Available online at www.elixirpublishers.com (Elixir International Journal)

Mechanical Engineering

Elixir Mech. Engg. 63 (2013) 18735-18739

ISSN: 2229-712X

Power coefficient enhancement of horizontal axis wind turbine using multiple nozzle system: An experimental investigation

A.V.Satyanarayana[1,*], K.V.Sharma[2] and B.Sreenivasa Reddy[3]

[1]Department of Mechanical Engineering, G.Pulla Reddy Engineering College(Autonomous), Kurnool, 518007, Andhapradesh , India
[2]Department of Mechanical Engineering, J.N.T.U.H College of Engineering College, Manthani, Karimnagar Dt., (A.P), 505212.
[3]G.Pulla Reddy Engineering College, Kurnool (A.P), 518007, India.

ARTICLE INFO

Article history:
Received: 6 August 2013;
Received in revised form:
24 October 2013;
Accepted: 25 October 2013;

Keywords
Betz Limit,
Actual and Theoretical Power Coefficient,
Multiple Nozzle System.

ABSTRACT

According to Betz, the maximum conversion efficiency of a wind turbine is 59.3%. But, the wind turbine works at efficiency of 25% to 35%. Hence, there is an opportunity to improve the efficiency of wind turbine. If, the efficiency of wind turbine is increased by at least 1%, it could turn into giant profits. Multiple nozzle system, therefore, if it is used, it increases the velocity of air, huge. The effect of multiple nozzle system is studied in the present article. The theoretical power coefficient and actual power coefficients of wind turbine are determined as part of the study. Few experiments were taken up earlier to increase wind speed using single nozzle system. But, multiple nozzle system is first ever, used in the history. The effect of conversion of heat energy into kinetic energy using multiple nozzle system is presented in this article. The design of multiple nozzle system obtained patents in India.

Introduction

An effort is carried to rise the efficiency of wind turbine using single nozzle system. They are developed under Duct Wind Turbine, Mantle Wind Turbine,Vertical Axis Wind Turbine with Convergent Nozzle, Diffuser Augmented Wind Turbine and Swift Wind Turbine etc. First ever, the duct type wind turbine is introduced by Lilley et. al [1].The efficiency can be increased by at least 65% from conventional wind turbine. An experiment using mantle nozzle to increase the efficiency of wind turbine is conducted by Frankovi et. al [2]. The profit due to mantle wind turbine is equal to five times to the conventional wind turbine. Few investigations are conducted by Touryan et al. [3], Macpherson et al. [4] and New man [5] on vertical axis wind turbine to increase the power coefficient using nozzle system. Under the guidance of Anderson Renewable Devices Company, Edinburg produced on novel design of 'Swift Wind Turbine' using cascade engineering. Such swift turbine supplies energy suitable to produce 1.5 kW of electric power with the cut in speed, in the range of 8.33 m/sec. The design of a solar stack to be used in rural areas of developing countries is presented by Grant et.al [6]. For a solar chimney, 36 meters high and 4 meters diameter, the air velocity of 3.53 m/s, the maximum theoretical power output was founded to be 49.24 watts. According to Kogan et al. [7, 8], power output is a function of the, diffuser inlet and exit pressure. In their analysis, the diffuser was characterized by the exit to the entrance area ratio of 3.5. The investigation concludes that the power output of DAWT is 4.25 times more than the power produced by conventional wind turbine.

NACA Airfoils

National Advisory Committee for Aeronautics (NACA) has developed airfoils under 4 digit series and 5 digit series. For 4 digit series, the camber as a percentage of the chord is represented by the first digit. The second digit represents the maximum camber from the end of leading edge of airfoil in ten's of percentage of the chord. The last two digits represent maximum thickness of airfoil as a percentage of the chord. The airfoils used in the present study resemble NACA 0012. Wind power generator, as long as the tower can with stand the drag, only lift force is paramount. According to the investigations of Sheldal [9] and Tangler [10] lift coefficient is high at 45^0 of attack for flat airfoils. The lift coefficient is determined from 0^0 to 180^0 of angles of attack.

Objectives of Study

The objectives of the present research study are:

1. Outer convergent nozzle and multiple nozzle system fabrication.
2. Studying the performance of laboratory model horizontal axis wind turbine with single nozzle system, multiple nozzle system and multiple nozzle system in the presence of electric heaters using wind tunnel.
3. Determining best angles of attack out of 0^0, 30^0, 45^0, 60^0 and 90^0 in the segment of a quarter circles.
4. Comparing actual and theoretical power coefficients of wind turbine in different modules of experiment. They are (i) without nozzle system (Module M_0) (ii) with outer nozzle system (Module M_1) (iii) with multiple nozzle system (Module M_2) (iv) Multiple nozzle system with heaters (Module M_4)

Instrumentation and Experimental Set Up

Rotating disc type anemometer is used to determine air velocity. A Non - contacting type tachometer is used to measure speed of driver and driven pulleys. The temperature of air is measured using K-type thermocouple. The inverter is connected to voltmeter and ammeter to determine actual power produced by wind turbine. All instruments used in the study are calibrated. Experimental setup consist wind tunnel and lab model wind turbine and multiple nozzle system. Wind tunnel produces wind at speed of 8.5 m/sec. A laboratory model horizontal axis wind

Tele:
E-mail addresses: sattu900@rediffmail.com

turbine is used to generate electricity. In the present investigation, a three bladed horizontal axis wind turbine is used. The wind turbine has length 0.24 m, height 1.45 m and of mass of blade 500 gm each. In warm countries like India and china atmospheric air occurs at a temperature of 45 ^{0}C to 50 ^{0}C, in summer. Electric heaters are used to obtain almost similar effect as in summer. 750 W capacity of electric heaters and made of aluminum tube with corrugated aluminum fins are used in the investigation. But, in wind farms air is heated using solar radiation.

Multiple Nozzle System

As a part of manufacture of multiple nozzle system, the outer convergent nozzle is fabricated first. It is fabricated with its outlet diameter equal to the wind turbine's rotor diameter. In the next stage of manufacture of multiple nozzle system, a series of internal convergent nozzles are fabricated.

Figure 1. Internal Convergent Nozzles

Figure 2. Multiple Nozzle system

The set of internal nozzle set is illustrated in figure 1. The assembly of outer nozzle and internal nozzle set is titled "Multiple Nozzle System". A perspective view of multiple nozzle system is illustrated in figure 2. More convergence results, more kinetic energy in the air. It can also convert wind's heat energy into kinetic energy to the certain extent. At the end of the nozzle system, length of internal nozzles is projected slightly outwards to keep air in the proper direction.

Line Diagrams of Experiment Modules M_0, M_1 and M_2

Line diagram of module M_0 is illustrated in figure 3. The direction of wind from wind tunnel to wind turbine is shown. No nozzle system is used at this stage of the experiment. Line diagram of module M_1 is shown in figure 4. The outer convergent nozzle is assembled with wind tunnel. Air from wind tunnel is allowed to pass through the outer convergent nozzle from wind tunnel. Wind turbine may suffer severe stresses if the nozzle system is assembled with it.

Experimental Procedure

In various modules of experiments stated above, the power coefficient of wind turbine is etermined at various blade orientations. Power coefficient is determined theoretically and experimentally. In each module of investigation the chord of all blade, is oriented at angles of 0^0, 30^0, 45^0, 60^0 and 90^0.

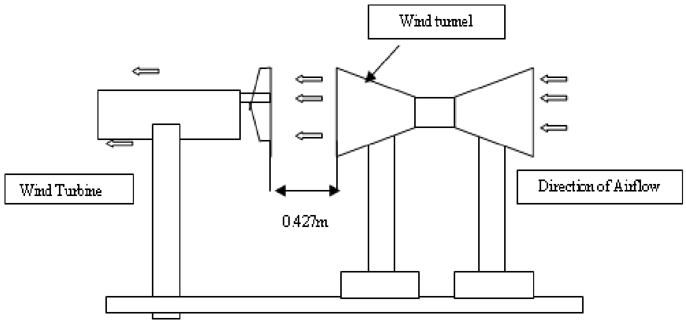

Figure 3. Line Diagram of Module M_0

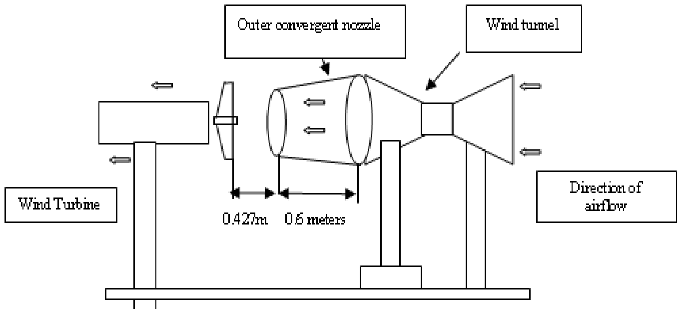

Figure 4. Line Diagram of Module M_1

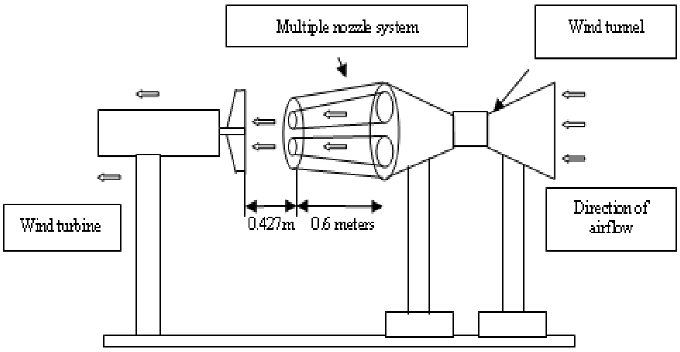

Figure 5. Line Diagram of Module M_2

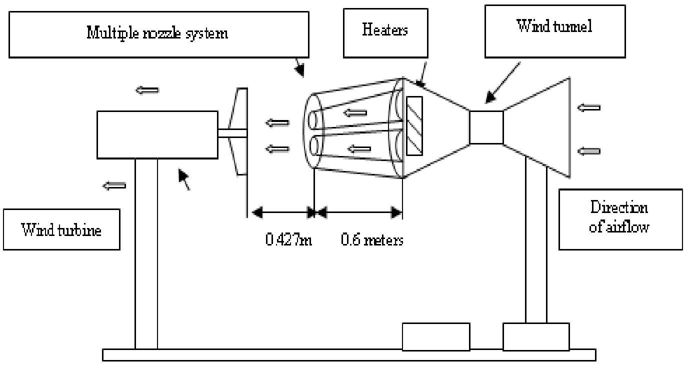

Figure 6Line Diagram of Module M_3

Figure 5 illustrates the application of multiple nozzle system. The location of electric heaters is illustrated in figure 6.

The air at high speed from wind tunnel is focused on to rotor of the turbine. In these modules, the efficiency of the lab model wind turbine is determined with and without using the nozzle system at different positions of blade. The horizontal shaft of the wind turbine rotates freely in bearings. Initially, the rotor is allowed to rotate freely, without connecting dynamo. Power coefficient is determined theoretically by knowing wind speed at the inlet and outlet of wind turbine. Later, actual power coefficient is determined when the shaft of the turbine is coupled with shaft of dynamo, using belt and pulley arrangement. The produced D.C current is then converted into A.C using an inverter. The ratio of power extracted to the power available in wind becomes the actual power coefficient. Theoretical power coefficient becomes the ratio of power producible by wind turbine to the actual power in the wind.

Power in wind (P_a) = $\frac{1}{2} \rho A V_i^3$ watts --------- 1.1

Power producible (P_e) = $\frac{1}{4}(g_c)\ \rho\ A\ (V_i^2 - V_e^2)\ (V_i + V_e)$ watts---1.2

Where, V_i and V_e indicates velocity of air at entry and exit of wind turbine and 'A' is the swept area of the rotor. The density of air determined used gas equation treating the air at atmospheric pressure. (11)

Results and Discussion

Experiment is conducted at 0^0, 30^0, 45^0, 60^0 and 90^0 of blade positions in the quarter segment of a circle when the temperature is almost 27^0C in first three modules. In the final module, air temperature increases approximately 10 ^{0}C more than the ambient temperature. The theoretical power coefficient and actual power coefficient is determined and tabulated in Table 1 to Table 4. In all modules, it is founded that at power coefficient is high at 45 degrees of attack. Hence, 45 degrees of attack is chosen for comparison.

Module M_0

Wind tunnel though it produces air at speed 8.5 m/sec, speed of air at the inlet of the turbine is only 6.7 m/sec. The power available in the wind with this velocity is 34.69 watts. Theoretical power of wind turbine is only 12.23 watts. Thus, the theoretical power coefficient becomes 0.35. But, actual power from the wind turbine is 9.36 watts. Friction losses in mechanical transmission reduce actual power. Therefore, actual power coefficient is 0.27. Power factor of the inverter is assumed to be 0.85 in the calculations.

Module M_1

The air velocity at the inlet of the wind turbine is increased to 12.50 m/sec. The wind turbine produces 89.5 watts of theoretical power and 75.69 watts of actual power. The air with velocity 12.5 m/sec consists power of 225.51 watts. Thus, theoretical power coefficient becomes 0.40 whereas; the actual power coefficient is 0.34.

Module M_2

The speed of air at the inlet of the turbine of the wind turbine is further increased to 14.2 m/sec due to multiple nozzle system. The wind turbine produces theoretical power of 155.44 watts and actual power of 138.65 watts. The air with velocity of 14.2 m/sec consists power of 331.16 watts. Therefore, the theoretical and actual power coefficients of wind turbine become 0.46 and 0.42 respectively.

Module M_3

The speed of air at the inlet of the turbine reaches 15 m/sec in this module. The wind turbine produces actual power of 170.29 watts and theoretical power of 186.44 watts. The air with velocity 15.0 m/sec has the power of 387.04 watts. Therefore, an actual and theoretical power coefficient of wind turbine becomes 0.44 and 0.49 respectively. Hence: it can be concluded that module M_3 works with maximum efficiency.

Figure 11 illustrates the working of wind turbine when multiple nozzle system is used. Figure 12 illustrates the instruments like wattmeter, volt meter and watt meter in measuring the electric power produced.

Table 1. Investigation for Module M_0 (without Nozzle System)

α	Ti ^{0}C	(ρ) kg/m^3	(Vi) m/s	(Pa) W	(Ve) m/sec	P_{eth} W	P_{eact} W	C_{pth}	C_{pact}
0	26.8^0	1.177	6.90	37.93	6.50	4.13	00	0.11	00
30	27.9^0	1.177	6.80	36.30	5.90	8.36	5.43	0.23	0.15
45	27.0^0	1.176	6.70	34.69	5.20	12.23	9.36	0.35	0.27
60	26.8^0	1.177	6.80	36.30	5.70	9.90	6.88	0.27	0.19
90	26.8^0	1.177	6.90	37.93	6.80	1.08	00	0.03	00

Table 2. Investigation for Module M_1 (with Single Nozzle System)

α	Ti ^{0}C	(ρ) kg/m^3	(Vi) m/s	(Pa) W	(Ve) m/sec	P_{eth} W	P_{eact} W	C_{pth}	C_{pact}
0	26.8^0	1.177	12.30	214.86	11.5	26.02	17.09	0.12	0.08
30	26.9^0	1.177	12.60	230.97	09.70	82.82	41.04	0.36	0.18
45	26.9^0	1.177	12.50	225.51	09.20	89.50	75.69	0.40	0.34
60	26.8^0	1.177	12.40	220.14	9.90	71.70	65.20	0.33	0.30
90	26.9^0	1.177	12.50	225.51	12.30	07.09	00.00	0.06	0.00

Table 3. Investigation for Module M_2 (with Multiple Nozzle System)

α	Ti ^{0}C	(ρ) kg/m^3	(Vi) m/s	(Pa) W	(Ve) m/sec	P_{eth} W	P_{eact} W	C_{pth}	C_{pact}
0	26.2^0	1.179	14.10	324.22	12.90	50.56	35.55	0.16	0.11
30	26.3	1.179	13.90	310.61	10.40	119.45	89.79	0.38	0.29
45	26.3	1.179	14.20	331.16	09.40	154.44	138.65	0.46	0.42
60	26.3	1.179	14.20	331.16	10.60	127.91	102.65	0.38	0.31
90	26.2	1.179	14.00	316.38	13.50	44.50	28.47	0.14	0.09

Table 4. Investigation for Module M_3 (with Multiple Nozzle System and Heaters)

α	Ti ^{0}C	(ρ) kg/m^3	(Vi) m/s	(Pa) W	(Ve) m/sec	P_{eth} W	P_{eact} W	C_{pth}	C_{pact}
0	29.1	1.168	15.0	386.71	13.8	81.44	61.87	00.21	0.16
30	29.4^0	1.167	14.9	378.70	10.80	154.85	132.45	00.41	0.35
45	29.3^0	1.169	15.0	387.04	9.50	186.44	170.29	00.49	0.44
60	29.4^0	1.167	15.1	394.15	10.80	164.30	134.01	00.42	0.34
90	29.3^0	1.169	15.1	394.83	13.8	62.19	39.46	00.16	0.10

Graphical Representation:

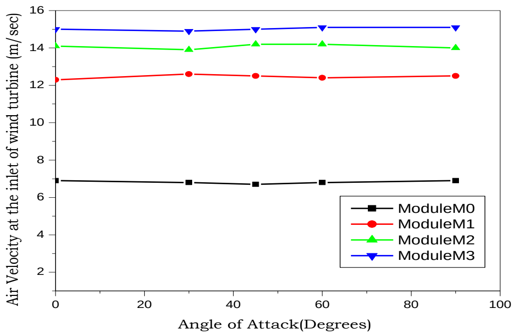

Figure 7. Variations in air velocity at inlet Wind Turbine from each Module

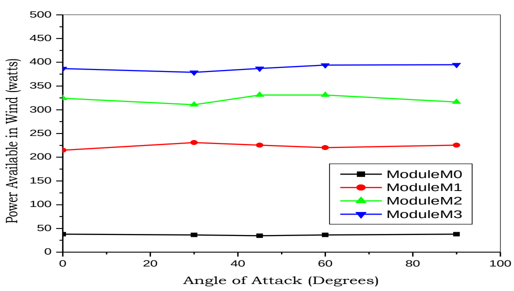

Figure 8. Variations of Available Power in Wind from each Module

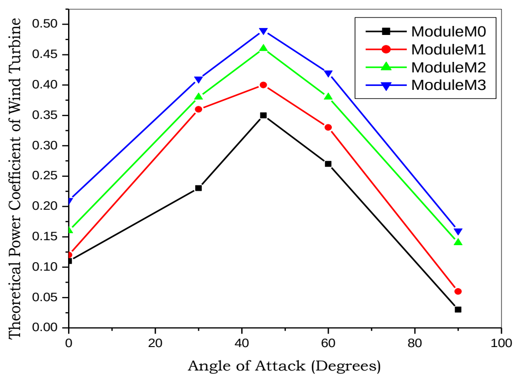

Figure 9. Variations of C_{pth} at Various Angles of Attack

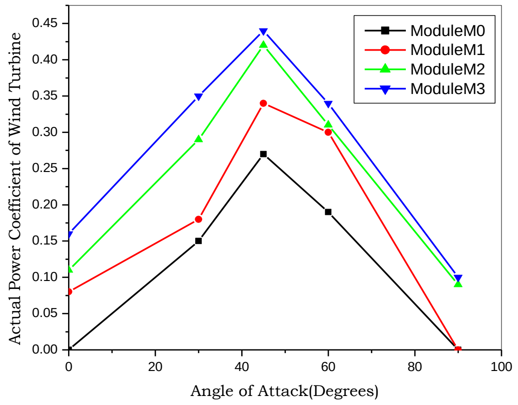

Figure 10. Variations of C_{pact} at Various Angles of Attack

Variations in turbine inlet velocity, power available in wind, theoretical power, and theoretical and actual power coefficients of wind turbine are illustrated from figure 7 to 10. Figure 7 and 8 illustrate the variations cut-in speed of wind turbine and power available in the wind. The turbine inlet velocity rises from each module. It is almost constant in the respective module of experiment. Little variations are occurred due to fluctuations in power supply to blower of wind tunnel. Thus, power available in wind also rises in the similar fashion. Figure 9 and 10 illustrates the rise in theoretical and actual power coefficients from one module to another module. The effective utilization of kinetic energy of air is occurred at 45^0 of attack.

Wind Turbine under Operation

Figure 11. Effect of Nozzle System

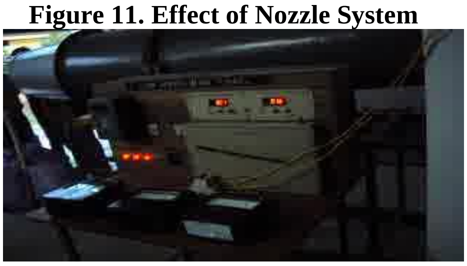

Figure 12. Power Measurement

Laboratory model wind turbine is placed at a distance 0.457 m from wind tunnel. Air from wind tunnel is concentrated on to the wind turbine. Air from the wind tunnel causes turbine to rotate. The air may not focus on to the rotor with enough momentum if, the turbine is located close to the tunnel. If it is placed far from the wind tunnel, the air domain between wind tunnel and wind turbine may absorb a portion of the velocity. By trial, it is found that the turbine with multiple nozzle system rotates at high speed whenever the distance between them is 0.457 m. Hence, all experiments are conducted at the same distance and, then performance of various modules is compared.

Sensitivity Analysis

Percentage increase in cut-in speed, power available in wind and power coefficient is shown in Table 4.8.

Table 4.8 Percentage increase in V_i, P_a and C_{pact}

Module	V_i	Rise in V_i from M_0	P_a (watts)	Rise In P_a from M_0	C_{pact}	Rise in C_{pact} from M_0
M_o	6.7	No change	614.12	No change	0.27	No change
M_1	12.5	12.92%	1687.5	174.78%	0.34	25.92%
M_2	14.2	111.94%	3538.9	476.24%	0.42	55.55%
M3	15.0	123.88%	4182.5	581.05%	0.46	70.37%

Conclusions

Out of 0^0, 30^0, 45^0,60^0 and 90^0 of angles of attack performance of wind turbine is maximum at 45^0.Multiple nozzle system rises the efficiency of wind turbine when compared to single nozzle system of same dimensions. More convergence causes converting some of heat energy of wind into its kinetic energy. From investigations, it was founded that the efficiency of turbine rises from 27% to 46% and, theoretical power coefficient rise is from 35% to 49%.

Acknowledgements

Authors are thankful to the management of G. Pulla Reddy Engineering College (Autonomous), Kurnool, Andhra Pradesh, India for providing facilities to conduct investigations.

References:

1. Lilley, G.M Rainbird, W.J “A Preliminary Report on the Design and Performance of a Ducted Wind Mill”, College of Aeronautics, Report 102, 1956

2. Bernard Frankovi and Ivan Vrsalovi, “New High Profitable Wind Turbines”, Renewable Energy, Volume 24, Issues 3-4, November 2001, pp. 491-499

3. K.J. Touryan, J.H. Strickland and D.E. Berg, “Electric Power from Vertical - Axis Wind Turbines”. Journal of Propulsion and Power, Vol. 3, No. 6, November / December 1987, pp. 481-493

4. R. B. MacPherson, “Design, Development and Testing of Low-Head High-Efficiency Kinetic Energy Machines -An Alternative for the Future”, M.Sc. thesis. University of Massachusetts, Amherst, USA, 1972.

5. B.G. Newman, “Actuator-Disc Theory for Vertical Axis Wind Turbines“. Wind Engineering and Industrial Aerodynamics” Vol. 15, 1983, pp. 347-355.

6. Grant AD & Dannecker RKW, “Investigations of a Building-Integrated Wind Turbine Module” Wind Energy, 2002, pp. 5.53-5.71.

7. A. Kogan, and A.Seginer, “Shrouded Aerogenerator of Design study II, Axis symmetrical, Shroud Performance, Fifth International Annual Conference on Aviation and Aeronautics, 1963, Israel.

8. A.Kogan and A. Seginer, “Shrouded Aerogenerator Design Study II, Axis Symmetric Shroud Performance”, Dept. of Aeronautical Engineering, Technion, 1963.

9. Robert E.Sheldahl and Paul C.Klimas, "Aerodynamic Characteristics Of Seven Symmetrical Aerofoil Sections Through 180-Degree Angle Of Attack For Use In Aerodynamic Analysis Of Vertical Axis Wind Turbines", A Report of Sandia National Laboratories

10. J.Tangler, "The Evolution of Rotor and Blade Design", NREL/CP-500-28410, Presented at the American Wind Energy Association Wind Power, Palm Springs, California, April 30, May 4 2000

11. G.D. Rai," Non-Conventional Energy Sources", Khanna Publishers, Delhi, IV edition, 2006.