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DESIGN AND ANALYSIS OF VENTURI TURBINE TO RECOVER WASTE AIR ENERGY IN INDUSTRIAL APPLICATIONS

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ABSTRACT

This study focused onexperimentation and simulations in the development of waste air recovery system in industrial applications. The energy recovered from exhaust and ventilation systems of the industrial and commercial applications by the efficient and effective design. Recovery of energy wasted and released in terms of air discharge to the atmosphere after primary application is experimented, tested, and proven in this report at most optimal way. Conventional power generation from wind turbine takes up large swept area and it requires higher wind speeds to deliver rated power output. Our objective was to use compact design, consistent output from the energy freely released in the atmosphere after primary use in industries and commercial sector.Waste air recovery from industrial applications and design of turbine discussed in this paper is done in such a way that exhaust air coming out of duct at the discharge is directed through a funnel arrangement maintaining all the pressure criteria. Further the turbine is installed where the velocity of air is increased with venturi effect and directed towards the low-level turbine with the help of a nozzle, it has produced power, even at a lower air velocity or wind speed from the exhaust and ventilation system at a consistent load.Computational analysis is carried out on the theoretical results achieved in earlier stage, wherein measurements recorded are used to compute the right sizing and tap higher potential area keeping in mind the various factors required to install and run wind turbine generator.

Keywords: Wind Power, Sustainable energy, CFD, Venturi, Nozzle, Turbine, Duct, Velocity

1. INTRODUCTION

Energy is most important element for progress of humanity, in terms of socio-economic development. Energy is vital part for the survival needs in the primary and secondary form. The demand for energy, mostly in the form of electricity has increased since its invention with continuous increase in population and industrial activities around the world.

Wind turbines are installed mostly in open atmosphere to trap the air stream which contains kinetic energy. Kinetic energy available in open atmosphere is utilized by turbine blades swept area to generate power. This paper emphasis on recovery of waste air from industrial applications through amplification of velocity in venturi. Reference to the Bernoulli and Venturi principles, the wind velocity will increase with respect to the difference in cross sections [4].

The increased use of fossil energy results an environmental destruction as well as global warming. To address this bigger challenge, the use of renewable forms of energy is promoted to be a substitute [2]. Good amount of research to enhance the wind turbine performance had been done with respect to technology like installing diffuser to regulate the flow rate passes through the rotor increases power generated by the turbine [3].Other investigation done by Ohya and Karasudani on diffuser [10], they executed wind lens technology analysis on wind turbines. Wind lens technology works on shroud at the inlet, diffuser and then the brim. The results of this testing were encouraging and had indicated higher power when compared to a regular wind turbine.

In an industrial and commercial set-up everywhere ventilation system is an essential part of the establishments. Industries use ventilation systems for cooling, exhausts, and circulation of air. Air after the primary purpose is released in the atmosphere. The project is defined based on the law of conservation of energy, also known as the first law of Thermodynamics, stated that the energy can neither be created nor destroyed but it can only be converted from one form of energy to another form of energy.

This law of Thermodynamics and law of conservation of energy are being applied here for developing the sustainable initiative which can contribute towards climate change and sustainable development of energy generation techniques. The ventilated or circulated air from the system when released to atmosphere is having energy which is otherwise untapped and wasted. Velocity of air released from such systems having lower density and lower wind speeds at consistent rates.

2. RESEARCH METHODOLOGY

In this experimental study, air released to the atmosphere from generator cooling system is used for detailed data collection, analysis, simulation, and experimentation purpose. Measurements of exhaust or waste air released in atmosphere after generator cooling is measured at various locations, this air is further tapped and accelerated using venturi mechanism. At lower wind velocity, the wind turbines do yield a non-optimal power. A lot of investigation had been done on the technology that can be used to increase the turbine efficiency by installing a diffuser kind of mechanism. In the diffuser, the flow rate passes through the rotor, is increased. Hence, the power generated by the wind turbine also increases [9]. Study of the wind resources, associated parameters, effects on primary system are carried out in first stage to establish the idea. Wind at accelerated velocity is used to drive horizontal axis wind turbine and to tap the energy in most efficient way which is otherwise wasted and released in atmosphere after primary use in industrial systems. The main objective of the study is to understand, prove, prototype and optimize the performance parameters of wind accelerating device without affecting the performance of primary source system i.e., cooling system generator. Also, to implement the numerically optimized concept, implement prototype for actual field testing, and its contribution for efficient use of waste air to generate sustainable electricity. Figure 1 illustrates the generator cooling system.

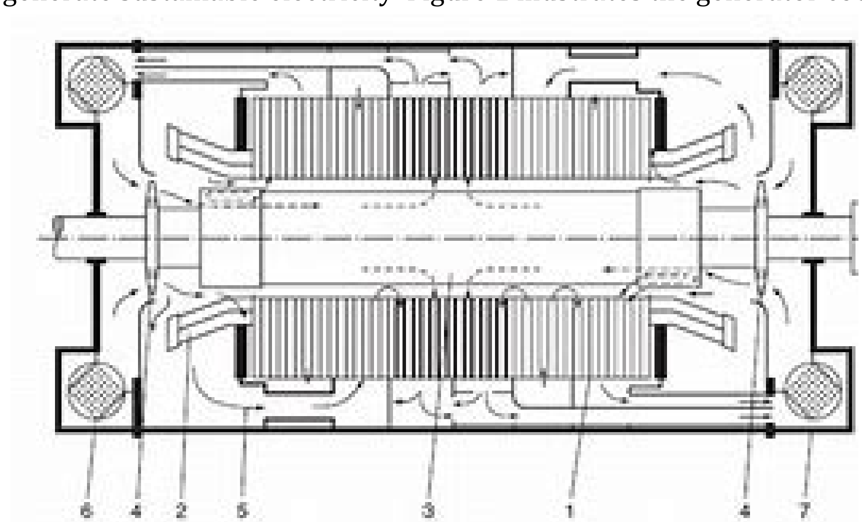

Figure 1 Illustration of Hydro Generator cooling system.

3. DESIGN SPECIFICATIONS

The experimentation carried out on-site, forced air cooling system is used for cooling electrical generator and air after circulation is released back to atmosphere outside the powerhouse. This system was selected as exhaust air will be available consistently, at the location where exhaust is released in the atmosphere adequate space is available to install the desired equipment and connect the electrical power generated to the nearest point of interconnection. Lilley and Rainbird in 1956 carried out experiment on ducted wind turbine [8], similar experiments were also executed by Foreman et al [3], the Lilley and Rainbird worked on the ducted wind turbine for studying the performance behaviors.

In a first stage data is collected, and accordingly theoretical calculations for modelling the venturi duct, sizing of wind turbine is simulated in theoretical model. This is done basis the air velocity data measured from on-site ventilation system duct discharge port. Measurements were recorded at various locations for existing ducting system, measurements are done at desired locations for air velocity and back pressure if any due to obstruction of free flow. Based on the actual measurements mathematical model is developed to calculate and estimate the potential available for wind energy generation system. These measurements have been used for designing exhaust air collector, accelerator mechanism and venturi system which can give maximum possible output and work in sync with existing system without any drawbacks. Measurements carried out at the primary system are given below in Table 1.

Table 1 Measurements of Ventilation system

Parameter	Dimensions (mm)
Diameter of Ventilation system tunnel	2000
Diameter of tunnel discharge port	2300
Diameter of gate	3200

Measurements were taken for air temperature and air velocity emerging out of duct and tunnel at various points to evaluate the potential and flow pattern on various load conditions. Table 2 indicates the actual measurements of wind velocity and temperature recorded during the process emerging out after primary application.

Table 2 Initial wind velocity measured at the end of the ventilation duct

Location	Velocity	Temperature
1	14.0	38.6
2	12.5	38.6
3	10.5	38.6
4	9.0	38.6

These measurements were further repeated by keeping the safe distance of 300 mm (0.3 meter) so as to ensure there is no back pressure creating on the primary system. Also to check the wind velocities in the open atmosphere which can be tapped for running wind turbine. Wind velocities measured are shown in Table 3.

Table 3 Initial Wind velocity measured at a distance of 300 mm from edge of discharge

Location	Velocity	Temperature
1	8.5	37.8
2	7.6	37.8
3	6.5	37.8
4	5.8	37.8

After the measurement of data at multiple levels, analysis of data is done to understand the potential and consistency for secondary use. This data of potential kinetic energy is then simulated to understand the power and energy capacity available for secondary use. Further to that simulations design of wind collector system, throat, venturi, turbine sizing, and installation requirements are evaluated. Power and energy estimation from this simulationsis shown in table 4 given below.

Table 4: Power and Energy Results from simulations

Particulars	Unit	Values
Kinetic Energy with Venturi	Watt	1430

Kinetic Energy without Venturi duct	Watt	302
Design Capacity of WTG with Venturi	Watt	422
Design Capacity of WTG without Venturi	Watt	89

Design Capacity of WTG with Venturi given above is computed as below:

$$\text{Power (P)} = \frac{1}{2}\eta\rho A V^3$$

Therefore, Power (P) $= \frac{1}{2}(0.30\ x\ 1.23\ x\ 0.87)\ x\ (13.9)^3$

= 422 Watt

Thereby, Power which can be produced by venturi turbine is thereby 4 to 5 times higher than the conventional turbine if put up in the path of exhaust air released in the atmosphere.

4. COMPUTATIONAL SIMULATION AND ANALYSIS

In this paper, ccomputational analysis is further carried out on the theoretical results achieved in earlier stage, wherein measurements recorded are used to compute the right sizing and tap higher potential area keeping in mind the various factors required to install and run wind turbine generator. This simulation results and selection is further used for deciding the wind collector system or convergent section, venturi, turbine size, generator rating, foundation, etc.

Power output scenarios are simulated based on the data captured and plotted on the chart as shown in Figure 2. Sizing of venturi is done basis the input wind velocity and desired output wind velocities from Bernoulli's theorem at various diameters, analysis of data is carried out as shown in figure 2.The data presented in chart is plotted based on the multiple scenarios analysed and simulated in excel model.

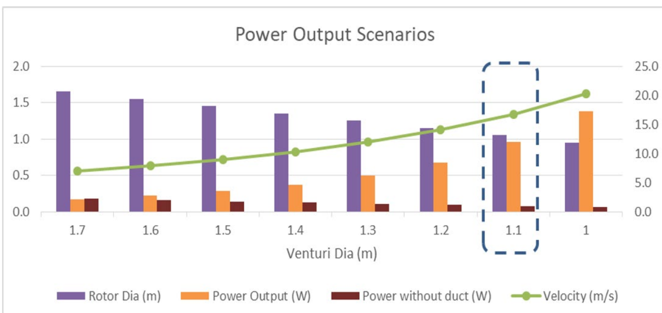

Figure 2 Simulation results of potential power scenarios.

5. SYSTEM DESIGN

Cylindrical inlet of the duct is designed to collect the air released in the atmosphere after cooling down the generator which is a primary application in this case. Air collected at lower wind velocity is converged through convergent section to accelerate the wind. After the convergent section venturi section is designed to achieve desired wind velocities. Figure 3 below shows the dimensions and geometry of model developed under this project.

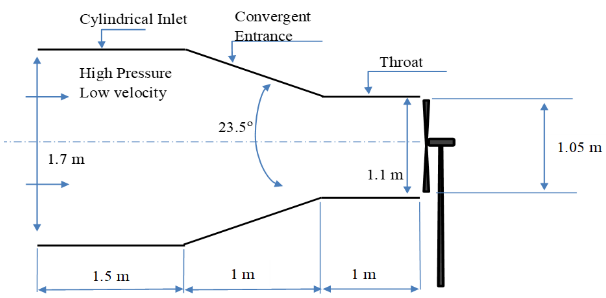

Figure 3 Dimensions and geometry of model

CAD drawings are prepared in the Autodesk software for wind collector, convergent section, venturi and frame. Its geometry is then imported to ANSYS.Reference to the potential energy available or which can be easily tapped for secondary application of waste air recovery further selection and sizing is evaluated. Basis the reference wind velocity which is right for cut-in and cut-out of wind turbine; air collector system and venturi system basic parameters are finalized for developing prototype. This data is shown in table 5.

Table 5 Design parameters

Parameter	Dimensions (mm)
Cylindrical Air collector diameter	1700
Venturi	1100
Rotor diameter	1050

To calculate the potential energy available and decide inputs for Wind turbine generator selection computation is done. After the design is done for wind collector system and amplification of wind velocity further analysis is done selection and sizing of wind turbine and generator. Parameters used for design and computation are given in table 6.

Table 6 Design and as built parameters

Parameter	Unit	Values
ρ (Density of Air)	Kg/m^3	1.23
D1 (Funnel diameter)	M	1.7
D2 (Venturi diameter)	M	1.1
A1 (Area of Funnel)	m^2	2.27
A2 (Area of Venturi)	m^2	0.95
V1 (Air Velocity at inlet)	m/s	6
V2 (Air Velocity at Venturi)	m/s	14.3
D3 (Rotor diameter)	M	1.05
A3 (Area of Rotor)	m^2	0.87

The wind energy available in the form of wind speed is converted in rotational energy by wind turbine blades and is limited to Betz Law [5]. During transforming this energy to mechanical energy and then to electrical energy, there are losses at each stage of conversion, these conversion losses are considered in the designing and selection of wind turbine generator as shown in table 7 below.

Table7 Losses at various stage in WTG assembly

Yield losses	Values
Blades	67%
Gear box & Coupling	90%
Generator	90%
Transformer	95%
Wire losses	97%
Total Yield Losses	50%

6. EXPERIMENTAL SETUP AND PROTOTYPE

As a part of on-site experimental set-up for testing the prototype, and to prove the concept in desired environment is developed further. First part of on-site experimentation set-up was to design, fabricate and manufacture ducts, venturi, frames, and support structures. The duct work is designed to capture the exhaust air leaving after generator cooling to atmosphere, increase velocity of air and concentrate the moving air flow before passing it through a relatively smaller throat section and to the turbine.

The fact that the funnel's output wind speed depends upon on the principle of mass flow rate and swept area, it is crucial to design the funnel with the given dimensions so that the speed ratio of 2 or more can be achieved. The highest input speed to out speed ratio that can be achieved from the variation of the design parameter which is obtained by increasing the diameter of the funnel.

After the structure is made ready reference to the design and expectations to achieve desired results, this structure is installed by taking all the precautionary care and safety concerns of industrial processes and procedures. In next step the structure fabricated and manufactured as per design requirements is installed in the area decided for testing and on-site experimentation, foundations are made ready to install the other equipment.

After the installation of designed ducts and venturi systems, parameters are verified and measured, these final as-built measurements are given in table 8.

Table 8 Design Parameters for duct and air flow system

Parameter	Dimension (m)
Outlet duct Diameter	2300
Space between main system and energy recovery system	300
Collector Section Diameter	1700
Venturi Diameter	1100

Further the measurements for back pressure in the exhaust air tunnel are measured and recorded after directly attaching the wind collector duct and subsequently the spacing is adjusted to achieve the standard back pressure in the tunnel to avoid any kind of impact on the operations of the main equipment and system. Chart below indicates the varying backpressure with space provided between ventilation outlet of generator cooling system and venturi duct. Data measured and analysed for the ventilation system is plotted and results are shown in figure 3.

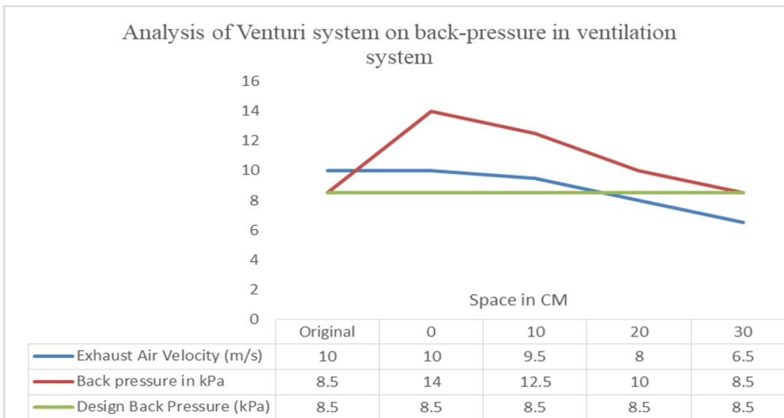

Figure 3 Analysis of measurements of primary system

6.1. COMPUTATIONAL FLUID DYANAMICS ANALYSIS (CFD)

The CFD analysis is done with the objective of work on model with different throat diameter as 1.1m which gives an understanding on actual fluid flow inside the turbine. Several simulations and computations are executed to check the relation between wind velocity and inside geometry of system through CFD simulation. It has shown how the wind speed is accelerating with change in throat diameter of duct. The simulation analysis provided suitable indication about the flow between the main air collector and acceleration and the blades.

Wind speed is accelerated to concentrate the air flow to the wind turbine blades through convergent section, which increases the velocity at turbine blades, whereas turbine was mounted at the end of throat. ANSYS R14.5 was used to study the behavior of air flow through venturi. Increase in the wind velocity has resulted in substantial enhancement in the kinetic energy hence power output of wind turbine generator.

Earlier researchers have carried out CFD analysis on Invelox which has diffuser installed in the way of air flow intercepting wind turbine [4]. They have also concluded that shrouded turbines have potential to generate higher power than the conventional turbines. Research and experimentation by Hansen [6] determines using momentum theory and computational fluid dynamic that the power amplification of a shrouded turbine is relative to the increase in flow rate or velocity through the turbine blades. The research group of Ohya [1, 3] have accomplished broad investigational and computational effort on flanged diffuser for horizontal axis wind turbines.

In the prototype design of actual model developed for testing the idea, modelling and analysis of venturi duct was carried out first with Solid model of venturi duct in structure in CATIA V5 software as shown in figure 4 according to size and dimensions of model, and its geometry is discussed in this section of paper.

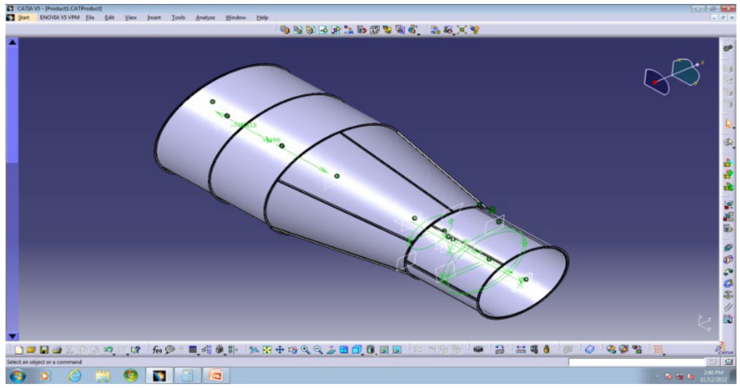

Figure 4 Solid model prepared in CATIA V5

Details of Solid model prepared in CATIA V5 further imported to ANSYS R15.5 for computational analysis of venturi section and its structural analysis using software solutions as shown in figure 5.

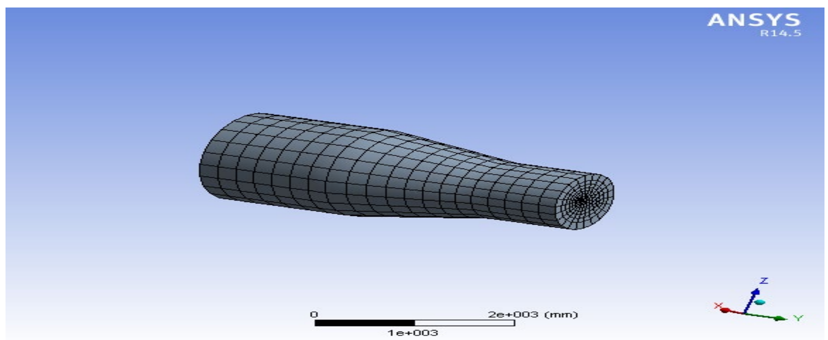

Figure 5 Structural Analysis done using ANSYS

Using ANSYS R14.5 a mechanized co-simulation workflow with motion simulations were carried out to understand the velocity and fluid flow through the different sections of wind acceleration structure. The simulation considering the turbulent model and air as a fluid flowing through it having inlet and outlets was drawn. Velocity streamlines for the flow are analysed based on the input and outputs. In a velocity contour as shown in figure 6 below assessment of the flow around the structure and wind turbine is executed.

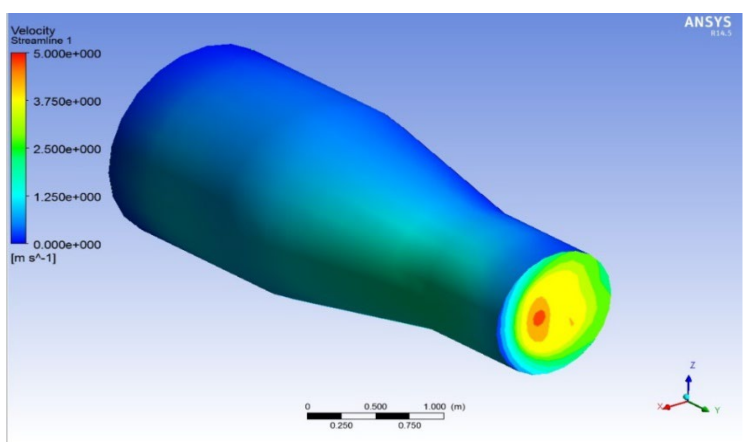

Figure 6 Fluid Flow and Velocity Analysis using ANSYS

Model was also tested in ANSYS for Boundary heat flux sensible wall CFD against measured data for the stream inside a venturi. This analysis has helped in understanding the mass flow rate, heat transfer rate on selected boundary zones as shown in figure 7 below.

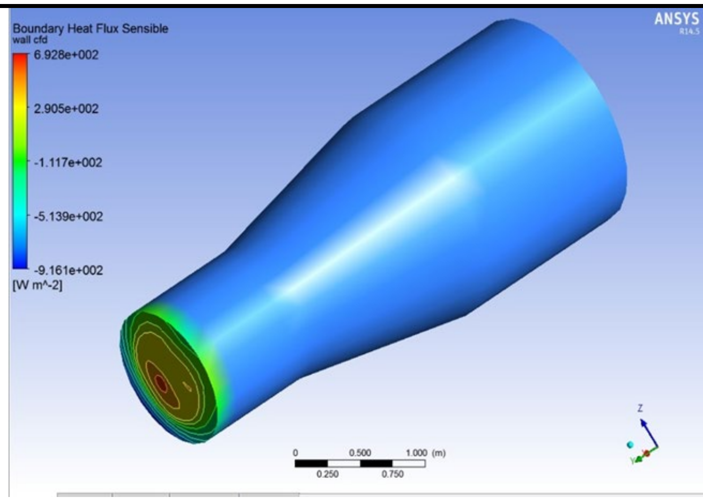

Figure 7 Boundary Head Flux Sensible (Wall CFD)

Pressure distribution over the wall is analyzed in CFD simulation to understand the distribution of pressure stream and its direction through the venturi from input to output. Force generated on the structure and wall of wind accelerating mechanism is simulated basis the input and output parameters as shown in figure 8.

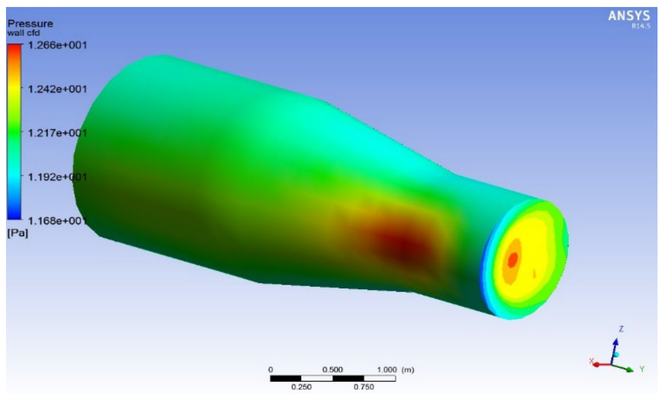

Figure 8 Pressure Wall CFD Simulation

Figure 9 below indicates the simulated model in Ansys.

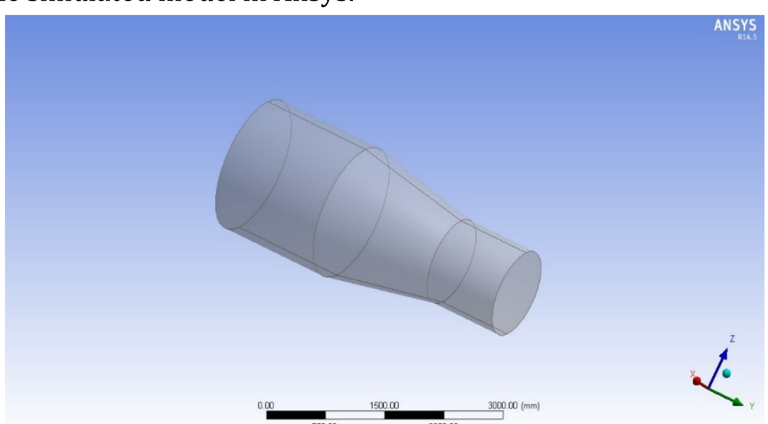

Figure 9 ANSYS model of velocity accelerating duct

Results of analysis done in ANSYS Fluent 14.5, and simulations performed for fluid flow and residual charts were created for different interactions. Considering the inputs and output parameters is simulated and results of continuity, velocities in X, Y and Z axis, energy and temperatures are plotted and showing in figure 10.

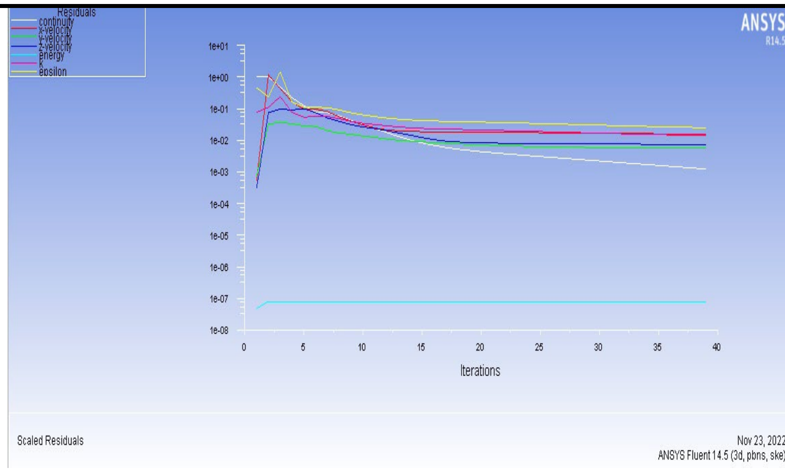

Figure 10 Residual analysis of wind velocity

7. MEASUREMENT ANALYSIS AND RESULTS

Free stream exhaust air flow coming out of tunnel is directed by the intake section due to its geometrical features into the convergent part of the ducted assembly installed after the tunnel maintaining adequate space to avoid building any back pressure in the tunnel. Further wind captured and channelled in the ducted assembly is directed into the wind concentrator, due to reducing cross section at the Venturi air gets naturally accelerated where the wind turbine is placed, and power is extracted. Figure 11 is the image captured during testing and operations of the venturi turbine in industrial application developed under this project scope and paper.

Figure 11 Wind turbine during testing

Testing was carried out primarily on the test bench at workshop to check the generator efficiencies, then the assembled Wind turbine was tried with wind flow through Venturi and finally installed on the location of generator ventilation duct discharge.

Generator purchased was tested first in the workshop for its performance. Testing of generator done in increments of 50 RPM until a maximum of 150 RPMs was reached. The max RPM was set by what the expected operation range for the turbine would be which was based on available resources. At each interval the current, voltage and wattage recorded.

The second part of testing carried out in the shrouded duct placed adjacent to ventilation duct discharge. This was done in three steps. The first step was to take multiple runs of data for an empty tunnel condition. This was done for the full range of tunnel setting, zero to one hundred percent in 25 percent increments in generator load. These multiple runs served purpose of understanding and to document the empty tunnel flow conditions. The third step in this part was to test the wind turbine in the venturi wind tunnel. This was completed by installing the wind turbine in the test section and running the turbine in 25 percent increments until the RPM reached 150. Various measurements were recorded during the operational phase.

The third part of these experiments was to test, empty tunnel conditions which consisted of the venturi pressure drop, dynamic pressure in the test section, total and static pressure upstream and downstream of the turbine. Measurements and readings for speed in revolutions per minute (RPM), Current in Ampere (A), Voltage (V) and Wattage (W) were recorded at wind turbine generator end. Summary of the measurements recorded during the experiment are given in Table 9.

Table 9 On-site test results of Power from WTG

Speed (RPM)	Current (A)	Voltage (V)	Wattage (W)
50	1.2	66.2	82
100	1.9	100.3	187
150	2.83	152	430

Apart from the parameters given in table 9 above, monitoring of performance was carried out for more than 10 hours. During the test the parameters monitored are captured at the interval of every one hour.

Parameters which were recorded on an hourly basis are Frequency (Hz), Voltage (V), Current (A), Power (W) and Energy in kWh. During the testing and monitoring time energy generated from the wind turbine generator was connected to the alternating current load through the inverter.

8. CONCLUSION

From the study of the research and experimentation carried out in detail on the waste air recovery system, it is concluded that power obtained through venturi turbine system in industrial applications of waste air is found to be 4-5 times more than power obtained by traditional wind turbine with respect to size. Also, there is no adverse impact on the environment and main equipment. There is no sound pollution caused due to venturi. Also, it can be stated that recovery of waste air in sustainable way is possible which can enhance the system efficiency and make alternate source of energy available to source. Wind Turbine Generator extracted the energy available in air released after primary use in industrial cooling application successfully and at constant load. Based on the actual results of WTG run in the industrial conditions, using venturi system has successfully delivered results of sustainable generation of electricity from waste or exhaust air otherwise released in atmosphere. In case of industrial applications, where air from system (hot air duct, etc.) is vent out into atmosphere could be used in horizontal duct which further can be channeled to give venturi effect. Here, since the flow of wind will be concentrated, loss of wind energy is observed comparatively lower. Final image of the system is shown in figure 12 below.

Figure 12 Final image of prototype

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

REFERENCES

Hansen, M. O. L., Sørensen, N. N., & Flay, R. G. J. (2000). Effect of placing a diffuser around a wind turbine. Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology, 3(4), 207-213.GWEC Global Wind Report 2018.

Abe, K. I., &Ohya, Y. (2004). An investigation of flow fields around flanged diffusers using CFD. Journal of wind engineering and industrial aerodynamics, 92(3-4), 315-330.D. Allaei, "Using CFD to predict the performance of innovating wind turbine generators"

El-Zahaby, A. M., Kabeel, A. E., Elsayed, S. S., &Obiaa, M. F. (2017). CFD analysis of flow fields for shrouded wind turbine's diffuser model with different flange angles. Alexandria Engineering Journal, 56(1), 171-179.

Pambudi, N. A., Febriyanto, R., Wibowo, K. M., Setyawan, N. D., Wardani, N. S., Saw, L. H., &Rudiyanto, B. (2019). The performance of shrouded wind turbine at low wind speed condition. Energy Procedia, 158, 260-265.

Zhu, H., Sueyoshi, M., Hu, C., & Yoshida, S. (2019). A study on a floating type shrouded wind turbine: Design, modeling and analysis. Renewable Energy, 134, 1099-1113.

Yıldız, R. E., &Ekinci, A. (2018, June). Design and Analysis of Shrouded Small-Scale Wind Turbine for Low Wind Speeds. In Journal of Physics: Conference Series (Vol. 1037, No. 4, p. 042017). IOP Publishing.

Pambudi, N. A., Febriyanto, R., Wibowo, K. M., Setyawan, N. D., Wardani, N. S., Saw, L. H., &Rudiyanto, B. (2019). The performance of shrouded wind turbine at low wind speed condition. Energy Procedia, 158, 260-265..

Lilley, G. M., &Rainbird, W. J. (1956). A preliminary report on the design and performance of ducted windmills.

Lozano, M. M., &Pulgar, L. G. D. (2012, September). Field measurement of the grounding impedance of a wind farm in Venezuela. In 2012 International Conference on Lightning Protection (ICLP) (pp. 1-6). IEEE.

Ohya, Y., &Karasudani, T. (2010). A shrouded wind turbine generating high output power with wind-lens technology. Energies, 3(4), 634-649.

Mertens, S. (2006). Wind energy in the built environment: concentrator effects of buildings