International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 11 Issue: 04 | Apr 2024 www.irjet.net p-ISSN: 2395-0072

Power Generation Using Exhaust Energy from Industrial Ducts

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ABSTRACT

This study investigates the potential of utilizing exhaust air from ducts in industrial or ventilation systems as a resource for wind turbine energy generation. The proposed system incorporates specially designed turbines strategically placed within the ducts to capture the kinetic energy of the moving air. Through computational simulations and experimental validations, this research aims to analyse the feasibility, efficiency, and environmental impact of harnessing this exhaust air as an additional renewable energy source. The findings from this study offer insights into a novel approach for maximizing energy recovery from existing infrastructures while contributing to sustainable energy production. Utilizing wind turbines to harness the energy potential of exhaust air from ducts presents an innovative approach in renewable energy generation. By strategically placing turbines within these ducts, the kinetic energy of the airflow can be captured and converted into electrical power. This method taps into an otherwise wasted resource, contributing to more efficient energy utilization within industrial or ventilation systems. The design and implementation of such turbines require careful engineering to optimize efficiency and ensure minimal disruption to the airflow. This approach holds promise for enhancing sustainability by tapping into untapped energy sources while reducing the carbon footprint of operations reliant on exhaust systems.

INTRODUCTION

Over the last couple of decades, mankind has realized that the continuous usage of petroleum fuels to meet the world's energy demand, over the course of more than a century, has led to innumerable consequences. An inclination towards other sources for energy has come into the forefront. Yet, we are still a long way from completely phasing out petroleum as an energy source altogether. In such a time, any progress towards reducing the amount of fuel consumed during energy generation is good progress and cannot be neglected. The rest is wasted in the form of exhaust heat and noise. So, there is a scope for reclaiming the wasted power produced by the industry. Turbine-based power generation through the exhaust gases has proven to be an efficient source of energy generation.

Turbine Based Power Generation: It works on the principle of conversion of kinetic energy into electric energy. In this process, a turbine is fixed near the opening of the silencer. A dynamo is attached to the turbine, which converts kinetic energy generated through the turbine into useful electrical energy.

Efforts are being made to establish more innovative energy generation systems, better in terms of performance and economy, to cope up with the swelling demand of energy. Recovery of the waste energy, i.e., conversion of one form of waste energy into other useful form, is one of the important such approaches. Many energy recovery systems are being studied and evolved globally for useful power generation.

Waste-to-energy (WtE) energy-from waste (EfW) is the process of generating energy in the form of electricity and/or heat from the primary treatment of waste, or the processing of waste into a fuel source.

Industrial waste heat (Exhaust air) is abundant and represents significant energy inefficiency for many processes.

This waste heat energy is carried by Duct systems in various industries, our aim is to generate electrical energy using this exhaust air and increase plant overall efficiency. Ducted exhaust air systems are used to extract contaminated air from industrial spaces and direct it outside.

THEORY

To fulfil the project, there has to be some calculations that are done prior to the manufacturing process to insure the required outcome and some afterwards. These calculations are the Power Coefficient, Swept Area. Tip Speed Ratio, λ, Specific Speed of the Windmill, Cut in Speed, Cut out Speed, Rated Wind Speed, Torque Coefficient, CtRotor Solidity, Thrust Coefficients, CT, Wind Power, Efficiency in Wind Power Extraction, Torque Extracted.

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Power Coefficient:

The power coefficient is the ratio of the actual power output to the theoretical power in the wind.

Power = Force X Velocity

Force = Rate of change of Momentum

But: Momentum = Mass X Velocity

For a fluid of density (ρ). Flows through a cross-sectional area of A, the mass flow rate ṁ is given by: ṁ= mass flow rate

Average Force $=1/2\ \rho A V^{2}$

$HT = 1/2 \rho A V^{3}$

$CP = HW/HT = HW\ (0.125\ \rho \pi D\ 2V^{3})$

Swept Area (AS)

This is the section of air that encloses the wind turbine or windmill in movement and interacts with the rotors to produce the rotation motion. For a Horizontal Axis Wind Turbine (HAWT), the swept area is circular in shape. On the other hand, for a Vertical Axis Wind Turbine (VAWT) with straight blade, the swept area us rectangular in shape.

The swept area for the HAWT is calculated by:

$\boldsymbol{AS} = \mathbf{1}/4\ (\boldsymbol{\pi} D^{2})$

Tip Speed

Tip Speed Ratio is ratio of the speed of the windmill rotor tip at radius R when rotating at Radians per second to the speed of the wind V m/s. When the windmill is stationery, the tip speed ratio is zero; this implies that rotor has stalled. This is experienced when the torque produced by the wind is below the level needed to overcome the resistance of the load. While with a tip speed ratio of 1, it implies that the blade tips are moving at the same speed as the wind (the wind's angle that is 'seen' by the blades will be). Whereas at a tip speed ratio of 2, the tips are moving at twice the speed of the wind and so on.

From empirical results, the optimal tip speed ratio to ensure maximum power extraction is achieved for a windmill with N blades is:

$\lambda = 1/4\ (\omega R/\ U0)$

Specific Speed of the Windmill

This is the angular velocity in revolution per minute at which a turbine will operate if scaled down in geometrical proportion to such a size that will develop unit power under unit head.

Cut in Speed

This is the speed at which the turbine starts to produce any useful power. It this is the lowest speed at which power develop by the wind turbine HW is greater than zero.

Cut out Speed

This is the speed at which the turbine stops to produce any useful power. This is the highest speed at which power develop by the wind turbine is just zero.

Rated wind speed

Wind speed at which the rated power is produced, this value defines the shape of the power curve.

Torque Coefficient (CT)

The Torque coefficient is the non-dimensional measure of the torque produced by a given size of rotor in a given wind speed. This is given as the ratio of the actual Torque produced to the torque due to the force of the wind on the rotors.

It is represented mathematically by:

$Ct = \mathrm{T}/\ (1/2\ \rho A s U)$

Where:

T- The actual torque produced (Nm)

$U0$ - Wind Speed (m/s)

AS - Swept Area (σ) R: Radius (m)

Rotor Solidity

Solidity of a windmill loosely refers to the proportion of a windmill rotors' swept area that is filled with solid blades. This is the ratio of the sum of the width or 'Chords' of all the blades to the circumference of the rotor.

Torque Extracted

In the windmill used for pumping water, Torque output is key. Torque is given by the ratio power extracted to rotor speed.

$\mathrm{T} = (\mathrm{PT}\ /\lambda v)$

DESIGN AND CALCULATIONS

Parameters:

d - Diameter of plastic pipe [m]

D-wing spread of rotor [m]

e- Pipe spacing [m]

h - Height of blades / tubes [m]

v - Wind speed [m/s]

F - Diameter of end plates [m]

The permanent magnet alternator (Axial flux coreless alternator) produces 1A and 12V at only n=130 rpm with an applied shaft torque Ts=1 Nm.

Basic equations

The maximum power of the rotor is estimated according to **Betz's law**,

$Ps = 1/2 * \rho * A * v^3 * Cp = 0.36hD * v^3$ [W]

Where,

$\rho = 1.2kg / (m^3)$ is the air density,

A = h*D the sweep area of the rotor blade

Cp= 0.593 the Betz coefficient.

However, there are aerodynamic and mechanical losses in the order of 50%. Our rotor shaft power equation then becomes

$Ps = 0.18hD * v^3$ [W]

The rotational speed is defined as,

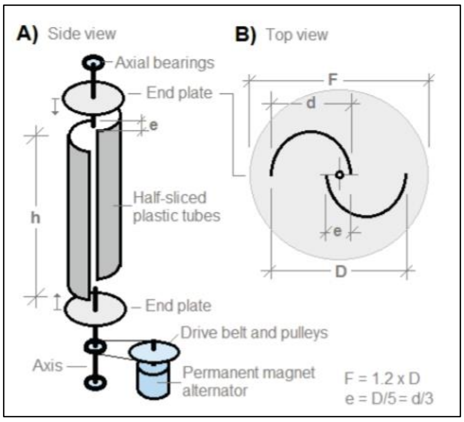
$\eta = (60/2\pi)*\omega$ [rpm]

Where,

Omega (ω) = $\lambda * v / r$ is the angular velocity in units of radians per second

r = D / 2 the radius of the rotor and $\lambda = 1$ the tip-speed ratio

Furthermore, the torque at the rotor shaft is given as,



$Ts = Ps * \omega$ [Nm]

It is now possible to calculate key parameters of the rotor using the above equations. For simplicity, the **height of the rotor is h = 1m** New power and torque values as a function of h is found by linear scaling of the calculated unit values. The rotor should start spinning for wind conditions defined as moderate breeze or wind start speed **v = 6 m/s**. The results are shown in Table below.

Rotor	d [cm]	e [cm]	D [m]	r [m]	ω[rad/s]	n [rpm]	Ps [W]	Ts [Nm]
1	10	3.33	0.167	0.0835	686	686	6.50	0.09
2	20	6.66	0.333	0.1665	36.036	344	12.95	0.36
3	30	10	0.500	0.2500	24.000	229	19.44	0.81

Table 1. Moderate breeze wind conditions: v = 6m / s and h = 1m

Let us now select rotor no. 2 due to the relatively compact size and the power of-12W at moderate breeze conditions. Table 2 shows the calculations as a function of wind speed.

V [m/s]	6	11	17	22
η [rpm]	344	630	975	1262
ω [rad/s]	36.04	66.07	102.10	132.13
Ps [W]	12.95	79.78	294.46	638.34
Ts [Nm]	0.36	1.207	2.884	4.831

Table 2. Power and torque as a function of wind speed for rotor no. 2 with wingspread D = 33.3 cm and gap e = 6.66 cm. The height of the rotor is h = 1m Wind values are from moderate breeze to near gale (28-33 knots) (force 7) conditions

COMPONENTS

1) Flange

Flanges in turbines are ring-shaped connectors that connect the bodies of the steel towers that support the wind turbines. These flanges are an important component for tower connection, and are usually installed with six or seven flanges in a wind turbine.

Material used: - MS grade en8

Figure 1: Flange

2) Shaft

Figure 2: Shaft

The shaft is responsible for converting the mechanical energy of the blades into the rotational energy and transmitting it to the generator which in turn uses this to be converted into electrical work. The shaft in a wind turbine is a critical component that converts the mechanical energy of the blades into rotational energy and transmits it to the generator. The generator then uses this energy to convert into electrical work. The shaft is also responsible for transferring the rotational energy from the rotor to the generator.

Material used: - MS grade EN8

3) Casing

Figure 3: Casing

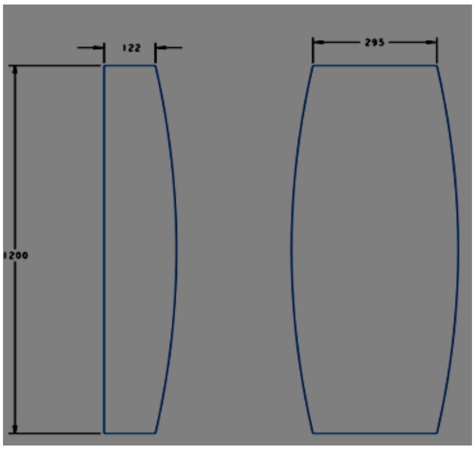
Casing in turbines refers to the outer shell or housing that encloses the internal components of the turbine, such as the rotor and stator. The outer shell or housing of a wind turbine is called the casing, which protects and encloses the turbine's components. The casing can also refer to an enclosing shell, tube, or surrounding material.

Material used: - mild steel (MS) grade EN8

4) Armature Coil

The high-speed shaft is attached to a coil of copper known as an armature inside the generator. The armature rotates at the same speed as the high-speed shaft. The armature is surrounded by a magnetic field, created by magnets within the generator. As the armature rotates through the magnetic field, a current is induced in the copper coil. The electricity generated in the copper coil is then extracted from the generator.

5) Blades



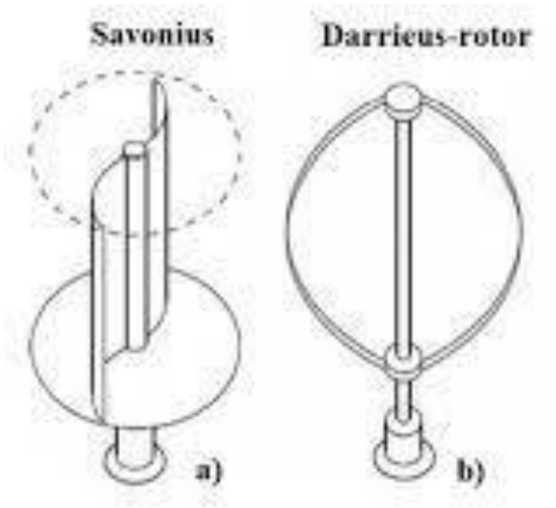


Figure 4. Types of Vertical Turbine

In the original versions of the Darrieus design, the aerofoils are arranged so that they are symmetrical and have zero rigging angle, that is, the angle that the aerofoils are set relative to the structure on which they are mounted. This arrangement is equally effective no matter which direction the wind is blowing in contrast to the conventional type, which must be rotated to face into the wind.

Wind turbine blades are typically made from composite materials, including fiberglass, carbon fiber, natural fibers, epoxy, aramid (Kevlar), and wood compounds. The blades are the most expensive part of a wind turbine and are subject to dynamic loads, such as gravity, centrifugal forces, and changes in gravity direction.

6) Alternator

A wind turbine alternator is an electrical machine that converts mechanical energy from wind turbine blades into electrical energy to power the turbine. It's a multiphase AC synchronous machine that produces a balanced AC voltage and current system. The rotoric and statoric magnetic fields work at the same speed, or rotate synchronously.

FINAL PROJECT

Figure 5. Blades

RESULT

RPM	Watt
100	0
160	7.8
200	19.5
300	59
400	100
500	117

Table 3. Power generation at different RPM

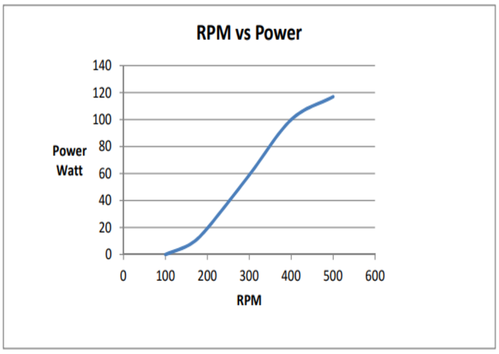


Figure 6. RPM v/s Graph

CONCLUSION

The vertical axis wind turbine, which has two different types of air foil profiles, attains a higher velocity than standard vertical axis wind turbine under the same conditions. The VAWT section with a parabolic blade profile can capture more air, allowing it to rotate even at lower wind speeds. The VAWT section with an elliptical air foil profile helps to accelerate the rotation of the parabolic air foil since the elliptical profile is more streamlined and attains higher velocities.

Vertical Axis Wind Turbines have the potential to capture wind from any direction since the rotor is perpendicular to the ground. This makes them more efficient in areas with turbulent wind conditions or frequent changes in wind direction. VAWTs are generally quieter than HAWTs since the blades rotate at a slower speed, resulting in less noise pollution. VAWT having parabolic and elliptical airfoil profiles attain higher velocities than standard VAWT but less velocity than **Savonius-Darrieus hybrid VAWT** operating under same conditions but both have higher velocities than the standard VAWT design.

1.) The combination of the turbine blades in practical gives the implementation of renewable energy and energy generation to calculated efficiency approximately.

2.) Through rigorous testing and analysis, it was observed that this blade configuration led to improved aerodynamic characteristics, resulting in higher energy output compared to traditional designs.

3.) The turbine exhibited stable operation under varying wind conditions, showcasing its reliability and suitability for small-scale renewable energy applications.

4.) It is found that slightly change in angle of the turbine blade will result in change in the rpm of the turbine

5.) Further optimization and fine-tuning of the blade design could potentially yield even greater energy generation capabilities, making it a promising technology for sustainable energy production.

6.) In theoretical calculation we got 3-4 m/s of wind speed at which the turbine will start to rotate but in practical testing we got 6 m/s at which turbine starts rotating

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