct with a turbine section in the center. Mathematical design of FBWEHS is done using empirical relations involved in convergent and divergent nozzle [10, 11]. Apart from the mathematical design, a 3-D modelling is done using the Solid Works and a prototype is implemented as a hardware model for checking the feasibility of FBWEHS. Each individual parts involved in FBWEHS are designed separately as follows:

2.1. Nested funnel design

Nested funnel structure is used for capturing the wind, because its ability to capture wind from all directions is possibly high. Other important factor is, the funnel design can be enhanced for smooth flow of wind into the duct by designing opening of funnel with best suitable angle. Designing of nested funnel needs a best suitable mathematical equations with the boundary conditions. Boundary conditions are needed for solving the mathematical equation. These boundary conditions are based on the inlet radius, outlet radius and the angle at which the inlet opening should be for smooth flow of wind across the walls of contour without any deviations. Another important note is number of boundary condition should be equal to the number of constants in the profile equation. On solving the mathematical equations with the boundary condition, gives the appropriate co-ordinates. By using this co-ordinates, nested funnel structure is designed in Solid Works.

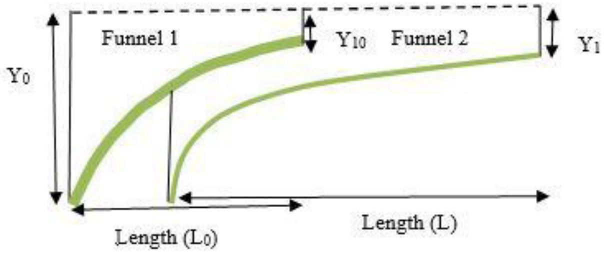


Fig. 1. Profile contour of nested funnel

Profile contour for nested funnel design is illustrated in Fig. 1. Here two mathematical equations were used, one equation is for designing the profile curve (thick curve) of funnel 1 having the dimensions as: Inner radius Y_0, outer radius Y_{10} and Length of profile curve Length L_0. In the case of funnel 1 both ends were closed as per the radius mentioned. Another equation for designing the profile curve (thin line) of funnel 2 having the dimensions as: Inner radius Y_0, Outer radius Y_1 and length of profile curve Length L. In the case of funnel 2 both inlet and outlet were opened as per the radius mentioned.Dotted line represents the reference axis and the thin and thick curvatures represents the contours.

2.2. Bent section design

The outlet of the nested funnel structure is connected to the inlet of bent section using a flange. This bent structure causes the height difference from the top of a funnel to ground level and through this, acceleration of wind flow is achieved. Fig. 2. represents the bent section design and there are certain parameters that should be considered while designing the bent section: the angle at which bending should be, radius and the length of the pipe that is needed to give bent arc of 90°. Parameters of the bent section is calculated using standard formulae and they are given as follows:

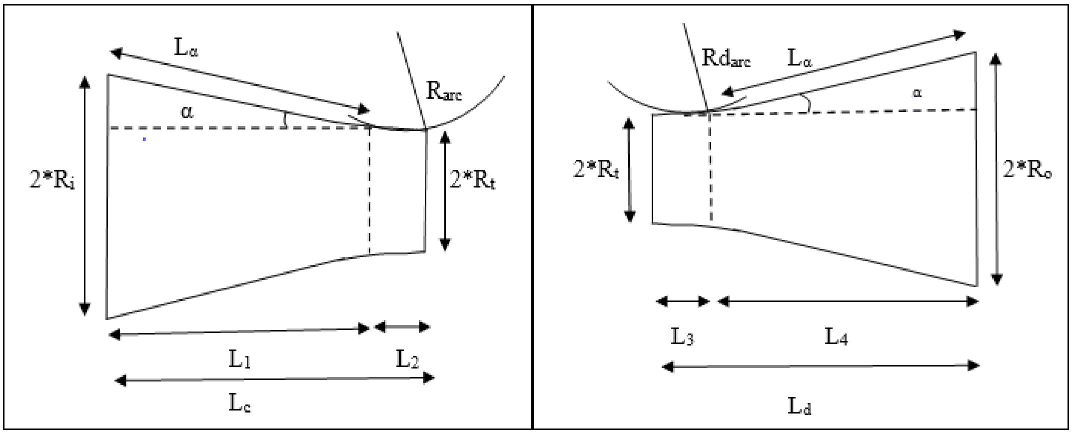
$$\text{Length of the bend arc or arc length} = \frac{R * a * \Pi}{180} \tag{1}$$

$$\text{Minimum bending radius } R = 5 * O.D \tag{2}$$

Where R is the minimum bending radius in meters or mm or cm; a is the desired angle in degree; $O.D$ is the outer diameter of the bent pipe and Π is 3.14. Important points to be considered while designing the bent section are: ensure that there is no flow separation, smooth flow, no turbulence or no disturbance in the flow.

2.3. Convergent-Divergent duct with turbine section in the center

In convergent, the cross sectional area smoothly decreases from a larger value to a smaller one. Here depending upon the area law, the flow is accelerated to maximum speeds at the exit of the converging section. Similarly in divergent, the cross sectional area smoothly increases from a lower value to a larger value depending up on the area law. A turbine section is placed in the center of convergent-divergent duct.



(a) (b)

Fig. 2. (a) Convergent design; (b) Divergent design

In the case of convergent, venturi effect take place and it is defined as the reduction in fluid pressure that results when a fluid flows through a constrained section of a pipe designed as per area law. In our case inlet velocities are low, so the flow is strictly a subsonic and the design of convergent section is illustrated in Fig. 3. (a)It is based on the nozzle design concept and continuity equation.

Formulae related to the convergent design is shown as follows:

Typical value for convergent section is standard and given by the ratio of arc radius to the throat radius [11].

Typical value for convergent is $\frac{R_{arc}}{R_t} = 1.5$ (3)

Convergent angle α should be in the range of 20° to 60° and the chosen angle, α =30°.

$$L_2 = R_{arc} * \sin\alpha \tag{4}$$

$$L_1 = \frac{R_i - R_t + R_{arc}(\cos\alpha - 1)}{\tan\alpha} \tag{5}$$

$$L_c = L_1 + L_2 \tag{6}$$

Where R_i is the inlet radius; R_t is the throat radius; R_{arc} is the arc radius; L_α is the angular length; L_1, L_2 & L_c are the lengths specified in the convergent design.

Divergent is also called as diffuser and it is designed for releasing the exhaust air flow from the turbine section into the atmosphere. While designing the diffuser, certain parameters to be considered and those are identifying the optimal location for diffuser intake, velocity, pressure at the entrance of diffuser, equivalent expansion angle and the area ratio. A neat sketch of divergent section is illustrated in Fig. 3. (b) It is also based on the nozzle design and continuity equation.Formulae related to the divergent design is shown as follows:Typical value for divergent section is standard and given by the ratio of arc radius to the throat radius [11].

Typical value for divergent is $\frac{Rd_{arc}}{R_t} = 0.4$ (7)

Divergent angle α should be in the range of 12° to 18° and the chosen angle, α =15°.

$$L_3 = Rd_{arc} * \sin\alpha \tag{8}$$

$$L_4 = \frac{R_o - R_t + Rd_{arc}(\cos\alpha - 1)}{\tan\alpha} \tag{9}$$

$$L_d = L_3 + L_4 \tag{10}$$

Where R_o is the outlet radius; R_t is the throat radius; Rd_{arc} is the arc radius; L_α is the angular length; L_3, L_4 & L_d are the lengths specified in the divergent design.

2.4. 3-D model of FBWEHS using Solid Works

Solid Works is used for creating solid models and assemblies using parametric features which determines the geometry or the shape of model or assembly [12]. FBWEHS is designed based on the parameters discussed for designing nested funnel, bent section and convergent-divergent duct with turbine section in the center. First, two mathematical equations that give nested funnel structure were solved in Microsoft-excel. These co-ordinates were saved in note pad or .txt and then imported into solid works. Once the co-ordinates were imported into Solid Works, a 2-D sketch is created as shown in Fig. 1.and 3-D model of nested funnel is created using revolve base option by taking reference axis.

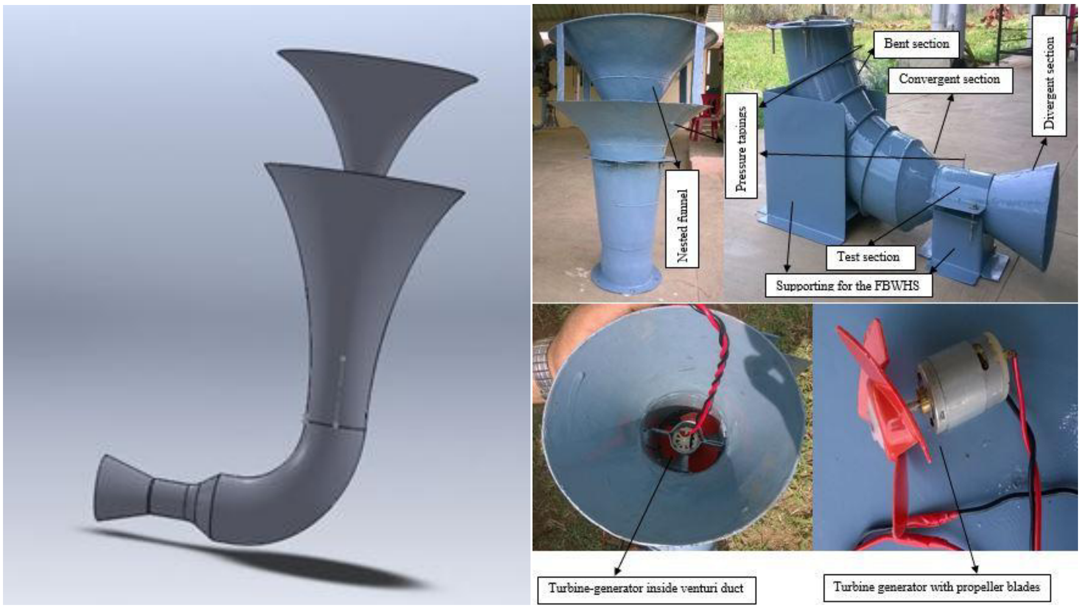


Fig. 3. (a) Solid Works 3-D model of FBWEHS; (b) Individual hardware parts of FBWEHS

Second, bent section is created using the parameters that is discussed in Fig. 2. Third, convergent-divergent duct is also designed based on the parameters discussed in Fig. 3. Here a 2-D sketch is drawn initially by taking reference axis then it is revolved using revolve base option to get a 3-D model of convergent-divergent duct. All the three parts that were designed separately were assembled together to form FBWEHS as illustrated in Fig. 3 using mate option in Solid Works assembly.

3. Experimental setup and wind tunnel testing

The experimental setup has been designed by scaling down the solid works model by 1:4 ratio. Scaling of the FBWEHS is done as per the available wind tunnel testing facilities. Iron Sheet metal is used for molding the design because of its less cost, flexibility. The designed model has its dimensions as follows: funnel inlet diameter is 500 mm, opening gap between two funnels is 250 mm, diameter of convergent inlet and divergent outlet is 150 mm, and turbine section diameter is 80 mm. Design of turbines blades having a rotor diameter of 70 mm is difficult, so a normal exciting exhaust fan blade is sized according to the diameter needed as shown in Fig. 4. (b). A small size generator coupled with turbine blade is used for generating electrical power. A clamping structure is used for fixing the turbine-generator inside the duct. A detailed and fully assembled model of FBWEHS is shown in Fig. 5.

Wind tunnel shown in Fig. 4. has a test section of 600*600*4000 mm dimension, nested funnel is placed inside the test section from the top position and outlet of the funnel is taken out from the bottom circular opening of the wind tunnel. The outlet of the funnel is connected to the bottom duct using flange.

Fig. 4. Experimental setup of FBWEHS and wind tunnel testing

Once the FBWEHS is fixed inside the tunnel, pressure tapings were connected to manometers. Here 1 to 30 manometers were there, out of them only 5 manometers were used, among them 2 manometers are for finding the input velocity using pressure relation as follows:

$$V = 3.65 \times \sqrt{h_2 - h_1} \qquad (11)$$

Manometers are used for measuring the pressure at different places of FBWEHS. Wind tunnel is made to operate at different rpm and for every specific rpm raise all the reading were taken including velocity at the throat, voltage and current from the generator, see in Table 1. Flow visualization of air into the nested funnel is analysed using smoke test in subsonic wind tunnel as shown in Fig. 5.

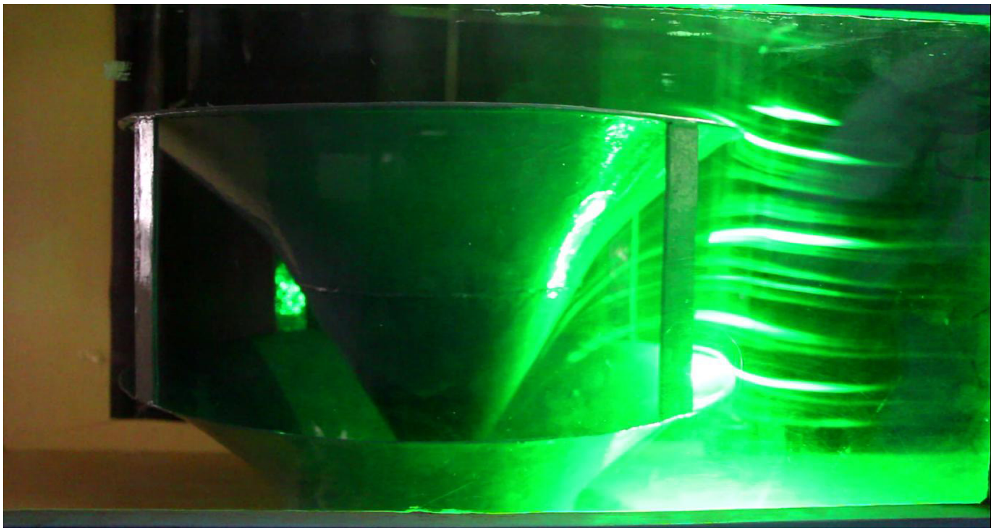


Fig. 5. Smoke test flow visual

Table 1.Wind power generated by FBWEHS.

Velocity at Funnel Inlet (m/s)	Pressure at inlet (psi)	Power available in the wind at inlet velocity (W)	Pressure at Bent section (psi)	Velocity at throat (m/s) (at the venturi)	Venturi Speed Ratio	Pressure at throat or turbine section (psi)	Power available in the wind at throat i.e. turbine section (W)	Output Voltage (Volts)	Output Current (Milli Amps)	Electrical Power Output (W)
0.5	10.7	0.0002	9.2	0.9	1.80	9.7	0.0017	0	0	0
1.15	10.7	0.0035	9.2	2.1	1.83	9.8	0.02	0	0	0
1.15	10.7	0.0035	9.2	3.7	3.22	9.8	0.12	0	0	0
2.58	10.5	0.04	9.1	4.3	1.66	9.7	0.19	0	0	0
3.05	10.5	0.07	9.1	5.4	1.77	9.7	0.37	0.01	1.15	0.0001
3.99	10.5	0.15	9.1	7.7	1.92	9.7	1.07	7.95	1.96	0.155
4.76	10.5	0.25	9.0	12.3	2.58	9.7	4.38	8.69	0.17	0.015
5.53	10.6	0.39	9.0	13.3	2.40	9.7	5.54	11.96	0.735	0.088
6.11	10.5	0.54	9.0	15.6	2.55	9.7	8.94	54.76	1.856	1.02
6.93	10.5	0.78	9.0	17.1	2.47	9.7	11.78	106.70	7.42	7.92
7.89	10.5	1.16	9.0	20.7	2.62	9.7	20.89	126.30	7.86	9.93

4. Conclusions

Results obtained from subsonic wind tunnel testing showed that FBWHES performs better in conversion of wind energy to electrical energy. FBWHES is also suitable for exploiting the wind energy at low wind regime areas as it is incorporated with venturi effect before the turbine section. FBWHES can offer solutions for many problem that are associated with tower mounted modern wind energy systems. Smoke test that is carried out in the subsonic wind tunnel gave the clear view of air flow visualization into the nested funnel.With this it is concluded that FBWHES will generate more power than the modern wind energy systems under similar wind turbine swept area and wind velocities by eliminating the yaw control.

Acknowledgements

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References

[1] Marie Boas Hall. The pneumatics of Hero of Alexandria. American Elsevier publishing company; 1971. p.141.

[2] James Manwell, Jan Mc Gowan, Anthony Rogers. Introduction: Modern wind energy and its origin. In Wind energy explained: Theory, design and application John Willey& Sons. Ltd.; 2009. p. 1-22

[3] US Dept. of Energy-EERE. History of wind energy. Energy.gov/eere/wind/history-wind-energy.

[4] L. Chen, F. L. Ponta, L. I. Lago. Perspectives on innovative concepts in wind-power generation. Energy for Sustainable Development 2011; 15: 398-410.

[5] Buyung Kosasih, Andrea Tondelli. Experimental study of shrouded micro-wind turbine. Procedia Engineering 2012; 49: 92-98.

[6] M. M. Ehsan, Enaiyat Ghani Ovy, H. A. Chowdhury, S. M. Ferdous. A proposal of implementation of ducted wind turbine integrated with solar system for reliable power generation in Bangladesh. International Journal of Renewable Energy Research 2012; vol. 2. no. 3: 397-403.

[7] Allaei D. Turbine-intake tower for wind energy conversion systems. US patent no: 7811048; Date of patent: Oct. 12, 2010.

[8] Allaei D., Andreopoulos Y. INVELOX: A new concept in wind energy harvesting. In: ASME 2013 7th International Conference on Energy Sustainability and 11thFuel Cell Science, Engineering and Technology Conference ES-Fuel Cell 2013-18311, Minneapolis, MN, USA; July 14-19, 2013. p. 1-5.

[9] Daryoush Allaei, Yiannis Andreopoulos. INVELOX: Description of a new concept in wind power and its performance evaluation. Energy 2014; 69: 336-344.

[10] John D., Anderson Jr. Fundamentals of aerodynamics. McGraw-Hills Inc; 1991. ISBN: 0-07-001679-8.

[11] George P. Sutton, Oscar Biblarz. Rocket propulsion elements. 8th ed. John Willey & Sons Inc; 2010. ISBN: 978-0-470-08024-5.

[12] Solid works user manual. www.solidworks.com.