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A Future Technology of Automobile Engine That Runs on Compressed Air as a Fuel

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ABSTRACT : *Heavily release of tail pipe emissions is the biggest challenge to 21st Century developments, causing serious threat to Global Warming. Worldwide fast utilizations of transport sector alone releases billion tones of excessive carbon dioxide in the atmosphere through tail pipe emissions. It is also leading to fast depletion of hydrocarbon fuel. On account of such challenges, continued researches are being carried out to supplement the energy by renewable resources and alternate energy to sustain hydrocarbon fuel. Now a days the major thrusts are being opted for utilization of wind energy, hydro-power, tidal and nuclear power generation. Simultaneously efforts are also made towards storage of the energy and appropriate conversion system and its better utilization. This paper focuses on study of energy storage and its re-utilization systems. at appropriate period of time. In this, a special focus is laid upon use of compressed atmospheric air as a viable alternative energy source. Such energy sources are preferred to be used as clean and zero pollution energy source that can help in mitigating the global warming.*

Keywords - *zero pollution, compressed air, air turbine, energy conversion, energy storage, injection angle*

I. INTRODUCTION

Worldwide huge demand of vehicles is resulting into a rapid consumption of fossil fuels and causing fast depletion of the energy resources. A noted geophysicist Marion King Hubbert [**1**] applied the Principles of Geology, Physics and Mathematics in 1956 for the future projection of oil production from the US reserve base. Hubbert indicated that, conventional crude-oil production would attain Peak Oil in 1970 and thereafter start depleting. This may cause serious threat to mankind within 40 years i.e. by 1995. This will also affect environment due to release of huge amount of pollutants in the atmosphere. Aleklett K. and Campbell C.J., [**2**] indicated in 2003 that, the world is depleting its resources of oil and gas at such a rate that this oil production is set to a peak and begins to decline by around 2010.

In India, vehicular pollution was estimated to have increased eight times over the earlier two decades. This source alone was estimated to contribute about 70 per cent of total air pollution. With 243.3 million tonnes of carbon released from the consumption and combustion of fossil fuels in 1999, India is ranked fifth in the world behind the U.S., China, Russia and Japan. India's contribution to world carbon emissions has increased many folds, due to the rapid pace of urbanization, shift from non-commercial to commercial fuels, increased vehicular usage and continued use of older and more inefficient coal-fired and fuel power-plants.

The release of billion tonnes of carbon dioxide and other pollutants, and their implications upon the environment and ecology are compelling force to search for an environment friendly alternative to oil. Such an alternative should ideally have a zero or near zero pollution level, low initial cost and running expenses, high degree of reliability, convenience and its versatility of utilizations. The use of compressed air for running prime mover like air turbines / engines offers a potential solution to these issues, which does not involve combustion process for producing shaft work. Thus the great advantages in terms of free of cost availability of air as a fuel and no emissions such as; carbon dioxide, carbon monoxide and nitrous oxides etc., are apparent from such air driven prime movers. Compressed air driven prime movers are also found to be cost effective compared to fossil fuel driven engines. It has perennial compressed air requirement which needs some source of energy for running compressor. The overall analysis shows that the compressed air system is quite attractive option for light vehicle applications as well as wind turbine farm for clean energy storage and it's availability at the time of peak hour power requirement and improvement of thermal power generation efficiency by storage of compressed air energy at non-peak hour and use of such clean energy at peak hours.

A study was carried about vehicles populations in the developing countries like: India, China, Taiwan etc. In India the data for transport vehicles registered from 1951 to 2004 is shown in **Table 1**.

Table No. 1

Total Number of Registered Motor Vehicles in India - 1951-2004 (In thousands)

Year (As on 31st March)	All Vehicles	Two Wheelers	Cars, Jeeps and Taxis	Buses	Goods Vehicles	Others*
1	2	3	4	5	6	7
1951	306	27	159	34	82	4
1956	426	41	203	47	119	16
1961	665	88	310	57	168	42
1966	1099	226	456	73	259	85
1971	1865	576	682	94	343	170
1976	2700	1057	779	115	351	398
1981	5391	2618	1160	162	554	897
1986	10577	6245	1780	227	863	1462
1991	21374	14200	2954	331	1356	2533
1996	33786	23252	4204	449	2031	3850
1997	37332	25729	4672	484	2343	4104
1998	41368	28642	5138	538	@ 2536	4514
1999	44875	31328	5556	540	@ 2554	4897
2000	48857	34118	6143	562	@ 2715	5319
2001	54991	38556	7058	634	@ 2948	5795
2002	58924	41581	7613	635	@ 2974	6121
2003(R)	67007	47519	8599	721	@ 3492	6676
2004 (P)	72718	51922	9451	768	@ 3749	6828

Note:

*: Others include tractors, trailers, three wheelers (passenger vehicles) and other miscellaneous vehicles which are not separately classified.

@: Includes Omni buses, (P): Provisional and (R): Revised

This data shows that in 2004, the percentage of population of two wheelers as shown in Fig. 1, in respect to the total vehicles was around 70-75%, whereas from the recent report, total vehicle's population in Uttar Pradesh, that largest State of India is around 10.5 million, out of which 8.2 million is only two wheeled (Source: Dainik Jagran- Jan' 2011). Thus the percentage of two wheelers has increased from 70% to 82% within 6 years. On other hand, globally transport sector alone is consuming huge quantity of hydrocarbon fuel and releasing about 77.8 percentage of air pollutants in the atmosphere. Recent study also indicates that in the developing countries like India, China, Taiwan etc., 80 percentage pollutants are generated by the motorbikes/two wheelers driven by internal combustion (IC) engines. As transport vehicles are major contributors to tail- pipe emission, generating around 77.8% air pollutants such as: Carbon Monoxide (CO), Carbon Dioxide (CO2) and unburned Hydrocarbon (HC). Thus the motorbikes/ two wheelers are contributing 50-60% air pollutants in the atmosphere and is a major player for global warming. This study also confirms that two wheelers / motorbike's IC engines are generating more than double the pollutants as compared to the remaining automobiles / transport vehicles.

In order to reduce the emission and eliminate 50- 60% of the exhausting pollutants, this paper presents a new concept of an air engine using compressed air as the potential power source to run motorbikes in place of using IC engines. Such motorbikes are proposed to be equipped with compressed air engines that transform the compressed air stored energy into mechanical work.

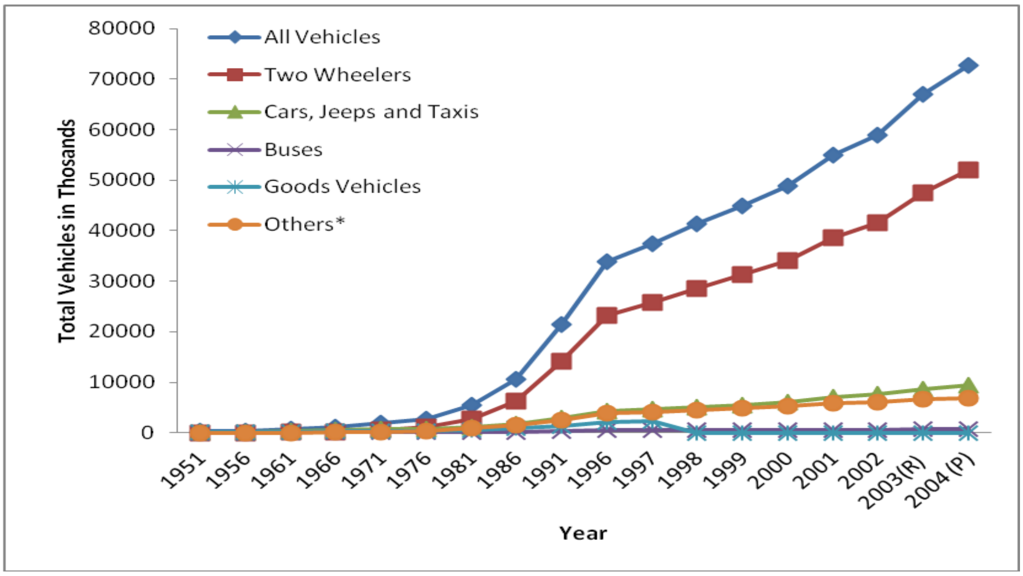

Fig.1 Yearwise Total Registered Vehicles in India

Compressed air has enormous potential as an alternative to these issues due to its zero pollutant capability and for running prime mover like air turbine. Pioneering work in the area of compressed air engine has been done by French technologist Guy Negre [**3**] and also by an inventor of quasi turbine G. Saint Hilaire [**4**]. Use of compressed air as working fluid offers a prime mover which does not involve combustion process for producing shaft work. Thus, great advantages in terms of free availability of air as fuel and the emissions free from Carbon Dioxide, Carbon Monoxide and Nitrous Oxides is apparent from such air motors. Compressed air driven prime movers are also found to be cost effective compared to fossil fuel driven engines. It only has perennial compressed air requirement which needs some source of energy for running compressor whose overall analysis shows that the compressed air system is quite attractive option for light vehicle applications.

From the author's earlier study [**5**], the compressed air driven prime movers are cost effective as compared to fossil fuel driven engines and may become a dominant technology in place of the electric, hydrogen cell and other alternative fueled vehicles available in the market [**6-7**]. Some of studies for performance optimization of the low capacity of air turbines have also been carried out in the author's earlier publications [**8**] and from other authors [**9-10**].

II. Power Conversion / Energy Storage System

The power conversion system (PCS) is a vital part of all energy storage systems. It interfaces the energy storage device and the load (the end-user). PCS cost is significant and it can be greater than 25% of the overall energy storage system. PCS cost ranges from Rs.4500/kW for UPS markets to Rs.55000/kW for standalone market. Some of the major PCS markets include:

- Motor drives
- Power supplies
- UPS (uninterrupted power supply)
- Electric vehicles
- Inverters/Converters for solar-hybrid systems, Micro-turbines, Fuel cells, Wind turbines

Power conversion system technology has been evolving slowly due to the limited distributed energy resource (DER) market. As a result, Energy Storage System cost has been high with low profit margins and the manufacturing volume has been low impacting reliability and quality of the Power Conversion System designs. What is needed is the significant reduction in overall cost with improved reliability, and development of state-of-the-art Power Conversion System with multiple uses, which increases production volumes for DER applications, improve controls and adaptability, and improve manufacturing.

2.1 Batteries Energy Storage System

These storage systems operate in varying environments and electrical conditions. In these storage systems there are many different types of battery technologies. The different storage technologies are having advantages under specific operational conditions and thus have their own capabilities and limitations. Some of these are as given ahead.

- Lead-Acid Battery- short cycle life
- Li-Ion -Lithium Ion Battery-High energy and 100% efficiency
- NaS -Sodium Sulfur Battery- can run at high temperature of 300 deg centigrade.
- PSB - Polysulfide Bromide Flow Battery- 75% efficiency
- VRB -Vanadium Redox Flow Battery- 85% efficiency

2.2 Super Capacitor Energy Storage

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 electrolytic capacitors. The electrodes are often made with porous carbon material. The electrolyte is either aqueous or organic. The aqueous capacitors have a lower energy density due to a lower cell voltage but are less expensive and work in a wider temperature range. 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.

2.3 Fly Wheel Energy Storage

Most modern flywheel energy storage systems consist of a massive rotating cylinder (consisting of a rim attached to the 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 interacts 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.

While high-power flywheels are developed and deployed for aerospace and UPS applications, there is an effort, pioneered by Beacon Power, to optimize low cost commercial flywheel designs for long duration operation (up to several hours). 2kW / 6kWh systems are in telecom service today. Megawatts for minutes or hours can be stored using a flywheel farm approach. Forty 25kW / 25 kWh wheels can store 1MW for 1 hour efficiently in a small footprint.

The stored energy can be approximated by: $E = (Iw_r^2)/2 = (mr_r^2w_r^2)/2 = (mv_r^2)/2$ **(1)**

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

2.4 Pumped Hydro Storage

Pumped hydro storage is the most widespread energy storage technology used in the world, according to the energy storage association (ESA). There are about 90 GW of pumped storage in operation, which equals about 3 percent of worldwide generation capacity. The system works by pumping water from a lower reservoir to a higher reservoir and then allowing the water move downhill to produce electricity when needed. Traditional iterations of the technology are ideal for populations that live close to high altitude terrain, like Switzerland, where pumped hydro has been used for a century.

2.5 Compressed Air Energy Storage

The Technology of air engine is not new. The Sterling air engine was developed in 1790-1810, but due to its limitation no much work was carried out. In view of fire problems in Coalmines and other volatile places, where high flammable fuel like fossil fuel vehicles are not adviseable, compressed air operated vehicles are normally being put in use.

III. VANED TYPE NOVEL AIR TURBINE AS PRIME-MOVER TO MOTORBIKE

In this study a vaned air turbine has been considered. This air turbine is tested in order to get an output of 6.50 to 7.20 HP for meeting starting torque requirements at 500–750 rpm at 4-6 bar air pressure. The average running torque is available at normal speed of 2000–2200 rpm at 2-3 bars air pressure. The air turbine with single inlet and exhaust has spring loaded vanes to maintain regular contact with the elliptical bore. The various efforts have been made to get optimum shaft output produced [**11**].

3.1 Mathematical Model

The high pressure jet of air at ambient temperature drives the rotor in novel air turbine due to both isobaric admission and adiabatic expansion. Such high pressure air when enters through the inlet passage, pushes the vane for producing rotational movement through this vane and thereafter air so collected between two consecutive vanes of the rotor is gradually expanded up to exit passage.

This isobaric admission and adiabatic expansion of high pressure air contribute in producing the shaft work from air turbine. Compressed air leaving the air turbine after expansion is sent out from the exit passage. It is assumed that the scavenging of the rotor is perfect and the work involved in recompression of the residual air is absent. Similar type of mathematical modeling is considered in earlier publications by authors and it is being reproduced here for maintaining continuity and benefits to the readers [12-**13**].

The total power output available W_{total} can be written as:

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

$$+n.(N/60).(p_4-p_5).\left[L.\left\{\frac{(X_{1\max}+X_{2\max}).(2r+X_{1\max})}{4}\right\}.\sin\theta\right]$$

IV. PRESENT WORK

A novel air turbine has been conceived for being used as prime mover for very light vehicle applications like; motorbike engine. Based on the above mathematical model, performance of proposed air turbine is analyzed and results are obtained and plotted for different independent and dependent parameters. For optimum design values, the air turbine has been fabricated suiting to the requirements of motorbike. The novel air turbine is fabricated for optimum dimensions and run on compressed air for its performance evaluation. Experimental set up consisting of a reciprocating compressor, compressed air storage tank, air flow regulator cum filter, air turbine and dynamometer is used for validation of the performance predicted by theoretical analysis. The independent and dependent variable considered for present study are detailed below:

4.1 Independent Variables:

i) Number of vanes (n=360 / θ)
ii) Diameter of the rotor (d) in m
iii) Diameter of the casing (D) in m
iv) Length of the rotor (L) in m
v) Speed of rotor (N) rpm
vi) Inlet / admission pressure of air (p_1 in bar)
vii) Admission / injection angle (ø) in degree

4.2 Dependent Variables:

i) Volume of two consecutive vanes (v_1) in m^3
ii) Volume of maximum expansion (v_2) in m^3
iii) Exit pressure (p_4) in bar
iv) Torque (T) in Nm
v) Total power output (W_{total}) in kW
vi) Expansion power output (W_{exp}) in kW
vii) Flow power output (W_{flow}) in kW

The various parametric investigations carried out in present work include optimization of vane angle (number of vanes in rotor), air admission / injection angles, rotor and casing diameter ratio and relation between vane angle and air injection angle with respect to different injection pressure 2-7 bar (15- 100 psi).

V. THEORETICAL AND EXPERIMENTAL RESULTS OF NOVEL AIR TURBINE

The air engine is conceptualized as a novel vaned type air turbine is shown in **Fig. 2**. The air turbine is considered to work on the reverse principle of vane type compressor. It is assumed that the total shaft work of the air turbine is cumulative effect of compressed air jet on vanes and the expansion of high pressure air. The compressed air at 20 bar is utilized for running air turbine which is stored in a storage cylinder. It is proposed to have storage capacity of 30 minutes duration. The compressed air cylinder is attached with filter, regulator and lubricator for regulating and maintaining the constant pressure during air admission so as to produce high torque at low speed of revolution. The vanes of novel air turbine are spring loaded to maintain their continuous contact with the casing wall to minimize leakage.

5.1 Theoretical Analysis

In present study the thermodynamic modeling of the air turbine has been carried out for the considered model. Theoretical analysis is carried out for varying compressed air injection pressure, number of vanes, casing diameter, rotor diameter, speed of rotation. Based on the theoretical result and analysis the final dimensions of the air turbine were fixed. A prototype of air turbine was developed and checked for its functionality. It has a casing of CI material with liner of high tensile steel. The vane rotor is also of high tensile steel and having 8 slots to accommodate 4 mm thickness vanes of self lubricating fiber material. The fiber vanes are spring loaded to maintain regular contact with casing liner.

5.2 Experimental Setup

The complete schematic of test setup is shown in **Fig. 3**. It consists of compressor, compressed air storage cylinder, supply of compressed air through air filter, regulator and lubricator to air turbine. The dynamometer consisting of load pulley, weight load and load dial gauge are also shown in the set up.

The experimental setup consisting of a heavy duty two stage compressor with suitable air storage tank, air filter, regulator and lubricator, novel air turbine, rope dynamometer has been created for validation of theoretical results.

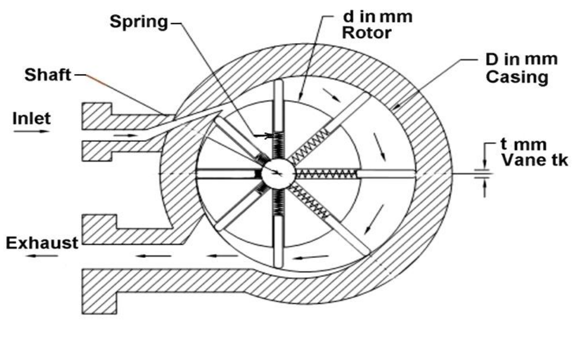

Figure 2: Air turbine- schematic model

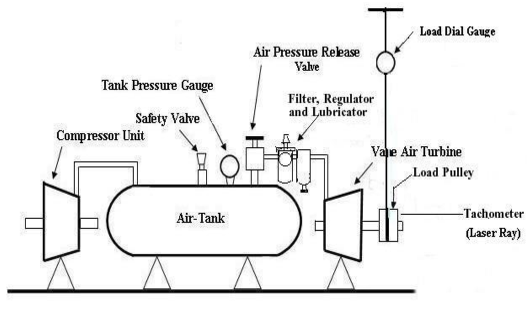

Figure 3: Experimental test setup

The actual setup of test rig of air engine / turbine was fabricated and air turbine was tested in the laboratory**.** The compressed air is produced by a heavy duty two stage compressor and stored in a suitable capacity of air tank to maintain nearly constant supply pressure of 300 psi. The compressed air is connected to air filter, regulator and lubricator to produce desired air pressure for testing. The data is recorded with various parametric conditions and performance evaluation of the prototype air turbine is carried out**.**

As shown in **Fig. 4**, it consists of a compressor and storage unit. The said unit comprises of the specifications of components used to perform the validation of Air Engine/Turbine such as: *compressor unit, compressed air storage tank, safety valve and air pressure gauge, air release valve, air filter, regulator and lubricator (FRL).* The actual setup of test rig of air engine / turbine was fabricated and air turbine was tested in the laboratory as shown in **Figs. 4** and **5.** The compressed air is produced by a heavy duty two stage compressor and stored in a suitable capacity of air tank to maintain nearly constant supply pressure of 20 bar. The compressed air is connected to air filter, regulator and lubricator to produce desired air pressure for running the air turbine and its testing. The data is recorded with various parametric conditions and performance evaluation of the prototype air turbine is carried out**.**

Fig. 4: Actual test rig with Compressor

Fig 5: Actual air turbine under test

(Note: All the measuring tools / instruments were validated within the specified limits of its tolerances before the record of reading and errors were not accounted for).

The most important aspects of design and analysis of the novel air engine are of optimizations of following parameters:

a) Size of air engine liner diameter (*D*), rotor diameter (*d*) and its relation (*d/D*).
b) Compressed air at which angle it should enters the air engine.
c) Number of vanes into the rotor depends upon angle between 2- consecutive vanes.
d) Air pressure is considered 2- 7 bar for operation.
e) Exit port is considered to be placed at an angle where re-compression should not start after expansion of air inside the air engine. The exit air is released at an angle 225^o or more with reference to which casing liner and rotor gap is nearly zero.

5.3 Validation of Experimental Results

The above experimental set up was used at HBTI, Kanpur in the fluid mechanics lab and compressor was used after attaining its pressure 300 psi. The nylon pressure tube was connected to storage tank outlet nozzle. Other end of pipe was connected to inlet of FRL attached with air engine test setup. The release valve of storage tank was regulated and Regulator of air engine FRL unit was adjusted at air pressure of 2 bar. The load on rope pulley attachment was adjusted with spring balance after adjusting the rope tension screw.

Under this condition speed of air engine / turbine was recorded with the help of laser dynamometer. Again the pressure regulator was adjusted at 3 bar and reading of air turbine speed was recorded. Similarly regulator pressure was again adjusted for 4, 5, 6 bar air pressure under same loading conditions and speeds were recorded for all pressure conditions.

This process was continued after increasing the loading on spring balance and speed of air turbine were recorded at 2, 3, 4, 5, 6 bar pressure. The process was repeated for different set of loadings and experimental readings were then compared with theoretical values. It was observed that at low air pressure, performance of turbine was about 97 % and at high pressure and heavy loading it was to the order of 72%. Thus the innovative novel turbine was found to develop maximum performance than the any available air motors developing same power.

5.4 Input Parameters

For comparison of theoretical and experimental power output parameters are listed in Table-2.

Table-2

Input parameters for comparison of theoretical results with experimental values

Symbols	Parameters
D=2*R*, *d*=2*r*	(100 mm,75 mm) i.e.(*d/D*)=0.75
p_1	20 psi (=1.4 bar), 40 psi (=2.7 bar), 60 psi (=4.1 bar), 80 psi (=5.5 bar), 100 psi (=7.0 bar)
p_4	$=(v_1/v_4)^{\gamma}.p_1 > p_5$ assuming adiabatic expansion
p_5	$(p_4/1.2)$ >1 atm = 1.0132 bar
n	Number of vanes (360 / θ)
N	500 rpm, 1000 rpm, 1500 rpm, 2500 rpm, 3000 rpm
L	45 mm length of rotor
γ	1.4 for air
θ	45^0 angle between 2-vanes, (i.e. rotor contains correspondingly 8 nos. of vanes)
Ø	60^0 angle at which compressed air through nozzle enters into rotor

5.5 Results and Discussion

Variation of performance efficiency = (variation in experimental and theoretical power divided by theoretical power) with respect to different injection pressure 2-7 bar is shown in **Fig. 6**. It depicts the variation of efficiency of air turbine for different injection pressure at different speeds of rotation. It is evident that at every injection pressure the efficiency goes down with increasing speed of rotation. This is due to the increase in friction losses on account of higher speed of rotation for a constant injection pressure. There also occur leakage losses at the mating surface of vane and casing which increase with increasing injection pressure. This higher leakage helps in overcoming the frictional resistance and reduces friction losses. On account of these factors, the efficiency of air turbine varies as shown below:

- 93% to 99% with variation of 6%, at speed 500 rpm for injection pressure 20 psi to 100 psi.
- 81.8% to 89.8% with variation of 8%, at the speed 1000 rpm for injection pressure 20 psi to 100 psi.
- 70.8% to 84.3% with variation of 13.5%, at the speed 1500 rpm for injection pressure 20 psi to 100 psi.
- 64.4% to 79.8% with variation of 15.4%, at the speed 2000 rpm for injection pressure 20 psi to 100 psi.
- 59.5% to 76.5% with variation of 17%, at the speed 2500 rpm for injection pressure 20 psi to 100 psi.
- 56.2% to 72.9% with variation of 16.7%, at the speed 3000 rpm for injection pressure 20 psi to 100 psi.

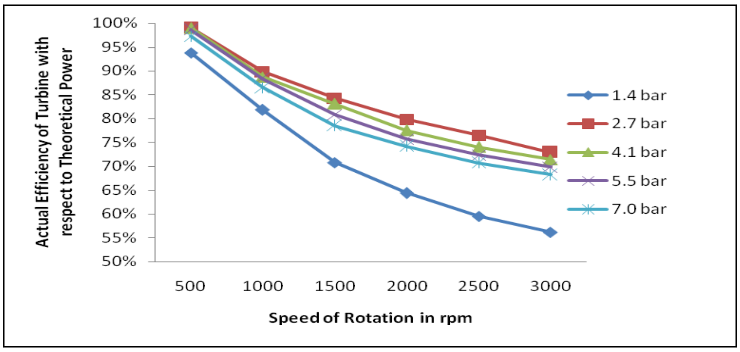

Figure 6: Performance of vane turbine with respect to experimental power

This shows that at lower speed of rotation, performance efficiency is higher and variation is small; whereas at higher speed rotation performance efficiency of turbine goes down and variation is also large. The graph at 20 psi (1.4 bar) shows the large variation in performance efficiency whereas for 40 -100 psi (2.7-7 bar), the variation in the performances are closer. This may be due to overcoming the frictional losses between vanes and casing. Thus overall performance of air turbine for working pressure ranging from 2.7-6 bar is found varying from 72%-97%.

VI. CONCLUSIONS

On the basis of above studies, following conclusions are drawn:

- Apart from all other options of storage of energy, the compressed air energy storage (CAES) is the option to improve upon the peak hour requirement of electric power generation.
- Wind turbines farm could be used as CAES system and from CAES, electric power can be generated during peak hour requirements and it can be utilized as a source for filling the compressed air storage tank for running the air engine of light vehicles without using electricity for compressor.
- The performance efficiency of the novel compressed air engine is found varying from 72%-97% and is suitable to run motorbike's air engine as zero pollution.
- If the compressed air technology is implemented in the light transport vehicles such as: motorbikes etc., it will practically generate zero pollution and compressed air engine technology will reduce the emission up to 50-60% as presently 80 % of pollution is generated due to the transport sector.

Thus CAES is definitely going to be the most attractive and efficient clean energy option for 21st century.

VII. Acknowledgements

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