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Study of Compressed Air Storage System as Clean Potential Energy for 21st Century

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Abstract - Worldwide transport sector alone releases billion tonnes of excessive carbon dioxide in the atmosphere through tail pipe emissions thereby causing serious threat to global warming. 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 laid upon the 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 some energy storage and energy conversion systems. Special focus is laid on use of compressed atmospheric air as a viable alternative energy source. Such energy storage system can be used as clean energy source as zero pollution sources, and help in mitigating the global warming.

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STUDY OF COMPRESSED AIR STORAGE SYSTEM AS CLEAN POTENTIAL ENERGY FOR 21ST CENTURY

Strictly as per the compliance and regulations of:

Study of Compressed Air Storage System as Clean Potential Energy for 21st Century

Bharat Raj Singh [α], Onkar Singh [Ω]

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Keywords : zero pollution, compressed air, air turbine, energy conversion, energy storage, injection angle.

Glossary

CAE	compressed air energy
CAES	compressed air energy storage
DER	distributed energy source
EC	electrochemical capacitors
EDL	electric double layer
ESA	energy storage association
ISEP	iowa stored energy park
MDI	metuore development international
PCS	power conversion source
UPS	uninterrupted power supply
PNM	public service Company of New Mexico

Nomenclature

d	diameter of rotor ($2r$) in meter
D	diameter of outer ($2R$) cylinder in meter
E	stored energy
I	moment of inertia of thin rim cylinder
L	length of rotor having vanes in meter
n	no. of vanes=(360/θ)
m	rim cylinder mass
N	no. of revolution per minute
P	pressure in bar
p_1, v_1	pressure and volume respectively at which air strike the Turbine,
p_4, v_4	pressure and volume respectively at which maximum expansion of air takes place,
p_5	pressure at which turbine releases the air to atmosphere.
r_r	radius of rim cylinder
v	volume in cu-m
v_r	linear rim velocity
w	theoretical work output in Nm
w_r	rotational velocity of rim cylinder(rad/sec)
W	theoretical power output (Nm/s)
X_{1i}	variable extended lengths of vane at point1
X_{2i}	variable extended lengths of vane at point 2

Subscripts

1, 2...4, 5	subscripts – indicates the positions of vanes in casing
i or *imp*	impingement
e or *exp*	expansion
t or *total*	total

Greek Symbols

α	angle BOF - see Fig. 5
α_1	angle LOF(=180-ϕ) - see Fig. 5
α_2	angle KOF(=180-θ-ϕ) - see Fig. 5
β	angle BAF – see Fig.5
γ	1.4 for air
θ	angle between 2-vanes(BOH) – see Fig. 5
ϕ	angle at which compressed air enters into rotor through nozzle
ξ_d	eccentricity *(R-r)*

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I. Introduction

Worldwide utilization of hydrocarbon fuel in transport sector, power sector and other industries is causing serious problem of global warming, air pollution, likely depletion of fossil fuel reserves and threat to the survival of mankind. This fact was predicted in 1956, by US based Chief Consultant and Oil Geologist Marion King Hubert [1] who stated that if oil is consumed with high rate, US Oil production may peak in 1970 and thereafter it will decline. It was also predicted that other countries may attain Peak Oil day within 20-30 Years and may suffer with oil crises within 40 years, when Oil wells are going to dry. The projection is illustrated with a bell shaped *Hubert Curve* based on the availability and consumption of the fossil fuel.

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.

Billion tonnes of release 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 [2-9]. 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 [10] 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.

The paper focuses towards the compressed air energy storage (CAES) and its uses in the transport technology, power generation by wind turbine farm and CAES during non peak hours and its availability for meeting the peak hour power requirement which could not be met otherwise through the thermal power plants. The running of light vehicles / motorbikes could curb emission by 50-60% in developing countries such as India, China, Taiwan, Romania etc. It is expected that CAES will be the major contributor of the clean energy potential during the 21st century.

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.

a) 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

b) 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.

c) 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. Flywheels can bridge the gap between short term ride-through and long term storage with excellent cyclic and load following characteristics. The choice of using solid steel versus composite rims is based on the system cost, weight, size, and performance trades of using dense steel (200 to 375 m/s tip speed) vs. a much lighter but stronger composite that can achieve much higher rim velocities (600 to 1000 m/s tip speed). Actual delivered energy depends on the speed range of the flywheel as it cannot deliver its rated power at very low speeds. For example, over 3:1 speed range, a flywheel will deliver ~90% of its stored energy to the electric load.

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:

$$E = (Iw_r^2)/2 = (mr_r^2w_r^2)/2 = (mv_r^2)/2$$

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.

d) 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.

e) 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. Various Options of Uses of Compressed Air Energy Storage (CAES)

a) Power Plant backup with CAES

Compressed air is not very old technology which takes excess energy from a power plant or renewable energy and uses it to run air compressors, which pump air into an underground cave or container where it is stored under pressure. When the air is released, it powers a turbine, creating electricity.

The technology, which involves storing off-peak-generated energy in the form of compressed air, usually in an underground reservoir, can trace its roots to the early 1960s, when the evaluation of gas turbine technology for power production began. It gained momentum during the next decade because of its promising thermal efficiency and response capabilities for providing load-following and peaking power support.

But since the commissioning only two existing CAES plants in the world-the 290-MW Huntorf plant in north Germany in 1978 and the 110-MW Alabama Electric Corp. plant in McIntosh, Ala., in 1991 have come up. One reason for this is that setting up a CAES facility is costly and requires finding a geologic formation that can support it. For example, both the German and Alabama plants store compressed air in mined salt caverns.

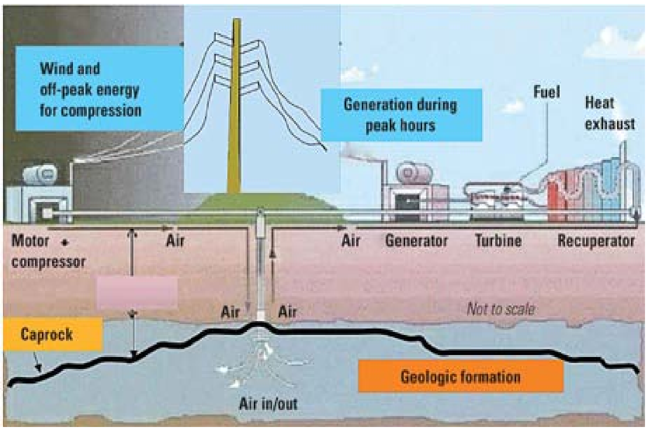

Figure 1 : Underground CAES backup by non Peak Hour Compression

CAES plants work like big batteries. electric motors drive compressors that compress air (at perhaps 1,100 psi) into an underground geologic formation during off-peak hours. When the electricity is needed most, the pre-compressed air (essentially replacing the compressor in a traditional combustion turbine) is used in modified combustion turbines to generate electricity (Figure 1). Natural gas or other fossil fuels are still required to run the turbines, but the process is more efficient-using up to 50% less natural gas than standard production, according to Sandia National Laboratories.

b) Wind Turbine Farm backup with CAES

Prompted CAES is being reviewed by the staggering growth of wind-powered capacity for its use as a load management tool as well as its capability to function as a stand-alone intermediate generation source for capturing energy arbitrage, capacity payments, and ancillary services.

As per recent announcement, Sandia was developing a stored energy park in an aquifer near Des Moines, Iowa, in collaboration with Public Service Co. of New Mexico (PNM) and more than 100 municipal utilities in Iowa, Minnesota, and the Dakotas. The Iowa Stored Energy Park (ISEP, www.isepa.com) will be a nominal 269-MW CAES plant with about 50 hours' worth of stored energy. As per the estimates, using Iowa's abundant wind power, it could account for 20% of the energy used annually at a typical municipal utility and save cities and their utilities as much as $5 million each year in purchased energy.

ISEP Project Manager Georgianne Peek said the project, expected to be operational by 2012, was "pretty far along." By June, ISEP developers were 95% certain that they had the right formation (based on seismic testing at the site), computer modeling, and data from a sister formation. The team is planning to conduct an analysis of the site's rock mechanics-a study similar to the one they did in 2000 for a 2,700-MW CAES plant proposed by CAES Development Co. for construction in Norton, Ohio and the project is still under development.

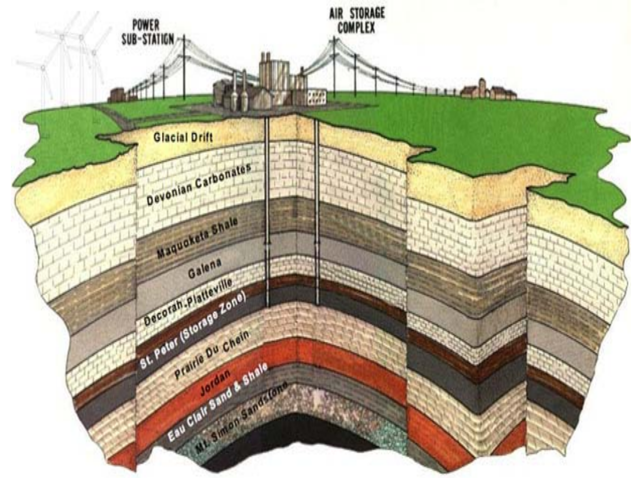

Figure 2 : Underground CAES backup by Wind Turbine Farm

c) The Submerged CAES

Recently in Europe, German generation giant E.ON gave an engineering professor at Nottingham University, Seamus Garvey, £236,000 ($333,500) to build two CAES prototypes-the first on land and then an underwater wave-powered version. Garvey, who thinks the idea makes abundant engineering sense, envisions large amounts of compressed air being stored under the sea in gigantic cone-like flexible containers, dubbed energy bags. Renewable energy primary harvesting machines would collect the energy in the form of compressed-air, then if the energy available exceeds the demand for electricity at that time, some air is inducted into storage, but the heat is extracted from that and fed into a small fraction of air that is being expanded. This presupposes that your 'wind farm' or 'tidal energy farm' or 'wave energy farm' or integrated mix of all of these is set up to deliver 'base load' most of the time, Garvey told *POWER*. At a depth of about 1,970 feet, he calculates that the bags could store some 6,945 MWh of energy for every cubic meter. Garvey's prototypes are in the process of development.

f) Compressed Air Engine / Turbine

Now from last two decades major thrust is being given by the researchers for development of compressed air engine. Some technical developments, which may be considered to work on 21st Century Energy Storage system and can work on compressed air or hybrid system as an alternative to fossil fuel for running light vehicles, are listed below:-

i. *Reciprocating Compressed Air Engine*

Guy Negre, a French Scientist, 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 demonstrated *in* Oct.'2004 publically [11]. The Air Car, developed by Luxembourg-based MDI Group founder and former Formula One engineer Guy Negre, is powered by a compressed air engine (CAE). It uses compressed air to push its pistons when running at speeds under 35 mph. At higher speeds-it can run up to 96 mph-the compressed air is heated by a secondary fuel source (biofuel, gasoline, or diesel) and expands before it enters the engine. The Air Car claims a fuel efficiency of about 100 mpg. The air is compressed using power from a regular electric outlet.

ii. *Rotary Hot Air Motor (Quasi-Turbine)*

Saint Hilaire G., an inventor developed zero pollution cars using Quasiturbine with a set of 14-engines parameters and disclosed on Sept'2005 using gasoline [12]. In the basic single rotor Quasiturbine engine, an oval housing surrounds a four-sided articulated rotor, which turns and moves within the housing. The sides of the rotor seal against the sides of the housing, and the corners of rotor seal against the inner periphery, dividing it into four chambers.

iii. *Vaned type Air Turbine*

In an effort to curb pollution, a revolutionary motorcycle engine that runs on air is under development. The prime mover is a vaned type air turbine. The prototype in question uses a compressed air tank to power a turbine and provide motive power to the motorcycle. The compressed air tanks can get recharged with pumps running off solar or other renewable energy, thus making them a cheaper, eco-friendly alternative to hybrid electric vehicles. The engine works by pushing compressed air into a small turbine. The air expands and turns the turbine, powering the motorbike. No fossil fuels are required, and the only waste product is the expended air.

The developers of the engine, states that the technology is commercially viable and could be available to consumers within a year. As of now, the only major challenge is to develop a compressed air tank that can withstand the demands of long journeys. The current technology allows for 30 minutes of running time and the researchers are now working to develop a high-pressure tank that is good enough to power the bike for six hours. Numerous studies for optimizing efficiency of these air turbines have been done [13- 17].

IV. Vaned Type Novel Air Turbine as Prime-Mover to Motorbike

In this study a vaned air turbine shown in Fig. 3, 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 [18-22].

a) *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 [23-36].

From Fig. 4, it is seen that work output is due to isobaric admission from E to 1, and adiabatic expansion from 1 to 4 and reference points 2, 3 in the figure shows the intermediate position of vanes. Thus, total work output due to thermodynamic process may be written as:

[Area under (E145CE)] = [Area under (E1BOE) +Area under (14AB1) – Area under (4AOD4) + Exit steady flow (45CD4)]

or

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

or $$w = [(w_1) + (w_2)] \quad (1)$$

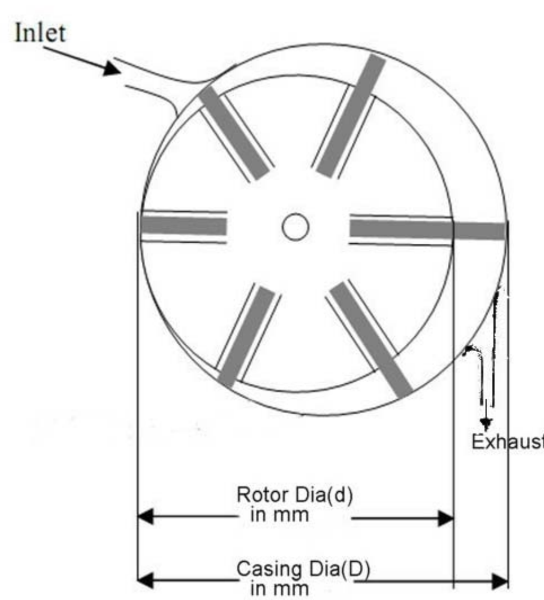

Figure 3 : Air Turbine Model

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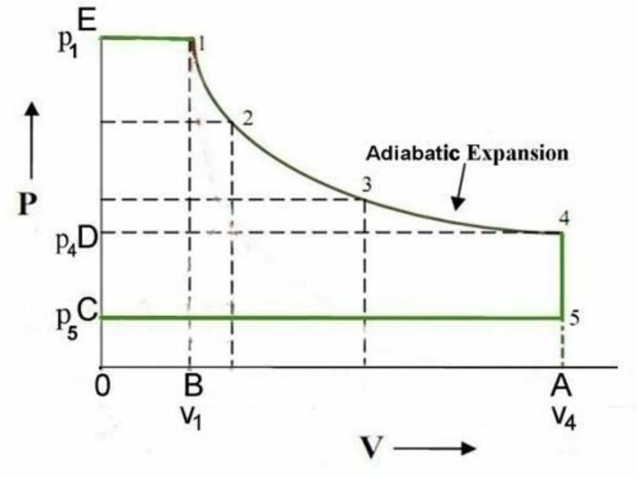

Figure 4 : Thermodynamic Processes (Isobaric, adiabatic and Isochoric Expansion)

Now thermodynamic expansion work (w_1), can be written as:

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

or

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

For adiabatic process, $p.v^{\gamma} = p_1.v_1^{\gamma} = p_4.v_4^{\gamma}$ = constant or $v_4 = \left(\frac{p_1}{p_4}\right)^{\frac{1}{\gamma}}.v_1$

Thus thermodynamic expansion work output would be:

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

The process of exit flow (4-5) takes place after the expansion process (E- 4) as shown in Fig. 4 and air is released to the atmosphere. In this process; till no over expansion takes place pressure p_4 can't fall below atmospheric pressure p_5. Thus at constant volume when pressure p_4 drops to exit pressure p_5 , no physical work is seen. Since turbine is functioning as positive displacement machine and hence under steady fluid flow at the exit of the turbine, the potential work is absorbed by the rotor and flow work (w_2), can be written as:

$$w_2 = \int_4^5 v.dp = v_4(p_4 - p_5) \quad (3)$$

Applying equations (2), (3) into equation (1), therefore net 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 [37] can be written as:

$$w_n = n.\left(\frac{\gamma}{\gamma - 1}\right).p_1.v_1\left\{1 - \left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\} + n.(p_4 - p_5).v_4 \quad (5)$$

where w_n is work output (in Nm), for complete *ne cycle.*

From Fig. 5, shows that when two consecutive vanes at OK and OL move to position OH and OB, the extended vane lengths varies from SK to IH and LM to BG, thus the variable length BG at variable α_i is assumed as $X_{at'variable'\alpha}$ can be written from the geometry:

$$BG = x_{at,variable'\alpha'} = R.cos\left[\sin^{-1}\left\{\left(\frac{R-r}{R}\right).\sin\alpha\right\}\right] + (R-r).\cos\alpha - r \quad (6)$$

where 2R=D is diameter of casing and 2r=d is diameter of rotor, α is angle ∠BOF, β is angle ∠BAF and θ is angle ∠HOB or ∠H'OF or ∠KOL, between two consecutive vanes and ϕ is angle ∠KOJ at which injection pressure admits to the air turbine.

Variable volume of cuboids B-G-I-H-B can be written as:

$$v_{cuboids} = L.\left\{\frac{(X_{1i} + X_{2i})(2r + X_{1i})}{4}\right\}.\sin\theta \quad (7)$$

where BG= X_{1i} and IH= X_{2i} variable length of vanes when rotate into turbine as shown in Fig. 5 and i stands for min or max length.

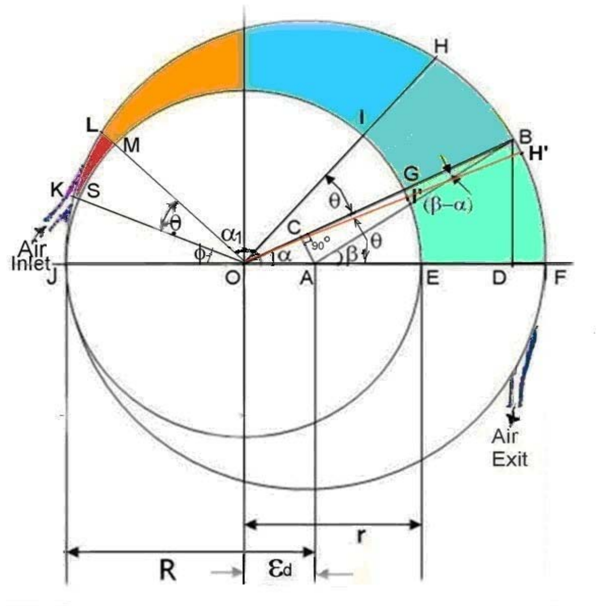

Figure 5 : Variable length BG and IH and injection angle ϕ

Thus the volume at;

a). inlet v_1 or v_{min} will fall between angle $\angle$ LOF= $\alpha_{1min} = (180 - \theta - \phi)$ and angle $\angle$ KOF= $\alpha_{2min} = (\alpha_{1min} + \theta) = (180 - \phi)$ as seen in **Fig. 5**, when air is admits into turbine at angle ϕ .

b). exit v_4 or v_{max} will fall between angle $\angle$ BOF $\alpha_{1max} = \alpha = 0$ and angle $\angle$ HOF $\alpha_{2max} = (\alpha_{1max} + \theta) = \theta$

Applying above conditions into equations (6), then LM=X_{1min} , SK=X_{2min}, FE=X_{1max}=Corresponding to BG at α =0 degree and I'H'=X_{2max}=Corresponding IH at $(\alpha + \theta) = \theta$ degree

Applying values of X_{1min} and X_{2min} to equation (7),

$$v_{min} = v_1 = L.\left\{\frac{(X_{1min} + X_{2min})(2r + X_{1min})}{4}\right\}.\sin\theta \quad (8)$$

Applying values of X_{1max} and $X_{2\,max}$ to equation (7),

$$v_{max} = v_4 = L.\left\{\frac{(X_{1max} + X_{2max})(2r + X_{1max})}{4}\right\}.\sin\theta \quad (9)$$

Applying values of v_1 and v_4 from equations (8) and (9) to equation (5), the total power output available W_{total} can be written as:

$$W_{total} = n.(N/60).\left(\frac{\gamma}{\gamma-1}\right).\left\{1-\left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\}p_1.\left[L.\left\{\frac{(X_{1min}+X_{2min}).(2r+X_{1min})}{4}\right\}.\sin\theta\right]$$
$$+n.(N/60).(p_4-p_5).\left[L.\left\{\frac{(X_{1max}+X_{2max}).(2r+X_{1max})}{4}\right\}.\sin\theta\right] \quad (10)$$

V. 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:

a) 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

b) 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).

VI. Theoretical and Experimental Results of Novel Air Turbine

The air engine is conceptualized as a novel vaned type air turbine is shown in Fig. 6. The air turbine

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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.

a) 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.

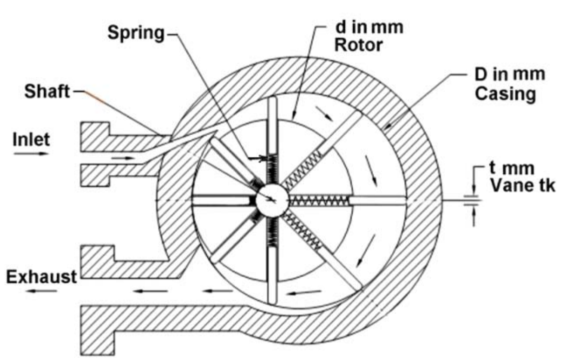

Figure 6 : Air turbine- schematic model

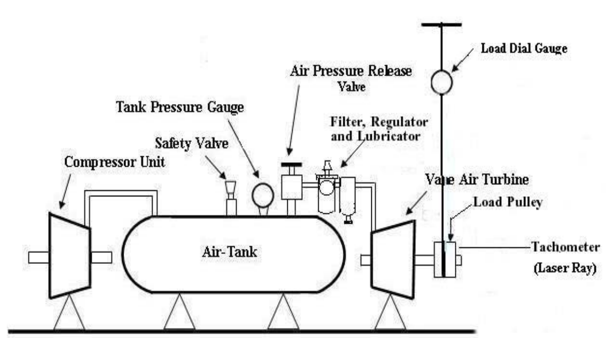

Figure 7 : Experimental test setup

b) Experimental Setup

The complete schematic of test setup is shown in Fig. 7. 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.

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. 7, 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.

i. *Compressor Unit*

As shown in Fig. 8, the specification of the 2-stage compressor is as under:

- The air compressor is of M/s ELGI Equipment ltd., Coimbatore, India's make. It is of two stage intercooled type and has specifications such as; TS 05 120H, Manufactured: 04/2003; 500 LPM, Maximum working pressure. 12Kgf/Cm^2, Speed; 925 RPM;
- The compressor is connected with an electric motor. The electric motor is of 05 HP (3.7 kW) - 3 phase, speed of rotation 1420 rpm, and runs at 415V, 8.2 Amps and 50 Hz frequency.

ii. *Compressed Air Storage Tank*

Compressed air storage cylinder / receiver is made of M/s ELGI Equipments Ltd., India's make and connected with 6 mm heavy duty steel tube attached with compressor unit exit nozzle point. The storage container has a capacity of 250 Ltrs (8.8 cuft) at atmospheric pressure and can attain 5000 Ltrs (176 cuft) of atmospheric air, when filled up to test pressure of 20 bar= (20.4 Kg f/Cm^2).

iii. *Safety Valve and Air Pressure Gauge*

Safety valve is introduced on storage tank to gauge the pressure and release automatically the pressure if it goes beyond the specified level of pressure 40 bar. The pressure gauge indicates the pressure attained in the storage tank for monitoring purpose.

iv. *Air Release Valve*

It is a unit by which compressed air is taken out. In this set up it is a manual pressure release link / latch which is rotated to regulate the air quantity to the air filter, air regulator and lubricator unit.

v. *Air Filter, Regulator and Lubricator (FRL)*

The filter, regulator and lubricator unit which ensures the life of air engine by filtering, regulating the desired pressure and lubricating the air engine to prevent the Tafcon 4 mm Vanes already fitted in to the slots of rotor. The filter, regulator and lubricator unit is used of SHAVO Make OLYMPION Filter, Regulator (BL set MAJ-200-M7EC); Model SB 13; ¼" BSP, Poly Bowl, 24 Micron and 0-20 bar regulator. It suits to regulate the desired pressure needed to be given to air engine through inlet pipe.

vi. *Construction of Air Engine*

The inner construction of air engine has following parts:

1. Housing / Casing of Air Engine

   It is made of cast iron with liner fitted inside to receive regular contact of vanes which prevents the leakage and develops rotational load on rotor.

2. Rotor and Vanes

   It is made of high tensile carbon steel of homogeneous material. Rotor length is decided depending upon the power load required and slots over the rotor periphery and to full length is cut to the depth more than the off-centre of Casing liner and Rotor diameters difference. Preferably CNC machine milling tools are to be used for very high precision and slots are made of 4+ (four plus) mm. size and accuracy is to be maintained to the order of micron. Tafcon vanes are fitted inside rotor slots and should be of exactly 4 mm. Vanes are required to slide inside the slots against centrifugal force and also loaded under spring to maintain regular contact with liner to avoid / reduce leakage between liner and vane contact once high pressure air enters to space of off centre between two consequent vanes as shown in Fig. 6.

3. Shaft and Load Pulley

   A pulley/sprocket is fitted with key over the extended portion of shaft. The shaft diameter is considered depending upon the load desired and for this novel engine it is of 17-18 mm (¾ ") diameter and extended about 35 mm 1 ½" approx.).

Fig. 8 : Heavy Duty 2-Stage Compressor

The actual setup of test rig of air engine / turbine was fabricated and air turbine was tested in the laboratory as shown in Figs. 8, 9, 10 and 11. 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.

Fig. 9 : Air filter, regulator and lubricator

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 as shown in Figure 2(e) and performance evaluation of the prototype air turbine is carried out.

Fig. 10 : Actual test rig of air turbine

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° or more with reference to which casing liner and rotor gap is nearly zero.

vii. *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.

Fig 11 : 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).

c) *Input Parameters*

For comparison of theoretical and experimental power output parameters are listed in Table-1.

Table-1

Input parameters for comparison of theoretical results with experimental values

Symbols	Parameters
D=2R, d=2r	(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	$=(v_1/v_4)^{\gamma}.p_1 \quad > p_5$ 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

VII. 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. 12.

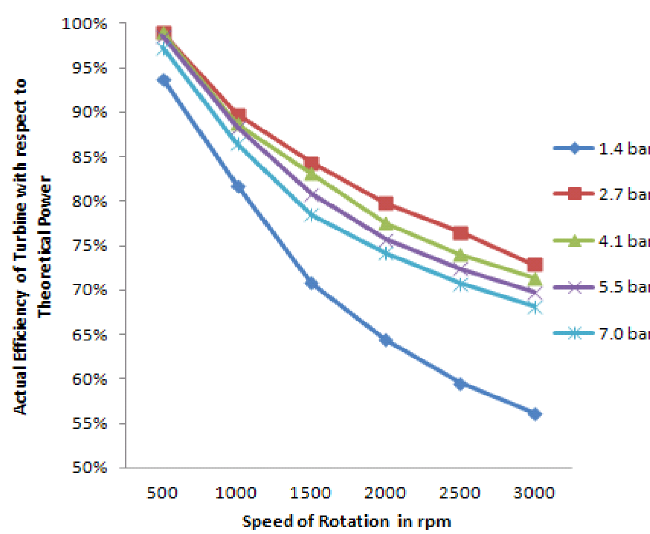

Figure 12 : Performance of vane turbine with respect to experimental power

Figure 12 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 of rotation 500 rpm for injection pressure 20 psi to 100 psi.
- 81.8% to 89.8% with variation of 8%, at the speed of rotation 1000 rpm for injection pressure 20 psi to 100 psi.
- 70.8% to 84.3% with variation of 13.5%, at the speed of rotation 1500 rpm for injection pressure 20 psi to 100 psi.
- 64.4% to 79.8% with variation of 15.4%, at the speed of rotation 2000 rpm for injection pressure 20 psi to 100 psi.
- 59.5% to 76.5% with variation of 17%, at the speed of rotation 2500 rpm for injection pressure 20 psi to 100 psi.
- 56.2% to 72.9% with variation of 16.7%, at the speed of rotation 3000 rpm for injection pressure 20 psi to 100 psi.

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%.

VIII. 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.

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