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Effect of Aerodynamic and Geometric Factors on the Exergetic and Energetic Performance of Wind Turbine Rotor

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Abstract

Wind energy conversion is recognized as one of the most promising option of the renewable energy. It is a clean source of renewable energy that can help the world to mitigate the pressing energy, environmental and economic challenges. The available wind power throughout the world is sufficient to make strategic and significant contributions to the energy supply. Saudi Arab, which has varied nature of climate, can easily utilized wind energy in all its regions except the central region. The wind rotor is the most important energy converter that utilizes a part of the available wind energy. The subject matter of this study is the effect of aerodynamic, geometric and climatic factors on the exergetic and energetic performance of this type of energy conversion system. A three bladed wind rotor with NACA 4424 aerofoil section and a tip speed ratio of five has been considered for the analysis. The results depict that the angle of attack has a most significant effect on energetic efficiency whereas rotor diameter and ambient pressure has insignificant effect on exergetic efficiency. The power produced is largely affected by the rotor diameter and the reference wind speed. The effect of reference temperature on exergetic efficiency has also been elaborated.

Keywords: Exergy, Energy, Power, Wind Rotor, Energetic Efficiency, Exergetic efficiency

INTRODUCTION

Energy is considered to be a key player in the generation of wealth and also a significant component in the economic development of any country. Improving the end-use energy efficiency is one of the most selective ways to reduce energy consumption in the industrial, commercial, transportation and residential sectors and associated pollutant emissions. The performance and control of wind turbines has become efficient through the use of wind rotor aerodynamics. Before this wind rotor aerodynamics was based theory of airplane and helicopter rotors. There are two types of wind turbines; horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) . Even though a HAWT can achieve higher efficiency than VAWT thereby increasing the power production and reducing system expenses per kW of power produced but this higher efficiency depends on its energy quality. It can be affected by high wind turbulence, wind fluctuations and directional variability of the wind whereas VAWT will be affected to a lesser value due to its lower height. Densely populated locations and urban centers qualify for low wind sources because these areas have by high wind turbulence, wind fluctuations and directional variability.

Rotor performance, particularly horizontal axis wind turbine (HAWT), analysis has been performed using several methods. Starting from Betz actuator disk theory of HAWT other theories like Blade Element Momentum method (BEM) Dixon and Hall [1], Vortex wake methods Afjeh and Keith [1986] and CFD codes Duque , et al. [1999] have been used for the analysis of the HAWT. Dixon and Hall (2010), Buhl and Marshall (2005) and Lindenburg (2003) have shown the process of combination of momentum, energy and blade element theories to arrive at the BEM theory for wind turbine. BEM is mainly employed as a tool of performance analysis because of its simplicity whereas vortex wake methods can adequately treat the effect of wake vortices but need computation burden like CFD methods. Efficient application of wind rotor aerodynamics and wind rotor specific aerofoil development has made it possible to possible to rotate the rotor at high speed and develop high power. Many investigations have been carried out to understand the aerodynamics of the rotors. These include design of new airfoil [Timmer and Roy (1993), Somer and Tangler (1996) and Dahl (1999)] and three-dimensional effect of rotating blade [Maeda and Bruinning (1996) and Hansen and Butterfield (1996)]. As the wind turbines are operating in the natural environment, turbines are always subjected to unsteady nature. This aspect has been thoroughly discussed by Hansen (1993).

Horizontal axis wind rotors (HAWT) use aerofoil sections. Previously aerofoil sections used in aviations such as NACA series were commonly used for wind rotors too. But these aerofoils showed performance degradation after certain Reynolds number, Schepers (1994). New airfoil families for HAWT are designing in Delft University of Technology, Timmer and Roy (1993), National Renewable Energy

Laboratory (NREL)[Wilson and Lissaman (1974)] and Riso National Laboratory[Dahl (1999)]. The wind energy conversion efficiency of the modern horizontal is wind turbines is about 45% whereas the theoretical maximum value is reported Singh, et al. (2012) as 59.2%. Singh et al. (2012) and Ameku et al.(2008) have demonstrated that maximum benefit of wind at low wind speeds can be obtained by using rotors with thinner aerofoil sections which have cut in speeds in the range of 2-3 m/s. They have argued the use of small wind turbines at smaller speeds. To mitigate this they propose thin aerofoil section blades for the blades and suggest the blades to be made from light alloys. Further they found that the exergy efficiency decreases both with the increase in density of air, humidity and the pressure differential between inlet and exit of the turbine.

The investigations concerning wind turbines have been carried out in two directions. The first has been purely aerodynamic nature which uses the wind tunnel tests, energy, momentum and blade element theories for the design and analysis of the turbines. These investigations, like Tangler (1993), Glauert (1926), and Buhl (2005), basically use aerodynamics for the design improvements of the wind turbine rotors. Another aspect of wind energy research is focused on availability of wind energy at a location based on exergy analysis of the wind turbine rotors. These investigations, like Burton et al. (2001), Lanzafame and Massina (2007) and Ozgener and Ozgener (2007) use thermodynamic analysis of the existing wind rotors for their performance optimization based on energy availability and economic considerations. Ozgener and Ozenger (2007) have coupled energy and economics analysis for a small wind energy generator. Rope et al(2010) Sahin et al(2006) and Baskut et al. (2010) are some of examples of research carried out on the exergical meteorological, environmental and reliability aspects of the wind energy.

The aim of present study was to carry out the energetic and exergetic investigation on the performance of a 3 bladed wind turbine having a rectangular plan form with NACA 4424 aerofoil cross section. The aerodynamic performance of the rotors in terms of lift and drag coefficients was obtained through wind tunnel test in a 300mm ×300 mm suction type low speed wind tunnel with 250 mm span NACA 4424 aerofoil. The aerodynamic data of the aerofoil is reported in Basharat and Mahir (2013) The rotational performance of three bladed small scale model of 225 mm rotor diameter wind turbine rotor was performed in a blow down low speed 600mm×600 mm wind tunnel. It may be added here that the meteorological variables, temperature and moisture, have an important role in the power output of a wind rotor. In dry type weather, like Riyadh, the temperature plays significantly higher role than the moisture. Therefore this study considers the effect of basic two parameters, velocity and temperature of the wind on the power output of the wind. Besides these the geometrical and other aerodynamic parameters have also been considered in this study.

ANALYSIS

The aerodynamic analysis of power generation by the turbine has been carried through the use of Betz theory as explained in [1] and given in equation (1)

$$P = \frac{1}{2}\rho A_R V_R^3 C_P \tag{1}$$

The turbine power coefficient C_P has been evaluated by using empirical equation formulated by Wilson et al. [26], where C_P has been correlated as in equation (2) with lift coefficient, C_L, drag coefficient, C_D, number of blades of the rotor Z and tip speed ratio λ.

$$C_P = \left(\frac{16}{27}\right)\lambda\left[\lambda + \frac{1.32+\left(\frac{\lambda-8}{20}\right)^2}{Z^{\frac{2}{3}}}\right]^{-1} \frac{0.57\lambda^2}{\frac{C_L}{C_D}\left(\lambda+\frac{1}{2Z}\right)} \tag{2}$$

Most of the human activity occurs in atmospheric boundary layer in which the wind speed increase from the earth following power law variation. Dixon and Hall (2010) have reported this variation in terms of 1/7 law in which velocity of the wind (V) at a particular height (H) is given relative to the values of the reference velocity (V_{ref}) measured at reference height (H_{ref}) as given in equation (3). Dixon and Hall (2010) suggested the value of n in this equation to be 0.28

$$V_{hub} = V_{ref} \times \left(\frac{H}{H_{ref}}\right)^{1/n} \tag{3}$$

Further the human activity is located within the lower strata of the troposphere in which the temperature of air decrease with the increase in altitude. David (2007) has reported air temperature (T_a) variation with height (h) as given in equation (4)

$$T_a = T_{ref} + a \times (H - H_{ref}) \quad \text{Where} \quad a = -0.0065^0 C/m \tag{4}$$

The temperature measured by the equation (4) is the static temperature variation in the atmospheric boundary layer for the lower region of troposphere. The actual temperature in presence of dry wind is different. The temperature of air in presence of wind depends both on the static temperature and the wind speed. Sahin et al. (2006) uses the following relation for calculation of wind temperature.

$$T_w = 35.74 + (9.6215 \times T_a) - \left(35.75 \times V_W^{\ 0.16}\right) + \left(0.4274 \times T_a \times V^{0.16}\right) \tag{5}$$

In the above equation, the temperatures are in ^{0}F and V is in miles/hour.

The power available in the wind is

$$P_W = \frac{1}{2}\rho_W A_W V_W^3 \tag{6}$$

The density, ρ, in this equation depends on ambient temperature T_a where as density in equation (1) depends on T_W. Also the areas considered in the equation are different.

The area A in equation (1) is the flow area of the rotor that is $A_R = \pi(R_t^2 - R_h^2)$ whereas the area in considered in equation (6) is the swept area of the rotor that is$A_W = \pi R_t^2$. Further the velocities to be considered in the equation (1) and (6) are different. For rotor velocity V_R is the velocity crossing the rotor which is less than the velocity V_W considered for the wind.

The energetic efficiency of the wind turbine depends on the available power of the wind and is written as the ratio of power produced by the rotor to the available wind power.

$$\eta_1 = \frac{P}{P_W} \tag{7}$$

Entropy-exergy analysis identifies maximum theoretical capability of energy systems. It [24] has pointed out that the difference between energy and exergy efficiency ranges from 10 to 25 percent and the range gets affected by the wind speed. He compared energy exergy efficiency of four types of wind power systems and has found exergy analysis to be a better tool for efficiency enhancement. Exergy analysis has been reported Baskut et al. (2010) as a vital tool for efficient energy utilization. It is a technique that uses conservation laws of mass and energy along with the second law of thermodynamics. Exergy is a measure of the maximum available useful work that can be done by a rotor in a given wind environment of pressure and temperature. Exergy analysis is always carried out with respect to a dead state or reference environment. The exergetic efficiency for the rotor has been evaluated through the use of method given by Ozgener and Ozgener (2007) and Sahin et al. (2006) which is

$$\eta_2 = \frac{P}{W_U} = \frac{P}{E\dot{x}_1 - E\dot{x}_2} \tag{8}$$

The rate of change in the exergy of the flow $E\dot{x}_1 - E\dot{x}_2$ is given as

$$E\dot{x}_1 - E\dot{x}_2 = \dot{m}\left[C_p(T_{02} - T_{01}) + T_a(C_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right) - \frac{Q_{loss}}{T_a})\right] \tag{9}$$

Where $m = {}^{\cdot}\rho AV$ and Q_{loss} the heat losses of wind turbine is given as

$$Q_{loss} = \dot{m}C_p\left(T_a - T_{Average}\right) \tag{10}$$

The average temperature $T_{Average}$ is the mean of input and output wind chill temperatures which are given by equation (5) whereas the temperature T_a is the ambient temperature at the hub height as given by equation(4)

RESULTS AND DISCUSSION

Results of the investigation are reported as the variation of first law efficiency, second law or exergy efficiency and power with variations in geometrical, ambient and aerodynamic parameters of the wind rotor. The wind rotor considered in this study has 3 blades, reference height of 10 meters, hub radius of 0.15 meters and a tip speed ratio of 5. The effect of change of control parameters was considered within ranges as specified in the table (1). These parameters, T_a, ^{V}ref and P_a, refer to the change ambient conditions prevailing in the central region of Saudi Arab.

Table 1: Values of Different Parameters of Wind Rotor

Fig. No	Variable	P_a (kPa)	T_a ^{0}C	V_{ref} m/s	h_{hub} (m)	R_{tip} (m)	α^0	Cl	Cd
1	α^0	96	10	10	50	7	0 to14	Ref[26]	Ref[26]
2	T_a	96	10 to50	10	50	7	8	0.9	0.007
3	D	96	10	10	50	14 to21	8	0.9	0.007
4	h_{hub}	96	10	10	50 to 85	7	8	0.9	0.007
5	V_{ref}	96	10	1 to 10	50	7	8	0.9	0.007
6	P_a	95 to 100	10	10	50	7	8	0.9	0.007

The variation of power produced by the wind rotor at different angles of attack with the variation of ambient temperature, figure (1) shows that the power steadily increases with the increase in angle of attack till the angle reaches 8^0, and then remains constant for a while and later decreases. Power produced decreases as the ambient temperature increases as a consequence of decrease in the mass flux through the rotor that is caused by the decrease in the mass density of air with the increase in the static ambient temperature. Figure (2) reveals the variation of variation of first law efficiency, exergy efficiency and power with angle of attack α of the aerofoil section of the wind rotor. An initial increase of these performance parameters observed up to $\alpha = 8^0$. After this value of angle of attack a decrease in all three parameters is observed. This is caused by the fact that lift coefficient fior the aerofoil section at the air speed of 10 m/s is maximum at $\alpha = 8^0$ beyond which the lift coefficient decreased . Since this value of angle of attack shows maximum value for power generated and both types of efficiencies that for variation in other parameters the value of angle of attack was fixed at $\alpha = 8^0$. The first law efficiency is seen to be higher at all values of α which is also reported by Sahin, et al. (2006), Rope, et al (2010) and Ozgener and Ozgener (2007). Figure (3) depicts the variation of energetic and exergetic efficiencies and power produced with changes in the ambient temperature. Amongst the efficiencies the exergy efficiency decreases at a faster rate than the energetic efficiency. All three variable parameters reveal a decrease in their values with the increase in the ambient temperature. This is also on the same lines as that in Ozgener and Ozgener (2007).

The decrease in the efficiencies and the power can be attributed to the decrease in the mass flux through the rotor as caused by the decrease in the density of the air due to increase in the static temperature of the ambient air. This decrease in the mass flux directly reflects as a decrease in the net output of the rotor. The decrease in wind power is not in the same proportion as the temperature governing the density near the rotor is based on wind chill temperature which is slightly higher than the ambient static temperature. Figure (4) shows the variation of energetic and exergetic efficiencies and the power with change in the diameter of the rotor. The increase in diameter causes the net mass flow increase through the rotor that increases the power output from the rotor as is depicted in the variation. But for the same increase the swept are of the rotor, $A_W = \pi R_t^2$, increases more than the flow area of the rotor that is $A_R = \pi(R_t^2 - R_h^2)$. This results in more increase in the wind power than the rotor power that results in decrease of the energetic efficiency of the rotor with increase in the diameter. A slight increase in the exergetic efficiency is observed with increase in the rotor diameter because the change in rotor diameter does not change the exergy of the wind as the increase in wind power. The effect of raising the hub height on the power produced and the efficiencies is shown in figure (5). It is visualized from the figure that both types of efficiencies and the power increase with increase in the hub height of the rotor. This increase is caused by the increase in both the velocity at the hub as the hub height increase and the decrease in the static temperature of the air that increases the density of the air. Both these effects increase the mass flux through the rotor that results in the increase in the power produced which increases the energetic and exergetic efficiency of the rotor. Figure (6) reveals the effect of wind velocity or V_{ref}. This figure show that the increase in reference velocity results in increase in both types of efficiencies and the power produced. The increase in these quantities is the result of mass flux change through the rotor and change in wind chill temperature. The increase of mass flux is experienced both by the rotor and the wind but decrease in wind chill temperature increases the density of the wind passing through the rotor. This phenomenon manifests in the increase of all the three parameters of the rotor. The change in the ambient pressure as seen in figure (7) has a little effect on power generated due to change in the density of the incoming air but it does not cause any tangible change in the energetic and the exergetic efficiencies of the wind rotor. The percentage changes in the three parameters through the change in the parameters considered in this study is tabulated in table (2). The table reveals that the power output and efficiencies of the rotor are more affected by the reference velocity, reference temperature and rotor diameter.

It may be added here that in the analysis of exergetic efficiency the reference temperature and pressure plays an important role. Usually the reference used in the literature like Ozgener and Ozgener (2007). and others the reference temperature is usually taken as 25^0C and 101.325 kPa. This reference does not work when the ambient temperature exceeds this value. The effect can be seen in figure (8). It shows the effect of reference temperature on exergetic efficiency. It can be deduced from the figure that as the ambient temperature increases to the value of reference temperature the exergetic efficiency tends to be nearly 100% which is not realistic in any sense. Further the exergetic efficiency in any case should not exceed the energetic efficiency. This dilemma is solved if the reference conditions are kept as the ambient available conditions like in this study or Baskut et al. (2010) because these conditions represent the maximum available energy that has to be harnessed by the wind rotor. Further the exergy represents the availability at a location which varies with latitude and longitude of that location. This quantity cannot be compared from place to place as availability is not the same? The application of this method to the study of Ozgener and Ozgener (2007) results in the exergetic and energetic efficiencies that looks creditable. This result is shown in figure (9) where it can be seen that energetic efficiencies at different reference velocities reach 35% and exergetic efficiencies are below 26%. Further it also shows higher efficiencies at lower reference velocities as at higher velocities the rotor cannot absorb the energy content of the medium as good as it can at lower kinetic energy levels.

Table 2: Percentage Changes in the Efficiencies and Power of Wind Rotor

Variable	Width of Change	Change in Energetic Efficiency ($\Delta\eta_1$)	Change in Exergetic Efficiency ($\Delta\eta_2$)	Change in Power ΔP (kW)
α	0^0-14^0	28%	26%	30%
T_a	10^0C-50^0C	5%	60%	25%
D	14 m to 21m	5%	0.02%	125%
h_{hub}	50 m to 85 m	0.1%	57%	56%
V_{ref}	1 m/s to 10 m/s	2%	100%	100%
P_a	95 kPa to 100 kPa	Nil	Nil	6%

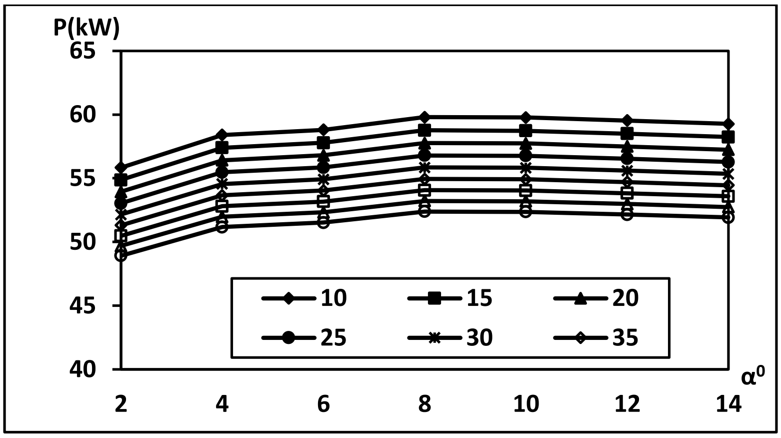

Fig (1) Variation of Power with Angle of Attack at Different Ambient Temperatures

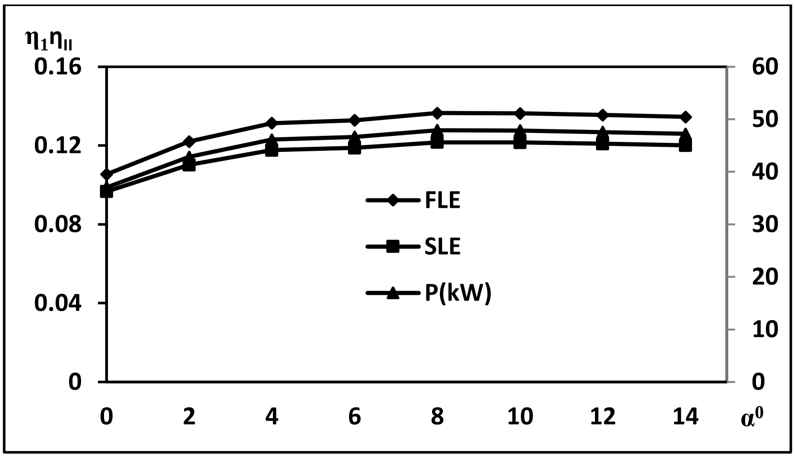

Fig (2) Variation of Power, Energetic and Exergetic Efficiency with Angle of Attack

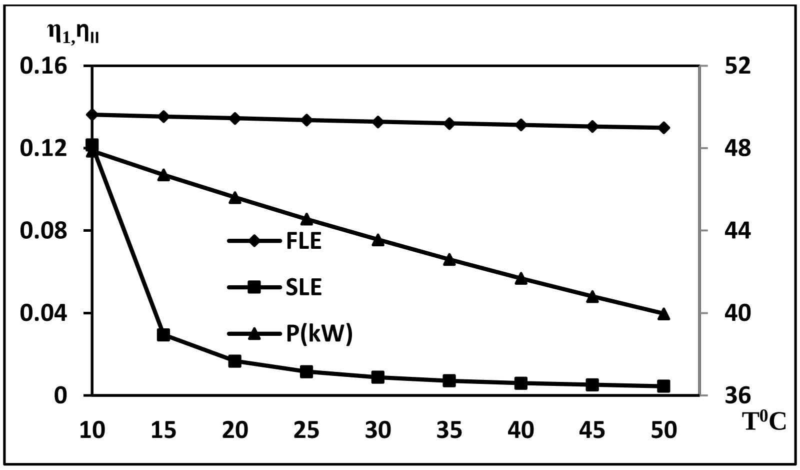

Fig (3) Variation of Power, Energetic and Exergetic Efficiency with ambient Temperature

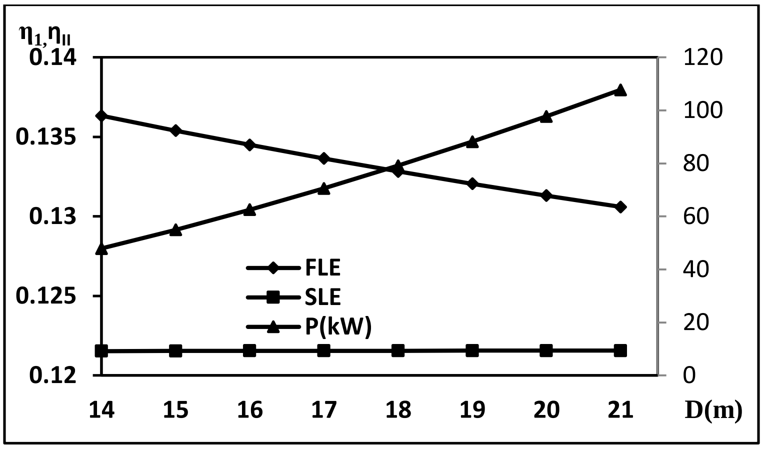

Fig (4) Variation of Power, Energetic and Exergetic Efficiency with Rotor Diameter

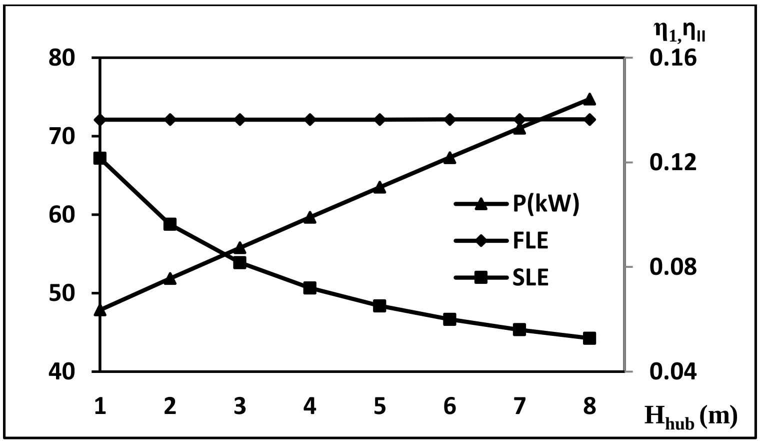

Fig (5) Variation of Power, Energetic and Exergetic Efficiency with Rotor Hub Height

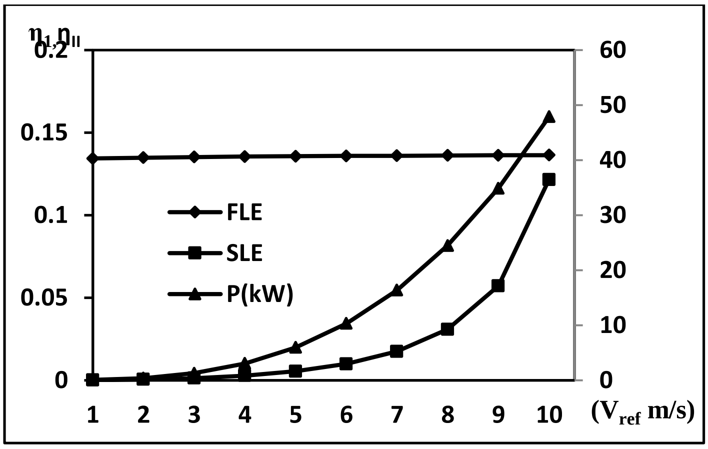

Fig (6) Variation of Power, Energetic and Exergetic Efficiency with Reference Velocity

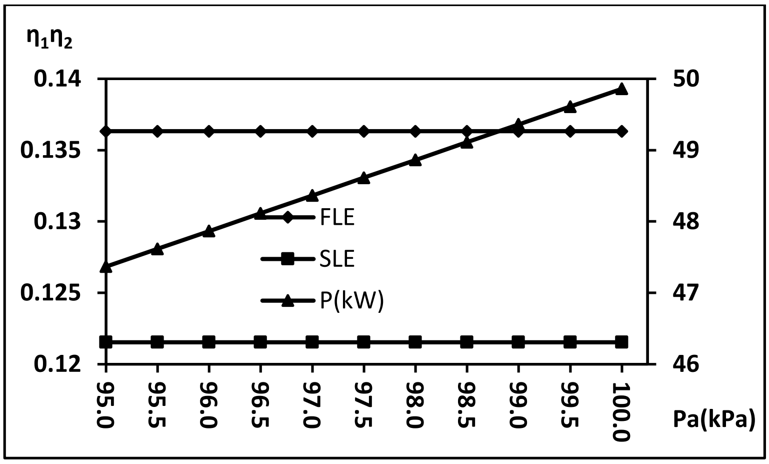

Fig (7) Variation of Power, Energetic and Exergetic Efficiency with Ambient Pressure

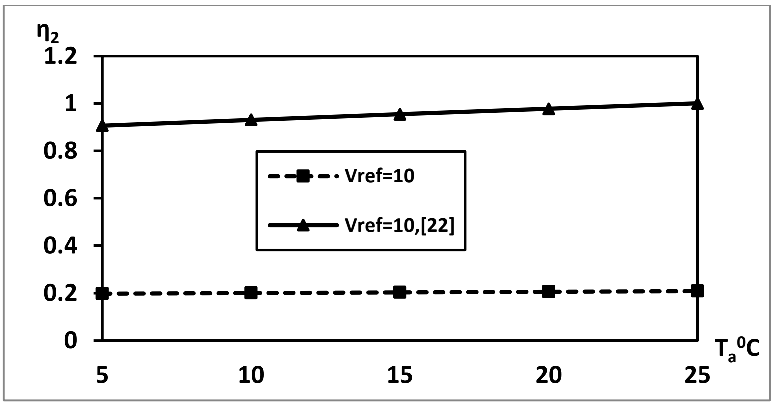

Fig (8) Effect of Reference Temperature on Energetic and Exergetic Efficiencies

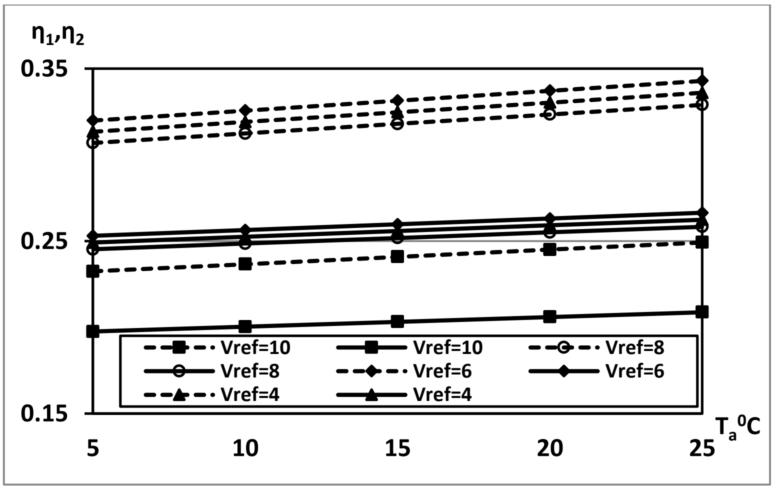

Fig (9) Variation of Energetic and Exergetic Efficiency with T_a and V_{ref} for Ref [22]

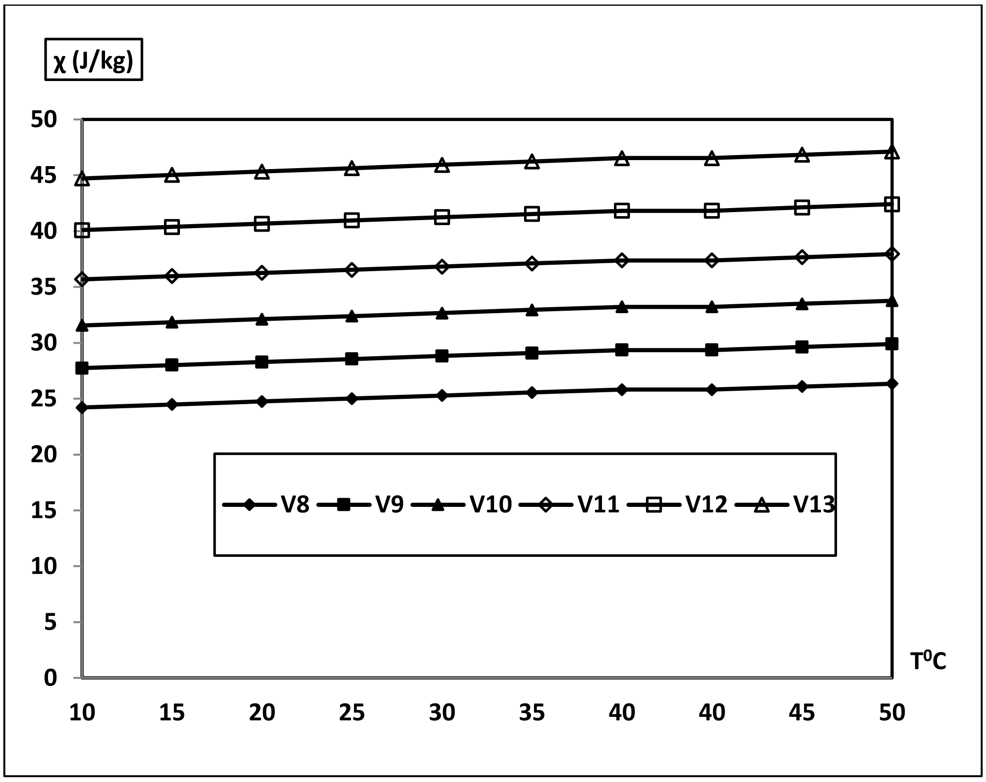

Fig (10) Variation of specific exergy destruction with ambient temperature and wind speed

CONCLUSIONS

Energetic and exergetic analysis of three bladed rotor having NACA 4424 blade profile have been carried out and effect of both aerodynamic and geometrical wind rotor parameters has been for the rotor under investigation the angle of attack of 8^0 is best suited with in the wind speed range considered. Energetic efficiency is mostly affected by the angle of attack of the rotor. Wind rotor diameter and ambient pressure has negligible effect of exergetic efficiency. The power produced is least effected by ambient atmospheric pressure. Energetic and exergetic efficiencies are not affected by the change in atmospheric pressure. The reference temperature to be used in the exergy analysis should be the local ambient temperature rather than 25^0C as normally used.

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NOMENCLATURE:

a	Temperature coefficient for height (^{0}C/m)
A_R	Flow area of rotor (m^2)
A_W	Swept area of rotor (m^2)
Cd	Drag coefficient for aerofoil of wind rotor
Cl	Lift coefficient of aerofoil of wind rotor
C_P	Power coefficient of Rotor
Cp	Specific heat ratio of air

D	Diameter of rotor (m)
E_x	Exergy of the wind
FLE	First law efficiency
H	Height of rotor (m)
H_{ref}	Reference height for measurement (m/s)
n	Velocity height exponent (0.28)
P	Power (kW)
Pa	Ambient pressure (kPa)
P_W	Wind power (kW)
R	Gas constant of air(kJ/kg-K)
R_t	Tip radius of the rotor (m)
R_h	Hub radius of the rotor (m)
SLE	Second law efficiency
T_a	ambient temperature of air (^{0}C)
T_{ref}	Temperature at reference height (^{0}C)
T_w	Wind Chill temperature (^{0}F)
V_R	Velocity of air across rotor (m/s)
V_{hub}	Velocity at the hub of the rotor (m/s)
V_{ref}	Velocity of wind at reference height (m/s)
V_W	Free stream wind velocity at reference height
W_U	Useful work (kJ)
Z	Number of rotor blades
α	Angle of attack of rotor aerofoil (^{0})
η_1	Energetic efficiency of the rotor
η_2	Exergetic efficiency of the rotor
λ	Tip speed ratio of wind rotor
ρ_R	Density of air at rotor (kg/m^3)
ρ_W	Density of wind (kg/m^3)
$\Delta\eta_1$	Change in energetic efficiency

$\Delta\eta_2$	Change in exergetic efficiency
ΔP	Change in rotor power (kW)
1	Upstream of rotor
2	Downstream of rotor