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

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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.

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

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 withstand the drag, only lift force is paramount. According to the investigations of Sheldal [9] and Tangler [10] lift coefficient is high at 450 of attack for flat airfoils. The lift coefficient is determined from 00 to 1800 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 00, 300, 450, 600 and 900 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 M0) (ii) with outer nozzle system (Module M1) (iii) with multiple nozzle system (Module M2) (iv) Multiple nozzle system with heaters (Module M3)

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...
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 500 gm each. In warm countries like India and China, atmospheric air occurs at a temperature of 45°C to 50°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.

**Line Diagrams of Experiment Modules M₀, M₁ and M₂**

Line diagram of module M₀ 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 M₁ 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 determined 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°, 30°, 45°, 60° and 90°.
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 produces the ratio of power producible by wind turbine to the actual power in the wind.

Power in wind ($P_i$) = $\frac{1}{2} \rho A V_i^3 \text{ watts}$
Power producible ($P_e$) = $\frac{1}{4}(g_\text{th}) \rho A (V_e^3 - V_i^3) \text{ watts}$

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°, 30°, 45°, 60°, 90° of blade positions in the quarter segment of a circle when the temperature is almost 27°C in first three modules. In the final module, air temperature increases approximately 10°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 found that at power coefficient is high at 45 degrees of attack. Hence, 45 degrees of attack is chosen for comparison.

Module M₀

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 M₁

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 M₂

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 M₃

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 M₃ 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>
<thead>
<tr>
<th>Angle of Attack (Degrees)</th>
<th>Air Measure with the wind turbine and nozzle system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module M₀</td>
<td></td>
</tr>
<tr>
<td>Module M₁</td>
<td></td>
</tr>
<tr>
<td>Module M₂</td>
<td></td>
</tr>
<tr>
<td>Module M₃</td>
<td></td>
</tr>
</tbody>
</table>

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
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 \( C_{pact} \)**

<table>
<thead>
<tr>
<th>Module</th>
<th>( V_i )</th>
<th>Rise in ( V_i ) from ( M_0 )</th>
<th>( P_a ) (watts)</th>
<th>Rise in ( P_a ) from ( M_0 )</th>
<th>( C_{pact} ) Rise in ( C_{pact} ) from ( M_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_0 )</td>
<td>6.7</td>
<td>No change</td>
<td>614.12</td>
<td>No change</td>
<td>0.27</td>
</tr>
<tr>
<td>( M_1 )</td>
<td>12.5</td>
<td>12.92%</td>
<td>1687.5</td>
<td>174.78%</td>
<td>0.34 25.92%</td>
</tr>
<tr>
<td>( M_2 )</td>
<td>14.2</td>
<td>111.94%</td>
<td>3583.9</td>
<td>476.24%</td>
<td>0.42 55.55%</td>
</tr>
<tr>
<td>( M_3 )</td>
<td>15.0</td>
<td>123.88%</td>
<td>4182.5</td>
<td>381.05%</td>
<td>0.46 70.37%</td>
</tr>
</tbody>
</table>

**Conclusions**

Out of \( 0^\circ, 30^\circ, 45^\circ, 60^\circ \) and \( 90^\circ \) of angles of attack performance of wind turbine is maximum at \( 45^\circ \). 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%.

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**References:**