Compressed Air as a Clean Energy Source for Vehicles

Bharat Raj Singh[1*] and Onkar Singh[2]

ABSTRACT

In today's civilization the excessive use of hydrocarbon fuels in transport sector is causing serious effect on environmental damage to the extent of 77.8% due to its tail pipe emission which mainly releases: carbon di-oxide, carbon mono-oxide, nitrous oxide, and other un-burnt gases contributing to green house gases. The excessive consumption of hydrocarbon fuel has also led to the danger of depletion of hydrocarbon fuel and oil wells are likely to be dried around 2047, leaving much disastrous effect like global warming, tsunami, hurricane and health hazards etc.. This paper describes the compressed air as a clean energy source that can be utilized with the help of suitable air driven engine to develop shaft work to run the light transport vehicles along with compressed air storage tank system. A novel rotary air engine has been designed and developed to produce 73-97% of its performance efficiency. Supplementing the hydrocarbon fueled vehicles with the use of compressed air for running vehicles will significantly control the emissions and enhance the energy sustainability.

Index Terms *:hydrocarbon fuel, environmental damage, tail pipe, green house gases, air as clean energy.*

1. INTRODUCTION

Global demand of transport vehicles is causing into a rapid consumption of fossil fuels and causing fast depletion of the energy resources. Marion King Hubbert [1], a noted geophysicist 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 and wells get dried around 2047.

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 2007 is shown in Figure 1.

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% of air pollutants in the atmosphere.

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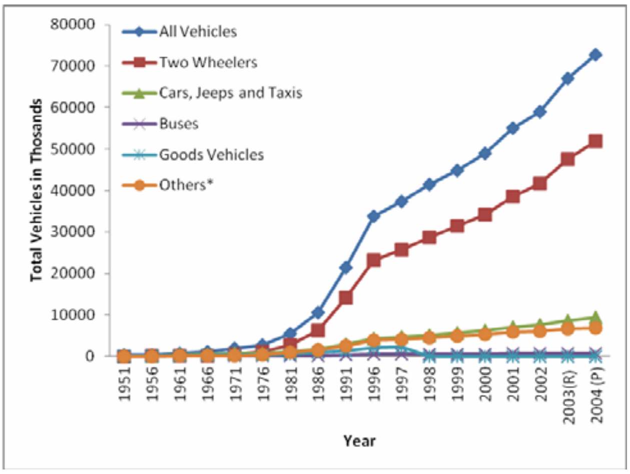

Fig.1. Yearwise total registered vehicles in India

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.

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 has the perennial requirement of compressed air which needs electrical energy for running compressor whose overall analysis shows that the compressed air system is quite attractive option for light vehicle applications [5]. Comparative study of emissions due to fossil fuel consumption with emissions in respect to air engines relying on compressed air production using electricity shows that the compressed air engine has less adverse impact on environment. In case of air engine, there is only one major source of air pollution i.e. emissions from power plants which are concentrated at one location and can be regulated through use of suitable effluent treatment technologies.

From the author's earlier study [6,7], 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 [8-9]. Some of studies for performance optimization of the low capacity of air turbines have also been carried out in the author's earlier publications [10-11] and from other authors [12-14].

2. AIR TURBINE MODEL

A vaned type air turbine as shown in Fig. 1 has been considered as substitution of engine. This air turbine works on the reverse of working principle of vane type compressor. Here total shaft work is cumulative effect of isobaric admission of compressed air jet on vanes and the adiabatic expansion of high pressure air. A prototype of air turbine has been developed and is found to be functional [15-17]. Vanes of novel air turbine are placed under spring loading to maintain their regular contact with the casing wall to minimize leakage.

The present objective is to investigate the performance of an air turbine with the variation of rotor / casing dimensions. The air turbine considered has capability to yield 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.

3. MATHEMATICAL MODELING

In this air turbine the high pressure air at ambient temperature drives the rotor in novel air turbine due to both isobaric admission and adiabatic expansion as shown in Fig. 2. 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. 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.

From Fig. 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 done due to thermodynamic process may be written as:

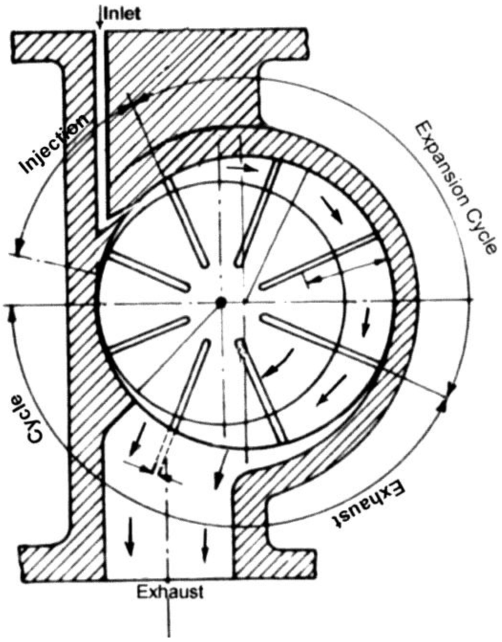

Fig.2. Air turbine- model

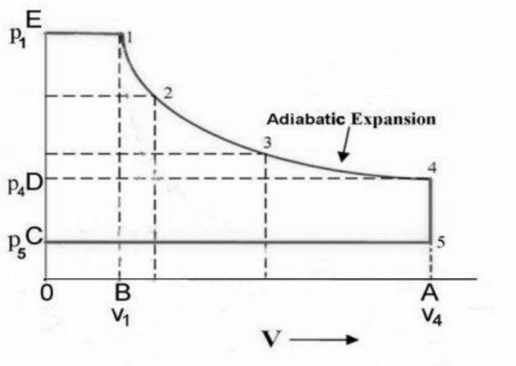

Fig.3. Thermodynamic processes (isobaric, adiabatic and isochoric expansion)

[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)]

$$W_{total} = n.(N/60).\left(\frac{\gamma}{\gamma-1}\right) p_1 v_1 \left\{1-\left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\} + n.(N/60).(p_4 - p_5)\, v_4 \quad (1)$$

where

$$W_{exp} = n.(N/60).\left(\frac{\gamma}{\gamma-1}\right) p_1 v_1 \left\{1-\left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\}$$

and $W_{flow} = n.(N/60).(p_4 - p_5)v_4$

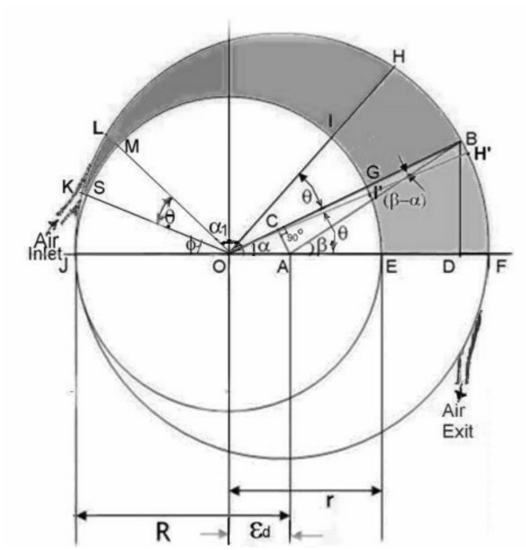

Fig. 4. Variable length BG and IH and injection angle φ

From Fig. 4, it is seen that when two consecutive vanes at OK and OL moves to position OH and OB, the extended vane lengths varies from SK to IH and LM to BG, thus the total power output available W_{total}, can be written as [18]:

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

where,

$$v_1 = v_{min} = L.\left\{\frac{(X_{1min}+X_{2min})(d+X_{1min})}{4}\right\}.\sin\theta,$$

and $v_4 = v_{max} = L.\left\{\frac{(X_{1max}+X_{2max})(d+X_{1max})}{4}\right\}.\sin\theta$

4. ASSUMPTIONS AND INVESTIGATION PARAMETERS

Following assumptions and investigation parameters are taken while analyzing the theoretical and experimental setup:

- The temperature of compressed air entering through inlet into rotor and casing space is at ambient temperature.
- Vanes are spring loaded and hence leakages across vane tip and casing liner are ignored.
- Friction between vane tip and casing liner is ignored.

Various input parameters are considered as shown in Table-2 for investigation. The effect of speed of rotation, rotor/casing diameter ratio and injection pressure on the expansion power output, flow work output and total power output from air turbine is studied. Here the vane angle θ, injection angle ϕ and speed of rotation N of the air turbine are considered to be constant for whole study. The results obtained have been plotted in Figs. 5 to 8, for the rotor/casing diameter ratio (d/D), as 0.75 at vane angle of 45°, injection angle of 60° at different injection pressures of 2-6 bar (30, 45, 60, 75 and 90 psi) and at the speed of rotations 500 rpm, 1000 rpm, 1500 rpm, 2000 rpm and 2500 rpm, at casing diameter 100 mm and rotor diameter 75 mm.

Table 1: Air turbine parameters

Symbols	Parameters
Rotor to Casing (d/D) ratio	0.75, when casing diameter is kept D=100 mm and rotor diameter d=75 mm.
p_1	2 bar (?30 psi), 3 bar (?45psi), 4bar (?60psi), 5bar (?75psi), 6bar (?90psi) – inlet pressures
p_4	$(v_1/v_4)^{\gamma}.p_1 > p_5$ assuming adiabatic expansion
p_5	(p_4/1.1)= 1.0132 bar- exit pressure
N	500 rpm, 1000 rpm, 1500 rpm, 2000 rpm, 2500 rpm and 3000 rpm
L	45 mm length of rotor (assumed minimum)
n	(360/θ) number of vanes in rotor
γ	1.4 for air
θ	45° angle between 2-vanes, (i.e. rotor contains correspondingly 8 number of vanes)
ϕ	60°, injection angle at which air enters into turbine.

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5. RESULTS AND DISCUSSION

5.1 *Theoretical Investigations*

From the author's earlier study for investigation of optimum input parameters, Fig. 5 shows that the theoretical power at different speed of rotation is increasing with increase of injection pressure. The rate of increase of power is higher at higher injection pressure compared to lower injection pressure. This can be attributed to the fact that at higher injection pressures the flow power and the expansion power is more. Due to higher admission pressure total amount of air admitted is more and it offers the overall increase in total power output.

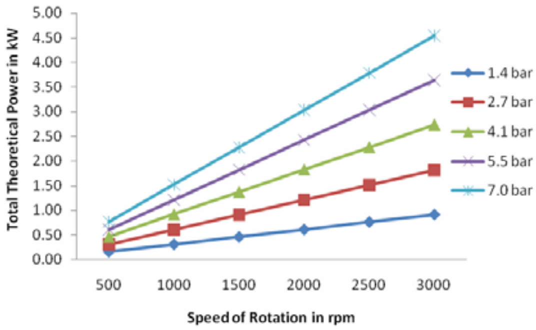


Fig. 5. Total theretical power output (*Wttheo*) vs speed of rotation

5.2 *Experimental Investigations*

5.2.1 Experimental Test setup : Schematic of experimental test setup as shown in Fig. 6 consists of compressor, compressed air storage cylinder, supply of compressed air through air filter, regulator and lubricator to air turbine.

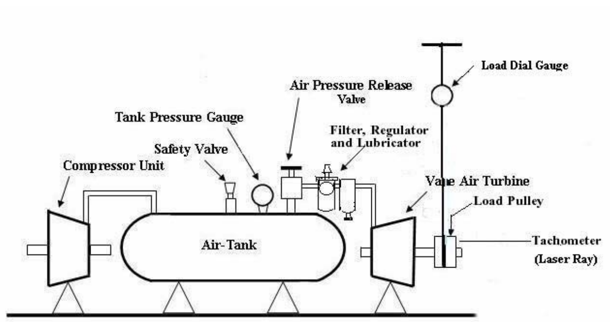
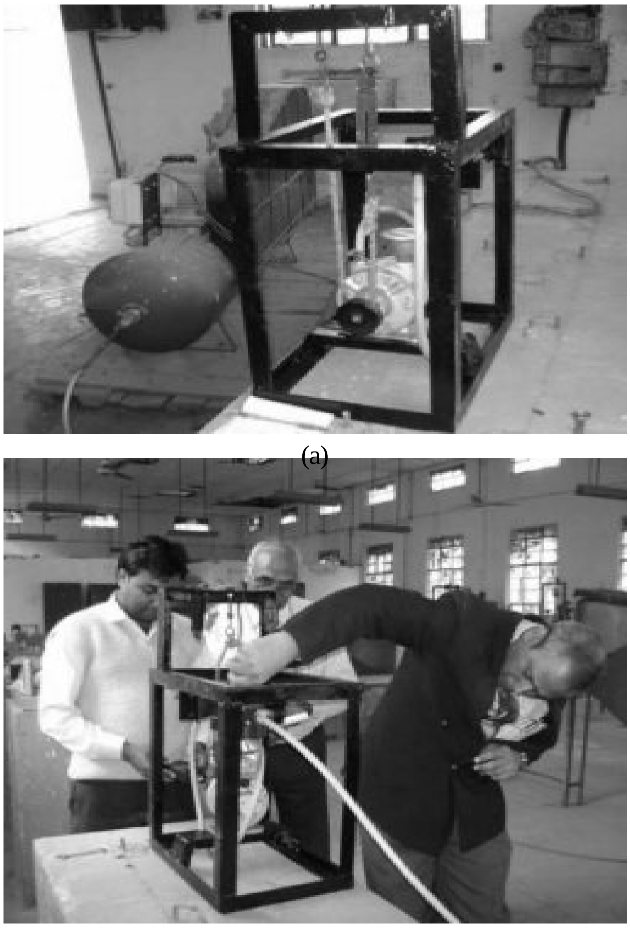


Fig. 6. Schematic Test Setup

It has a heavy duty two stage compressor with suitable air storage tank, air filter, regulator and lubricator, novel air turbine, rope dynamometer for validation of theoretical results as shown in Figs.7 (a) and (b).



(a)

(b)

Fig. 7. Actual (a) test rig and (b) air turbine under test

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.

5.2.2 Experimental Results : Performance evaluation is conducted on a compressed air driven vaned type novel air turbine. The comparison of theoretical total shaft outputs with respect to experimental values are carried out on following optimum input parameters such as high pressure air 1.4 bar (20 psi), 2.8 bar (40 psi), 4.2 bar (60 psi), 5.6 bar (80 psi) and 7 bar (100 psi), at different input parameters (injection angle 60°, vane angle 45°, L=45 mm, and d= 75 mm rotor diameter and D= 100 mm casing diameter (or d/D=0.75).

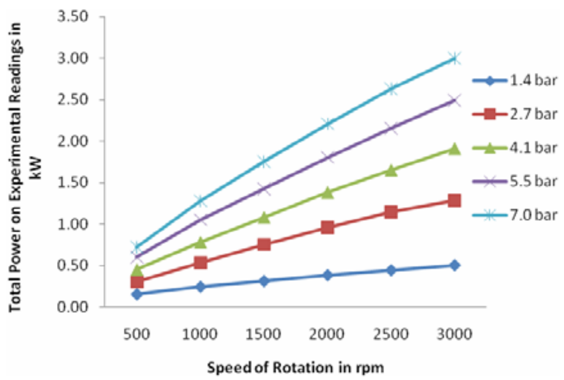


Fig. 8. Total experimental power (W_{texper}) versus speed of rotation

Figure 8 shows that the experimental values of power output increases with higher injection pressure and at different speeds of rotation. Comparison of power output for theoretical and experimental conditions shows that for a given injection pressure the experimental power output is less than theoretical value at same operating condition. This is because of leakage at interface of vane and casing, throttling of air at admission, and friction losses. From Figs. 5 and 8, the theoretical performance of the air turbine can be compared with the experimental performance. It is seen that the results obtained experimentally match significantly with the theoretical results to the extent of around 70% to 98% for different operating parameters.

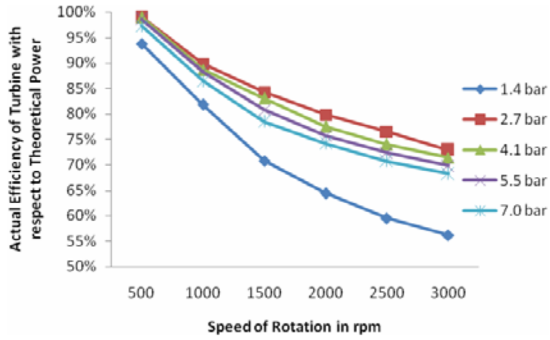


Fig. 9. Actual performance of vane turbine with respect to theoretical power

Figure 9 depicts the variation of performance efficiency of air turbine for different injection pressure at different speeds of rotation such as: 99%, 89.8%, 84.3%, 79.8%, 76.5% and 72.5% at speed of rotation 500 rpm, 1000 rpm, 1500 rpm, 2000 rpm, 2500 rpm and 3000 rpm respectively when injection pressure varies from 2.8 - 4.2 bar. But the performance efficiency for injection pressure 1.4 bar is not in parity with higher pressure. This indicates that turbine power output is utilized in overcoming the friction losses at injection pressure 1.4 bar and centrifugal forces on vanes are also not effective at speed of rotation 500-3000 rpm. Thus air turbine offers best performance at injection pressure 2.8 to 4.2 bar (40-60 psi) which can be easily created.

6. CONCLUSION

Based on the considered input parameters and above investigations, following conclusions are drawn:

- The expansion power output is found maximum as 3.65 kW for moderate / minimum air consumption.
- The significant contribution of exit flow power with respect to total power output varies from 6.68% to 11.33%.
- The total optimal power output is obtained as 3.98 kW for minimum air consumption, at rotor/casing diameter ratio 0.70, injection pressure 6 bar and speed of rotation 2500 rpm.

- The theoretical optimum shaft power output 3.98 kW match significantly from the results obtained experimentally and performance efficiency of the novel air turbine ranges from 72.5% to 99% for injection pressure 2.8- 4.2 bar.
- The compressed air engine technology offers nearly zero pollution vehicles hence this technology should be extensively tried for mitigating the environmental pollution.

From these results it is emerged out that the air turbine engine having casing diameter = 100 mm and rotor diameter = 75 mm, can be easily equipped on two wheelers as a replacement to IC Engines. Further, if this technology is implemented widely in developing countries where major contributors of CO_2 are two wheelers in 70-80 % population of vehicles, this can curb the emission 50-60%. Thus the compressed air technology can be used as alternative to fossil fuel and contribute to energy sustainability. This can also check the global warming to larger extent.

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REFERENCES

[1] Hubbert M.K., Nuclear energy and the fossil fuels; Amer. Petrol. Inst. Drilling and Production Practice, *Proc. Spring Meeting, San Antonio, Texas. 7-25*(1956).

[2] Aleklett K. and Campbell C.J., The Peak and Decline of World Oil and Gas Production- *Minerals and Energy, Raw Materials Report, Volume 18, Number 1, 2003, pp. 5-20* (2003), DOI: 10.1080/14041040310008374.

[3] Negre Guy and Negre Cyril, Compressed Air - The Most Sustainable Energy Carrier for Community Vehicles, Speech in front of assembly at Kultur gathered for Fuel Cells World, Tuesday 29th June '(2004).

[4] Saint Hilaire G., Saint Hilaire R. and Saint Hilaire, Y., Quasiturbine zero pollution car using gasoline, *Festival at Le Lundi, Montreal Gazette, 26 September (2005)*, DOI: 10.1115/GT2007-27088

[5] Singh B.R. and Singh O., Use of Non-Conventional Energy for Sustainability to Fossil Fuel, National Conference on Recent Trend on Mechanical Engineering, RAME-2007, held on 28-29th March'2007 at Baba Sahab Dr. Bhim Rao Ambedkar College of Agricultural Engineering and Technology, Etawah-Proceedings, (2007), pp 130-136.

[6] Singh B.R. and Singh O., Uses of Wind Power as a Non-Conventional/Renewable Energy for Sustainability, National Conference on State of Art Technology in Mechanical Engineering, STEM-2007, held on October 29-31, at College of Technology, G.B. Pant University, Pant Nagar, UP-Proceedings (2007), pp 503-515.

[7] Honton E. J., Hydrogen Fuel Cell Car, presented at 15th Annual US Conference and Hydrogen Expo, April'2004, USA.

[8] Rose Robert and William J. Vincent, Fuel Cell Vehicle World Survey 2003, Breakthrough Technologies Institute, February' 2004, Washington, D.C.

[9] Singh B.R. and Singh O., Study of Compressed Air as an alternative to fossil fuel for Automobile Engines, International Conference on Challenges and Strategies for Sustainable Energy and Environment-held on 10-11th June at UPTU, Lucknow, UP-Proceedings (2006), pp 179-191.

[10] Singh B.R. and Singh O., A Study on Sustainable Energy Sources and its Conversion Systems towards Development of an Efficient Zero Pollution Novel Turbine to be used as Prime-mover to the Light Vehicle, 2008 ASME International Mechanical Engineering Congress and Exposition, held on October 31-November 6, at Boston, Massachusetts, USA(2008), *Paper No. IMECE -2008 -66803*, DOI: 10.1115/IMECE2008-66803.

[11] Singh B.R. and Singh Onkar, Development of a vaned type novel Air Turbine, International Journal of Mechanical Engineering Science (The manuscript was

received on 21st December 2007 and was accepted after revision for publication on 03rd June 2008), *Proc. IMechE Vol. 222 Part C, pp 2419-2426* (2008), DOI: 10.1243/09544062JMES993.

[12] Badr O., O'Callaghan P. W., and Probert S. D., Multi-vane expanders: geometry and vane kinematics, *Applied Energy, 19(3) (1985)*, pp. 159-82.

[13] Badr O., Probert S. D., and O'Callaghan P.W., Performances of Multi-vane Expanders, *Applied Energy, 20 (1985),* pp.207- 234.

[14] Shen Yu-Ta, and Hwang Yean-Ren, Design and implementation of an air-powered motorcycle, *Applied Energy, 86 (2009),* pp. 1105–1110.

[15] Singh B.R. and Singh O., Study of Influence of Vane Angle on Shaft Output of a Multi Vane Air Turbine"-*International Journal of Renewable and Sustainable Energy,* AIP, New York, USA.ISSN:1941-7012 (2010), *Vol.2 Number 3, pp. 033101-16,* DOI: 10.1063/1.3424712.

[16] Singh B.R. and Singh O., Analytical Investigations on Different Air Injection Angles to Optimize Power Output of a Vaned Type Air Turbine»-*Internatinal Journal of Power and Energy,* Westminster, London-SW1H 9JJ, UK, Proc. of IMechE, Part A: JPE-837, ISSN 0957-6509; (2009), *Vol. 224, Number 3, 2010, pp. 305-312,* DOI: 10.1243/09576509JPE837.

[17] Singh B.R., and Singh O., Study of Effect of Rotor Vanes to Rotor-Casing Dimensions on Performance of a Zero Pollution Vane Type Novel Air Turbine»-*International Journal of the Physical Sciences,* 5170-00200, Nairobi-73023 Victoria Island, Lagos, ISSN 1992-1950; (2010), Vol.5(5), 2010, pp. 547-556

[18] Singh Onkar, Reciprocating and Rotary Compressor, Applied Thermodynamics, *New Age International (P) Ltd.*, Publishers, New Delhi, India, ISBN: 978-81-224-2583-3, Feb, (2009), pp797-798.