STREAM TUBE MODEL ANALYSIS USING HAWT & BETZ CRITERIA JUSTIFICATION

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Abstract: The paper solely covers performance analysis of Stream tube model using Horizontal axis wind turbine (HAWT) and finally Justification of Betz Limit. Analyzing and testing of Stream tube model done at Energy Center, Maulana Azad National Institute of Technology, Bhopal, India. Experimental setup involves design and fabrication of Stream Tube model, to achieve desired power co-efficient at various Perturbation factor. Analysis of operation of this stream tube model had been done at various wind speeds recorded at the Center. Average output power of the model and operating conditions shows that the model can be tested for large power generation. Computational study is done for power output and power coefficient for different wind speeds.

Keywords: Stream Tube Model, HAWT, Perturbation factor, Power Co-efficient.

I. INTRODUCTION

Wind energy is that kinetic energy associated with the movement of large masses of air. These motions are the result of uneven atmospheric heating by sun creating differences in temperature, pressure and density. Wind energy can be available for as much of 24- hours a day but not the constant energy because of speed of wind is not constant all over day. In this case, when at peak demand of the system the supply can be provided by the energy storage system. It is a clean, cheap, eco-friendly and reliable renewable source of energy. History of wind turbines dates back to 17th and 18th century A.D. It was in late 1800s when wind mills were used for electricity generation [1]. Recent research and developments came up with various types of wind turbines out of which Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs) are the most commonly used turbines [2]. Horizontal Axis Wind Turbines have some drawbacks and more advantages that make HAWTs widely used commercially [2]. These some drawbacks are result of design of this Stream tube model HAWT. The focus of this research work is based on design of tunnel wind turbine such that it extracts power from a low wind speed which is recorded on hourly basis on experimental site and finally justifies the Betz criteria. We have tried to show in our paper that by adjusting the ranges of perturbation factor can greatly affect the way in which we utilize the wind power. Way we look at the wind power generation Less noise level is expected due to low Tip Speed Ratio (TSR) [3]. For a given swept area,

‾there are factors affecting power generation such as rotor rotation velocity, power coefficient, perturbation factor, blade orientation [5]. Variation in power coefficients for different wind speed and for different Perturbation factor is analyzed. Power coefficient, Cp, defines the efficiency of any wind energy conversion system (WECS) [4] [6]. This Stream tube model using HAWT is such designed that it generates the power according to the Betz Limit. Which explains that at maximum power extraction condition, the upstream wind velocity is reduced to two third, in ideal case, and downstream velocity is reduced to one-third, i.e., maximum value of power coefficient in an ideal case is 16/27 i.e. 59.26% [3]. Practically, no wind turbine has a power coefficient more than 16/27.

II. THEORETICAL ANALYSIS OF WIND TURBINE

Wind turbine is a device which basically converts the power present in wind to the electrical power or mechanical power as output. Wind turbine works on the principle of extracting energy from air. The energy extracted is directly proportional to available wind speed. A small stream tube HAWT model setup was placed on rooftop of the Energy Center building in MANIT, Bhopal, India. The parameters available as input data are wind speed, number of blades, swept area. Based on these primarily available data, important results were calculated, which describe the performance of a wind turbine.

A. Rotor Swept Area

The swept area is the section of air enclosing the turbine in its movement. VAWTs have rectangular shaped swept area but For HAWTs, swept area is circular in shape. Swept for this stream tube model Area, in A (m2), is given by:

$$A = \pi R^2 \tag{1}$$

Where R is the radius of 4 bladed Horizontal axis turbine used in this stream tube model in meter.

B. Energy available in the wind

Energy available in the wind (P_0) is the kinetic energy associated with the mass of moving wind [5].It is proportional to cube of wind speed. This energy is available in the wind before the wind strikes on the rotor. Aero turbine converts the wind energy in the form of mechanical energy.

$$P_0 = (1/2)\,\rho A_1 \mu_0^3 \tag{2}$$

Where μ_0 is the upstream velocity or speed of free wind in unperturbed state and ρ is Density of wind = 1.205 kg/m^3 and A_1 is the area of Inlet of Stream Tube model.

C. Velocity of wind at turbine

The speed obtain at the turbine in this model is denoted by (μ1) and calculated by

$$\mu_1 = \mu_0 - 2a \tag{3}$$

Where "a" is perturbation factor.

D. Downstream velocity

It is the velocity which is available at the output of the stream tube model

$$\mu_2 = 2\mu_1 - \mu_0 \quad (4)$$

Where μ_2 is the downstream velocity and μ_0 is the velocity of wind at inlet of the stream tube model.

E. Power coefficient

Power coefficient is defined as the fraction of available power in the wind that can be extracted.

$$C_p = 4a\,(1-a)^2 \quad (5)$$

Where C_p is the power coefficient.
In ideal condition, value of C_p does not exceed 16/27 or 0.593, according to Betz criterion. Power coefficient defines the how much fractional power is available in wind at the output and also shows the efficiency of the wind turbine for upstream velocity & perturbation factor.

F. power extracted by the turbine

Power extracted by the wind is the product of power coefficient and the power present in wind at inlet. In HAWT stream tube model it can written as

$$P_t = C_p * P_0 \quad (6)$$

Where P_t is power extracted by turbine. Here C_p depends on the perturbation factor which varies as the upstream velocity of wind varies. And the other factor P_0 Power in wind depends on the air density, velocity of wind and the area A_1 through which wind is coming at turbine i.e. Inlet of the stream tube model.

III. SPECIFICATIONS OF THE MODEL

The developed model is a four-bladed structured Horizontal axis wind turbine stream tube model erected with help of supporting structure. Blades of the turbine are pivoted inside the stream tube with an inlet and an outlet.
Physical and technical specifications are listed in table 1.

Table:1 Description of parts used in the model

S. No.	Model Description		
	Particulars of parts	Material Used	Quantity Used
1.	Stream Tube	GI sheet	1
2.	Turbine Blades	Fiber Sheets	4
3.	Supporting Frame	MS Sheets	1
4.	Gear Assembly	Spur Gear(07)	1

Fabrication of the model was done at MANIT, Bhopal. The enlisted particulars were assembled in accordance with modeling and designing of the model using auto-CAD.
The testing parameters of the HAWT Stream tube model are listed as:

Rotor Radius	: 0.052m
Swept Area of the rotor	: 0.0085m^2
Total Length of the model	: 0.88m
Inlet to Blade	: 0.43m
Outlet to Blade	: 0.45m
Inlet Radius	: 0.04m
Inlet area	: 0.005m^2
Outlet radius	: 0.075m
Outlet area	: 0.017m^2

In this model we used two circular areas one is inlet and other is outlet. The material used in fabrication is sheet of Galvanized iron. This sheet is used because of its light weight and it can be folded easily to make fabrication easy. And here to limit project cost in desired value we used this sheet because of its low cost. Galvanized sheet have long life than any alternative coating.

Fig.1. dimensional view of the Stream tube model

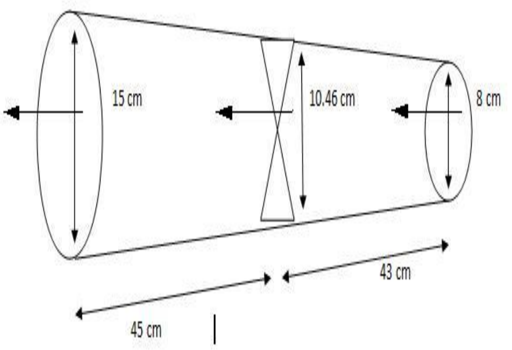


Fig. 2. Swept Area covered by HAWT while rotation

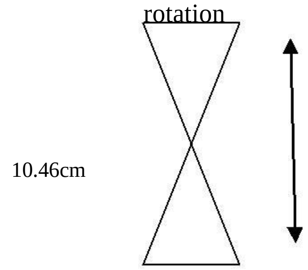


Fig. 2. Shows the area swept by the rotor of the model while rotation. In HAWTs, the shape of swept area is defined by rotor radius.
Using (1), swept area of the model is calculated

$$A = \pi R^2$$
$$= 3.14*(.052)^2 = 0.0085 \text{ m}^2$$

A. Stream Tube

The main emphasized structure of the model is the frame of Stream tube. The Tunnel is made up of Galvanized Iron sheet. Length of the Stream tube model measures from inlet to outlet is 0.88m. For bladed HAWT to be placed inside the frame.

B. Blades

Blades acts as the driving force from wind exerts on them. These rotating blades are placed inside the tunnel in such a way that no wind passes through the gap between them. The turbine used here is of 4 bladed.

C. Supporting Frame

Most important feature of stream tube model is supporting frame. This model uses a supporting frame made of mild steel sheet, in conical shape with both ends open. The smaller opening is attached with stream tube with axis of cone perpendicular to the base of stream tube.

IV. RESULTS AND ANALYSIS

The performance testing of the hexagonal VAWT model was done at rooftop of Energy Center, MANIT Bhopal, India, 23.2500° N, 77.4167° E, and 430 m above sea level. Wind data for various rotors speeds and at different time were recorded using digital anemometer installed in the center. Based on these primary data, computational study was done to obtain the performance efficiency of this stream tube model. Table 2 shows the results obtained by computational methodology.

Table: 2 results of computed parameters

[a] All values corrected to three decimal places

Perturbation factor, a	**Upstream Velocity, μ_0 (m/s)**		**Computed parameters**			
		Wind velocity at turbine (μ_1)	***Wind velocity at output (μ_2)***	***Power coefficient, C_p***	***Output power of Wind, Po (Watts)***	***Extracted power by turbine, (P_t)***
0.10	1.4	1.2	1.1	0.324	0.0147	0.0047
0.20	1.5	1.2	0.9	0.512	0.0181	0.0092
0.25	1.8	1.3	0.8	0.562	0.0314	0.0176
0.29	1.9	1.3	0.7	0.584	0.0369	0.0215
0.33	2.0	1.3	0.6	0.592	0.0431	0.0255
0.41	2.1	1.2	0.3	0.570	0.0499	0.0284
0.47	2.3	1.2	0.1	0.528	0.0655	0.0345
0.59	2.4	1.0	-0.4	0.396	0.0745	0.0295
0.67	2.5	0.8	-0.9	0.291	0.0842	0.0245
0.75	2.7	0.6	-1.5	0.187	0.1060	0.0198

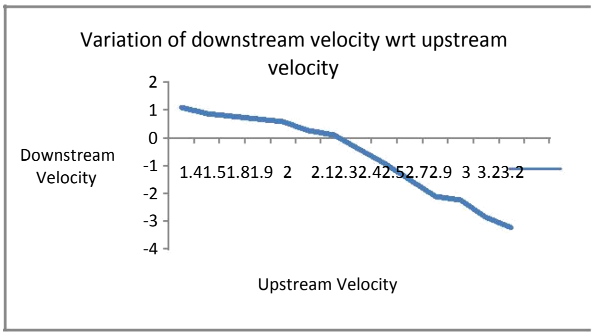
The computational study involved [1] [3] [5] & [7].

It shows the variation in values of power from the wind is much more than that of power output from wind. This is due to the fact that a lot of power is consumed in rotating the turbine. Power in the wind is proportional to cube of wind speed while power extracted from the wind is proportional to the Power coefficient. Hence there is difference in amount of power extracted from wind and input power of the wind at the turbine.

A. Downstream Velocity

The downstream velocity of wind is available at the outlet of stream tube model. Downstream velocity is gradually decreasing with the increase in wind speed at the inlet means upstream velocity. At a point where upstream velocity crosses critical velocity the downstream velocity becomes zero and afterward found negative. This condition is called stall condition of turbine. In this condition rotor rotates in opposite direction and extract the power from output of the stream tube model.

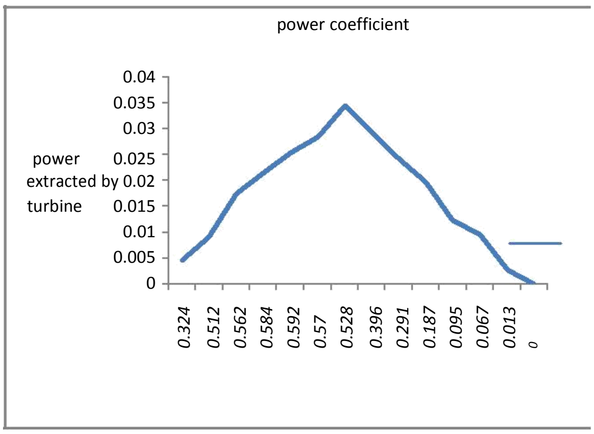
Fig. 3. Downstream velocity vs upstream velocity Chart



B. Power extracted by turbine

Power extracted by turbine is depend on the power coefficient of wind, up to some point it increase in direct proportion with power coefficient but after a critical point it decreases gradually.

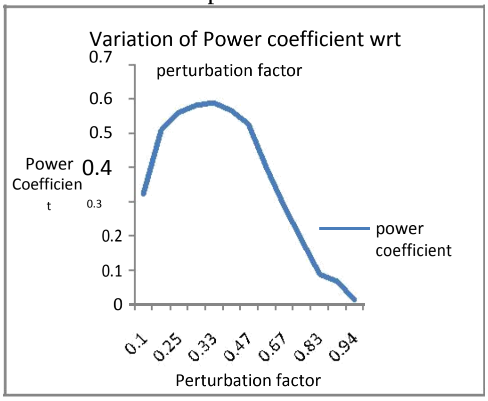
Fig. 4. Variation of power extracted by turbine w.r.t. power coefficient



C. Power Coefficient

For various recorded wind speeds, power coefficient is obtained in a range of 0.592, for V = 2.0 m/s, to 0.187, for V = 2.7 m/s.

Fig. 5. Variation of Power coefficient w.r.t. perturbation factor



V. CONCLUSION

For this stream tube model for maximum power coefficient the power at turbine has its peak value. The coefficient of power is 0.592 when perturbation factor is 0.33 therefore this justifies the Betz Limit. Here a Condition arrives at a>0.5, the downstream velocity becomes negative, i.e., blades start rotating in opposite direction. This is due to the low pressure and viscosity produced on downstream. This is a satisfactory result as far as the size of the model and availability of wind is concerned.

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