International Journal of Energy and Environmental Engineering
ISSN: 2008-9163 e ISSN:2251-6832
Vol. 2 / No.4 (pp.33-44) / Fall 2011

Compressed air energy storage system based engine for running light vehicle

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Received: 26 July. 2011 Accepted: 31 Oct. 2011

ABSTRACT

Globally excessive consumption of hydrocarbon fuel in transport sector is a serious threat to the civilization due to the paucity of fuel in future. Also this growing use of vehicles for transport is contributing about 70% of total air pollution and causing environmental and ecological imbalances. Thus the worldwide fast depletion of conventional energy resources and impact of emissions on environment necessitates the search of alternative non-conventional energy sources, and other direct energy conversion systems. This paper deals with the study of sustainable renewable energy resources and their conversion system. Air has been considered as a sustainable renewable energy resource and an emission free compressed air driven engine has been analyzed for better and sustainable energy future in this paper. Here parametric study of a vane type novel air turbine is carried out for arriving at optimal turbine specifications and operating conditions. The optimum power output obtained ranges from: 1.0 kW, 4.0 kW and 9.0 kW at D= 50 mm, 100 mm and 150 mm respectively, when rotor/ casing ratio $(d/D) = 0.70$, vane angle (θ) is kept 30^o to 45^o (vanes =12 to 8 nos.), and other parameters such as: injection angle (60^o), injection pressure (6 bar) and speed of rotation (2500rpm) are kept constant throughout the study.

Keywords

fossil fuel, pollution, emission, depletion, energy source, energy conversion.

1. Introduction

Worldwide depletion of conventional energy resources [1, 2], is necessitaes the search of alternatives resources such as: non- conventional and renewable energy sources, for sustainable future energy sources. India is a develoing country and average income per person is very low to meet out the minimum requirement of person. Maximum population of country is still living in villages where transport is either bicycle or motorbike. Current hike rate of fossil fuel prices up to 30-40 % every year has made the situation alarming. With this pace by 2010 prices may go double than what is today and by 2030-40, it may touch to Rs.1000 per litre. A time will come when common person would not be able to purchase fuel to run the motorbike. It is not only due to rate of increase of vehicles in India, but it is a worldwide problem as 80 % of fossil fuel being consumed in transport with increasing mobility of persons and transportation of daily consumable materials through road transport. Thus, the need of the day is to explore possibility of alternatives for fossil fuel to make environment free from emission and make children healthy**.**

It is also seen that researches were carried out on multi vane expander for its various parameters such as: geometry, end friction, optimizing the efficiency [3-12] and pneumatic hybrid power system [13-16]. The work of pressure regulation of turbine, performance efficiency of Rankine

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cycle, multi-stage turbine compressor models, experimental investigation on rotary vane expander, three-stage expander into a CO^2 refrigeration system, endface friction of the revolving vane mechanism, and design and implementation of an air-powered motorcycle have also been studied [17-23].This paper deals with study of renewable/non-conventional energy to maintain energy sustainability in 21st century and utilizing compressed air as an attractive alternative for the development of emission free engine, which can lead to better future both environmentally and ecologically. For this a compressed air driven novel air turbine has been considered and parametric evaluation done for arriving at optimal specifications of casing to rotor dimensions and operating conditions.

2. Literature Revie8w

In general terminology, sustainability can be stated as; meeting the needs of current and future mankind/generations through simultaneous environmental, social and economic improvements [24], whereas sustainability of the energy resource is to preserve the oil and make brighter future of mankind by adding alternative energy sources such as: non-conventional and or renewable energy which is going to help current problem to some extent. Now worldwide researchers/inventors are paying full attention towards this issue. It is also learnt that there are two distinct reasons for search of alternative to fossil fuel and make sustainable energy source; the first one is depletion of oil resources which is causing civilization vulnerable, thereby many researchers, technologists and scientist have spoken [25, 26] as to why alternative to fossil fuel is required and other one is higher rate of emission due to rapid use of hydrocarbon fuel.

The study on efforts made for reducing the pollution have also been done related to duel fuel systems such as: effect of exhaust gas recirculation (EGR) on combustion and pollution of dual fuel engines [27], partial substitution of diesel fuel by natural gas [28], using for maldehyde as an additive on the performance of an homogenous charge compression ignition (HCCI) engine fueled with natural gas [29].

2.1 Alternatives to Energy Resources

Many researches are being carried out to find the alternative to fossil fuel. Apart from them non-conventional energy such as windmill operated devices, bio-diesel and di-methyl ether, hydrogen cell, photovoltaic cell, battery operated vehicles are being used as an alternative to fossil fuel.

2.1.1 Use of Wind Energy**:** Windmills are being used very effectively for irrigation as well as power generation, where high velocity air is running in atmosphere, due to geological conditions. Wind power is the kinetic energy of wind, or the extraction of this energy by wind turbines. In 2004, wind farm power became the least expensive form of new power generation, dipping below the cost per kilowatt-hour of coal-fired plants. Wind power is growing faster than any other form of electrical generation, at about 37%, up from 25% growth in 2002. In the late-1990s, the cost of wind power was about five times than its cost in 2005. The downward trend is expected to continue due to mass production of multi-megawatt turbines.

2.2 Energy Conversion and Storage Systems

There are many energy conversion systems which are in practice for utilizing energy whenever there is a disruption in regular supply, which is listed [30] as follows:

2.2.1 Super Capacitor: Electrochemical capacitors (EC) store electrical energy in the two series capacitors of the electric double layer (EDL), which is formed between each of the electrodes and the electrolyte ions. The distance over which the charge separation occurs is just a few angstroms. The capacitance and energy density of these devices is thousands of times larger than than electrolytic capacitors. The asymmetrical capacitors that use metal for one of the electrodes have a significantly larger energy density than the symmetric ones and have lower leakage currentelectrolytic capacitors. The asymmetrical capacitors that use metal for one of the electrodes have a significantly larger energy density than the symmetric ones and have lower leakage current.

2.2.2 Flywheels: Most modern flywheel energy storage systems consist of a massive rotating cylinder (comprised of a rim attached to a shaft) that is substantially supported on a stator by magnetically levitated bearings that eliminate bearing wear and increase system life. To maintain efficiency, the flywheel system is operated in a low vacuum environment to reduce drag. The flywheel is connected to a motor / generator mounted onto the stator that, through some power electronics interact with the utility grid. Some of the key features of flywheels are little maintenance, long life (20 years or 10s of thousands of deep cycles) and environmentally inert material. The stored energy can be approximated by:

$$E = (I\omega^2)/2 = (mr^2\omega^2)/2 = (mv^2)/2$$

where ω is the rotational velocity (rad /sec), I is the moment of inertia for the thin rim cylinder, m is the cylinder mass and v is linear rim velocity.

2.2.3 Compressed Air Storage System: The air engine technology is very old and was in process of development parallel to combustion technology. It is on record that Sterling air engine was developed in 1790-1810, but due to some limitations much work was not carried out. The uses of such engines are limited such as in Coalmines where fire problem are predominant and other high flammable places where fossil fuel vehicles are not advisable to be utilized. The technology again took its rolling pace in 1979 when cost of petroleum product had gone very high, but from 1979 to 1998 much work did not take place. Since the last two decades lot of researches are being made to tap down air freely available in atmosphere and compressing it for storage in cylinders for its further use. This compressed air can be used to run combustion engine with mixture of gas and air getting fired at compression stroke at TDC. Compressed air helps for fire stroke when ignition takes place. Thus efficiency of IC engine gets improved and without running all four stroke cycle it runs on two stroke cycles. The air engines so far developed are basically running on hybrid such as compressed air and gases and are not 100% zero pollution.

3. Compressed air as an alternative to fossil fuel

Compressed air can be suitably used as working fluid for running air engines and has many advantages being emission free and environment friendly.

3.1 Availability of Air

Air is natural source and available freely in atmosphere, which can be stored after compressing it to desired pressure such as 90- 350 psi.This is the only source, which can be stored at very high pressure and can be retained without any loss after lapse or with passage of time. Compressed air can drive many domestic appliances such as vacuum cleaner, mixers, pumps, electric generator when electric power fails instead of using inverter to have clumsy arrangements of battery, etc.

3.2 Sustainability, Economics and Advantages

Compressed air is most sustainable. It has no volatility or temperature or much weather effect. Once compressed air is stored through compressor, it will be available at any time without any loss of pressure. Thus sustainability of compressed air is much better compared to other available alternate of fossil fuel. Battery needs constant maintenance even for charging and discharging cycle. Hydrogen Cell is very costly due to its storage problems. Wind Mills, Photo Cells also need some storage devices may be of high bank capacitors or batteries, which will need constant and recurring expenditures on its upkeep.

3.3 Influences on Environment and Ecology

Compressed air as an alternate for running light vehicles using air turbine will have no ill effect on ecology and reduce the health hazards due to the vehicles. Emissions at the power plants generating electricity required for running compressors to get compressed air can be suitably controlled. Thus overall pollution due to these compressed air vehicles will be less than existing fossil fuel-based systems.

3.4 Cost Comparison

In case the compressed air is being used in place of fossil fuel, the air is freely available in atmosphere and offers zero cost of basic working fluid and the cost involvement in its compression is also nominal. The costing analysis for the vaned air turbine based engine under study is as-detailed below;

- Cost of 10 to 15 HP electric motor coupled with 2-3 stage compressors: Rs. 25,000.00
- Cost of electricity for filling the compressed air cylinder once*: Rs. 5.00 to Rs. 7.00
- Consumption of electric power for running it for 5-10** min to fill the cylinder of 1.2 m long and 0.65 m dia at 15-20 bar (225 – 300 psi) may cost {(10 kwh X Rs 4.00# to 5.00#).(60 min / 8 min**average) = (Rs.5.00 to 7.00} including depreciation, running and maintenance of compressor devices.

  # - Cost of electricity per unit in Rupees]
- Once cylinder is filled with compressed air, it can run vehicle up to 40 km.
- Cost of running vehicle per km using compressed air: Re. 0.12 to Rs. 0.17
- The present cost of running vehicle per km using hydrocarbon fuel : Re. 0.62 to Rs. 0.75

This shows that the motor bike may run 40 km in Rs.5.00 to Rs. 7.00, whereas cost of same travel distance with hydrocarbon fuel may be around Rs. 25.00 to Rs.30.00 and hence compressed air cost is almost one fifth of fossil fuel cost. On the other hand, in the absence of fossil fuel combustion, air as working fluid offers advantage of giving zero pollution engines. Thus the use of compressed air is economical too apart from being environmental friendly.

3.5 Advantages/Disadvantages of Air Engine Compared to the Electric Motors

Air engines are having much of advantages as compared to the electric motors such as: it can easily be used in volatile atmospheres, deliver more power that of same size of electric motor, operate without any type of auxiliary speed reducers, cause no harm on overloads, torque produced is controlled by simple flow control by means of valves by regulating the pressure, generate very less heat. The only drawback is noticed that the torque produced by the air engines suffers in a great way; when the flow of air or the pressure gets disturbed.

4. Development of compressed air engine

There is need of devising an efficient compressed air engine so that maximum specific power could be produced. Such compressed air engine will have requirement of compressors for producing compressed air as working fluid. Thus there are two issues, one for developing an efficient compressed air engine and other one to have efficient compressor and air storage system. In this area development of air engines are being made very fast. Some of the works developed so far are given as bellow:

- A French Scientist Guy Negre, in 1998 developed compressed air 4- cylinders engine run on air and gasoline, claims zero pollution cars and got 52 - patents registered since 1998 to 2004. The car was publically demonstrated in Oct.'2004 [31].
- A Canadian inventor G. Saint-Hilaire, developed zero pollution cars using Quasiturbine with a set of 14-engines parameters and disclosed on Sept' 2005 using gasoline [32].
- Indian duo Scientists studied the various aspects of efficiency improvements of wind turbine, tip speed ratio etc.[33-36] and developed an air turbine engine in 2010, which can be utilized as prime-mover to light vehicle or motor-bike efficiently[37-45] on the high pressure of compressed air as driving force at ambient temperature. The impulse and dynamic action of high pressure are responsible for the shaft work from air turbine.

4.1 Air Turbine and its Mathematical Model

A vaned type air turbine as shown in Figs. 1 and 2 has been considered. Air turbine is considered to work on the reverse of working principle of vane type compressor.

In this arrangement total shaft work is cumulative effect of isobaric admission of compressed air jet on vanes and the adiabatic expansion of high pressure air. In an earlier study conducted by authors a prototype of air turbine was developed and its functionality was ensured. Vanes of novel air turbine were placed under spring loading to maintain their regular contact with the casing wall to minimize leakage. The present objecttive is to investigate the performance of an air turbine with the variation of rotor/casing dimensions. The air turbine considered has capability toyield output of 5.50 to 6.80 HP at 4-6 bar air pressure and for speed of 2000–2500 rpm, which is suitable for a motorbike. A cylinder for the storage of compressed air with a minimum capacity of storing air for the requirement of 30 min running at initial stage and maximum pressure of 20 bar is used as a source of compressed air.

The mathematical model shown here is already presented in author's earlier publication [46] which is now reproduced here for maintaining the continuity and benefits to the readers. The high pressure jet of air at ambient temperature drives the rotor in novel air turbine due to both isobaric admission and adiabatic expansion. The compressed air when enters through the inlet passage, pushes the vane for producing rotational movement and thereafter air so collected between two consecutive vanes of the rotor is gradually expanded up to exit passage, also contributes to the shaft out. This isobaric admission and adiabatic expansion of high pressure air both produces the total shaft power output from air turbine. Compressed air leaving the air turbine after expansion is sent out from the exit passage. Since scavenging of the rotor is perfect, thus the work involved in recompression of the residual air is absent.

From Figure 3, it is seen that work output is due to isobaric admission (E to 1), adiabatic expansion (1 to 4) and steady exit flow work (4 to 5). Thus, total work donedue to thermodynamic process may be written as:

[Area under (E145CE)] = [Area under (E1BOE) +Area under (14AB1) – Area under (4AOD4) + Steady Flow (45CD4)]

Total Work output = [Thermodynamic expansion work (w_1)] + [Exit steady flow work (w_2)]

$$[(w_1)(w_2)\} \quad (1)$$

From the above equation (1) thermodynamic expansion work can be written as:

$$w_1 = p_1.v_1 + \left(\frac{p_1.v_1 - p_4.v_4}{\gamma - 1}\right) - p_4.v_4 \quad \text{or}$$

$$w_1 = \left[\left(\frac{\gamma}{\gamma - 1}\right).(p_1.v_1 - p_4.v_4)\right] \quad (2)$$

From the above equation (1) steady flow work can be written as

$$w_2 = \int_4^5 v.dp = (p.v_4 - p_5.v_5) \quad (3)$$

After the expansion process during exit flow the pressure p_4 cannot fall below atmospheric pressure p_5 . Thus, from equation (1) the work output will be:

$$w = (w_1 + w_2) = \left(\frac{\gamma}{\gamma-1}\right).p_1.v_1.\left\{1 - \left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\} + (p_4 - p_5).v_4 \quad (4)$$

When air turbine is having *n* number of vanes, then shaft output [**47**] can be written as,

Applying values of v_1 and v_4 to equation (4)**,** the total power output available W_{total} , can be written as:

$$W_{total} = n.(N/60).\left(\frac{\gamma}{\gamma-1}\right).\left\{1 - \left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\} p_1.\left[L.\left\{\frac{(X_{1min} + X_{2min}).(2r + X_{1min})}{4}\right\}.\sin\theta\right]$$
$$+ n.(N/60).(p_4 - p_5).\left[L.\left\{\frac{(X_{1max} + X_{2max}).(2r + X_{1max})}{4}\right\}.\sin\theta\right] \quad (5)$$

Where

$$X_{1min} = R.cos\left[\sin^{-1}\left\{\left(\frac{R-r}{R}\right).\sin(180 - \theta - \phi)\right\}\right] + \left[(R-r).\cos(180 - \theta - \phi) - r\right]$$

$$X_{2min} = R.cos\left[\sin^{-1}\left\{\left(\frac{R-r}{R}\right).\sin(180 - \phi)\right\}\right] + \left[(R-r).\cos(180 - \phi) - r\right]$$

$$X_{1max} = (D - d) = 2(R - r),$$

and $X_{2max} = R.cos\left[\sin^{-1}\left\{\left(\frac{R-r}{R}\right).\sin\theta\right\}\right] + \{(R-r).\cos\theta\} - r$

4.2 Assumptions of Input Parameter

Detailed analysis of varying injection angles was carried out in earlier publications for expansion work, flow work, percentage contribution of expansion and flow work and total works at different injection pressure 2- 6 bar and different speed of rotation 500-2500 rpm. The contribution of total expansion work was found large when injection angle of air turbine is kept above 30^o and found maximum when it is 60^o, at constant: vane angle= 45^o (i.e. 8 vanes), injection pressure= 6 bar and speed of rotation=2500 rpm.

In this study various input parameters are listed in Table 1 for investigation of for larger shaft output at different rotor to casing diameter ratios (*d/D*) with respect to different vane angles when casing diameter (*D*) is kept 50mm, 100 mm and 150mm, injection pressure= 6 bar (90 psi), injection angle=60^o and speed of rotation=2500 rpm.

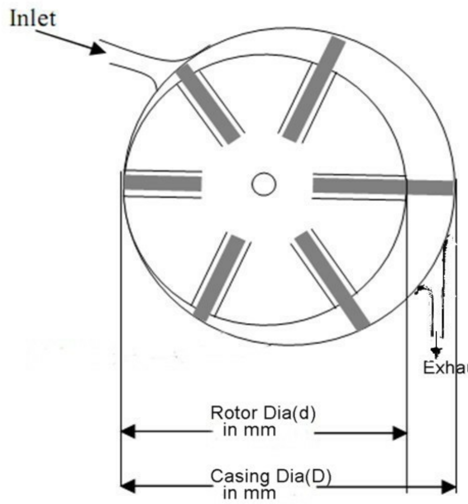

Fig.1 Air Turbine-Schematic Drawing

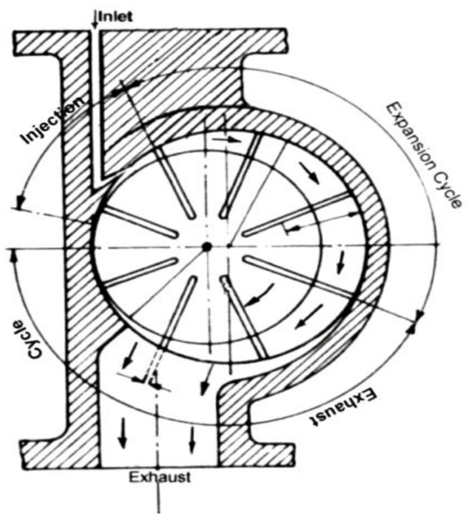

Fig.2 Air Turbine- Mode

4.3 Results and Discussion

Based on the various input parameters listed in Table1 and using mathematical model, the effects of different rotor to casing diameters ratios with respect to different vane angles at speed of rotation 2500 rpm and injection pressure 6 bar, the total power outputs obtained from air turbine are studied and compared considering casing diameter as D=50 mm, 100 mm and 150 mm. Here the injection angle ϕ of the air turbine is considered to be constant at 60^o as it was found to develop optimum shaft output in earlier studies. The results obtained have been plotted in Fig. 4, 5 and 6 for the rotor to casing diameter ratio (*d/D*)= 0.70 at different vane angles of 30^o, 36^o, 45^o, 60^o, 90^o and at constant injection angle of 60^o and injection pressures of 6 bar (90 psi) at the speed of rotation 2500 rpm. Fig. 7 shows the comparative results.

Case 1: Power output (Wt), when D=50 mm

Fig 4 shows that the total power from air turbine becomes large, for a particular vane angle and for different range of rotor/casing diameter ratio when injection pressure is 6 bar, speed of rotation is 2500 rpm, and it ranges from:

- 0.19 kW- 0.72 kW, when rotor to casing diameter ratios are of 0.95-0.80 and vane angle is kept 30^o (vanes 12 nos.) and
- 0.87 kW- 1.0 kW, when rotor to casing diameter ratios are of 0.75-0.70 and vane angle is kept 36^o (vanes nos. 10)

Case 2: Power output (Wt), when D=100 mm

Fig 5 shows that the total output power from

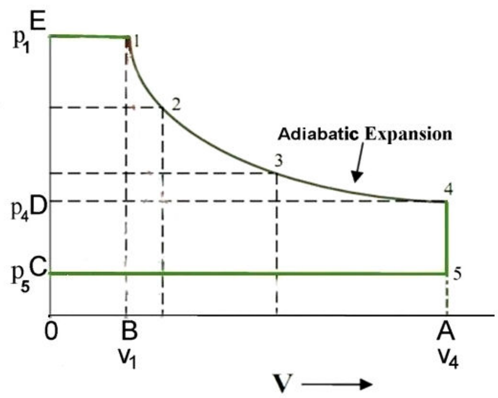

Fig. 3 Thermodynamic Processes (Isobaric, adiabatic and Isochoric Expansion)

the air turbine becomes maximum for a par ticular vane angle and for different range of rotor/casing diameter ratio when injection pressure is 6 bar, speed of rotation is 2500 rpm, and it ranges from 0.8 kW- 2.9 kW, when rotor to casing diameter ratios are of 0.95-0.80 and vane angle is kept 30^o (vanes nos. 12).and 3.5 kW- 4.0 kW, when rotor to casing diameter ratios are of 0.75-0.70 and vane angle is kept 36^o (vanes nos. 10)

Case 3: Power output (Wt), when D=150 mm

Fig 6 shows that the total output power from the air turbine becomes maximum for a particular vane angle and for different range of rotor/casing diameter ratio when injection pressure is 6 bar, speed of rotation is 2500 rpm, and it ranges from:

- 1.9 kW- 6.5 kW, when rotor to casing diameter ratios are of 0.95-0.80 and vane angle is kept 30^o (vanes nos. 12). and
- 7.8 kW- 9.0 kW, when rotor to casing diame
- ter ratios are of 0.75-0.70 and vane angle is kept 36^o (vanes nos. 10)

Case 4: Comparison of Power output (Wt), when D=50 mm, 100mm and 150mm

Fig 7 shows that the total power output is seen maximum for a particular rotor / casing size and varies as: 1.0 kW, 4.0 kW and 9.0 kW at *D*= 50 mm, 100 mm and 150 mm respectively when (*d/D*) = 0.70, and vane angle (θ) is kept 30^o-45^o (vane numbers=12-8)

Table 1: Input Parameters

Symbols	Parameters
d/D ratio	0.70 when casing diameter is kept *D*=50 mm, 100 mm, and 150 mm
p_1	6 bar (=90 psi)
p_4	$(v_1 / v_4)^{\gamma} . p_1 > p_5$ assuming adiabatic expansion
p_5	$(p_4 / 1.2)$ >1.0132 bar (atmospheric pressure)
θ	30^o, 36^o, 45^o, 60^o, 90^o (i.e. rotor contains correspondingly 12, 10, 8, 6, 4 number of vanes)
N	2500 rpm (as total power is directly proportion to rpm)
L	45 mm length of rotor
γ	1.4 for air
n	Number of vanes = (360 / θ)
ϕ	60^o angle at which compressed air enters through nozzle into rotor

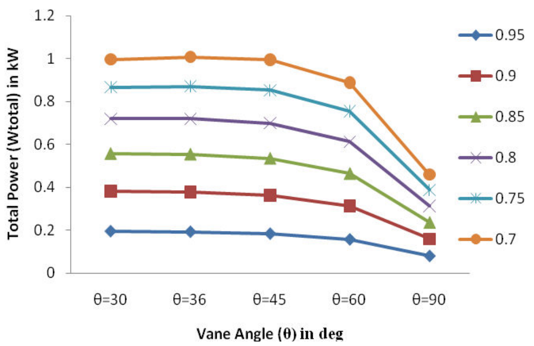

Fig.4: Total power output (*Wt*) versus different Rotor / Casing ratio at different vane angle when *D*=50 mm

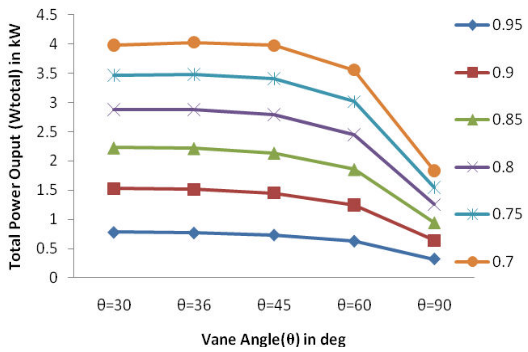

Fig.5: Total power output (*Wt*) versus different Rotor / Casing ratio at different vane angle when *D*=100 mm

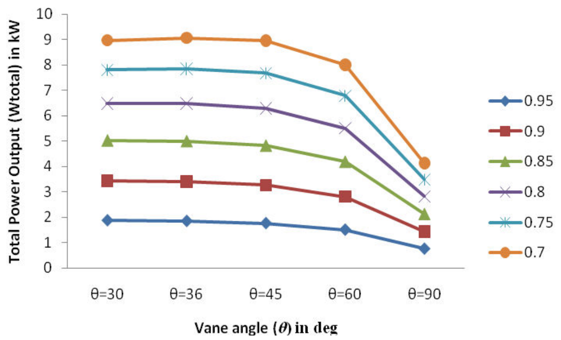

Fig.6: Total power output (*Wt*) versus different Rotor / Casing ratio at different vane angle when *D*=150 mm

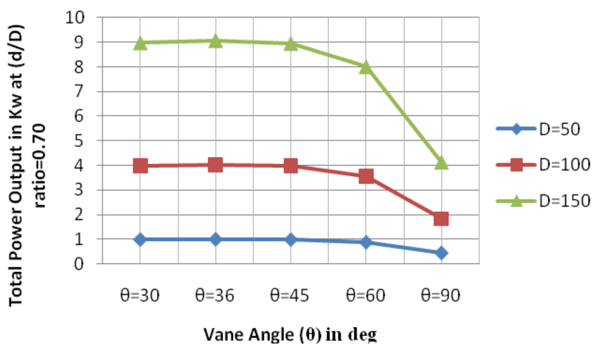

Fig.7: Total power output (*Wt*) versus vane angles when rotor / casing diameter (*d/D*) ratio is 0.70 when *D*=50 mm, 100 mm, and 150 mm

5. Conclusions

In view of fast depleting fossil fuel reserves and growing energy requirements, compressed air storage system has immense potential to be utilized as an alternative to fossil fuel. From the present study, the following conclusions are drawn:

- The atmospheric air having enormous reserves as working fluid could reduce the tail pipe emission and resolve the environmental and ecological problems to a large extent.
- Compressed air driven engines will offer an attractive alternative to meet the forthcoming fossil fuel crisis.
- The total output power from the novel air turbine under theoretical considerations is seen to be maximum for the higher injection air pressure and there exists an optimum value of rotor/casing diameter ratio for injection pressure 6 bar, speed of rotation 2500 rpm and at particular vane angles and it ranges from: 1.0 kW,4.0 kW and 9.0 kW at *(d/D) = 0.70* at *D*= 50 mm, 100 mm and 150 mm respectively when vane angle (θ) is kept 36^o (vane number 10).

Thus optimum shaft power output of a novel vaned type air turbine is obtained when the design parameters for rotor diameter to casing diameter (*d/D*) ratios is kept between 0.70 to 0.75 and vane angle is 30-45^o (i.e. rotor vane numbers 12 - 8), which develops desired shaft output for a particular size of vane turbine. Such air turbine is suitable for running light vehicle / motorbike and found cost effective, develops 75-97% performance efficiency of converted / stored energy and releases zero emission as compared to fossil fuel energy resources.

Nomenclature

d	diameter of rotor (*2r*) in meter
D	diameter of outer (*2R*) cylinder in meter
L	length of rotor having vanes in meter
n	no. of vanes=(360/*θ*)
N	no. of revolution per minute
p_1, v_1	pressure (in bar) and volume (in m^3) respectively at which air strike the Turbine,
p_4, v_4	pressure (in bar) and volume (in m^3) respectively at maximum expansion of air
p_5	pressure (in bar) at which turbine releases the air to atmosphere.
v	volume in in m^3
w	theoretical work output in Nm
W	theoretical power output (Nm/s)
X_{1i}	variable extended lengths of vane at point 1 in metre

X_{2i} variable extended lengths of vane at point 2 in metre

Subscripts

$_{1, 2...4, 5}$	subscripts – Indicates the positions of vanes in casing.
e, exp	expansion
f, flow	flow
min	minimum
max	maximum
t, total	total

Greek symbols

α	angle BOF
α_1	angle LOF (=180-ϕ)
α_2	angle KOF (=180-θ-ϕ)
β	angle BAF
γ	1.4 for air
θ	angle between 2-vanes(BOH)
ϕ	angle at which compressed air enters into rotor through nozzle

Acknowledgments

The Authors would like to express thanks to the Management of School of Management Sciences, Technical Campus, Lucknow and Harcourt Butler Technological Institute, Kanpur for their support to avail facilities of Library and Laboratories.

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