Estimation of Power and Mechanical Efficiency of Compressed Air Powered Quad Bike

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Abstract: Present work explains the working of the compressed-air vehicle (CAV) which is powered by an air engine using compressed air. Instead of mixing fuel with air and burning it in the engine to drive pistons with hot expanding gases, compressed-air vehicles use the expansion of compressed air to drive the piston. In a compressed air engine, air alone can be used as the fuel. Using air is the most suitable option because it drastically reduces weight of the vehicle and improves the efficiency. Present paper emphasises on conversion of a 4 stroke single cylinder SI engine into a compressed air engine with the minimum possible modification of the existing design.

Keywords: compressed air engine; mechanical efficiency; emissions; non-polluting vehicle

1. Introduction

Though fossil fuels meet the most of the worlds energy demand they are getting depleted rapidly also combustion products cause global warming which pose a great danger to the environment [6]. One of the possible alternatives is air powered vehicle which is free from pollution. Air is compressed to higher pressure at a low cost [2, 3]. Pneumatic control system plays very important role in industrial system owing to the advantages of easy maintenance, cleanliness, readily available, and cheap source, etc [12]. Compressed air was also used in some of vehicle for boosting the initial torque. Turbo charging has become one of the renowned techniques to enhance power and improve the efficiencies of the automotive engine that completely runs on compressed air. Compressed air is clean, safe, simple and efficient [2]. When air at atmospheric pressure is mechanically compressed by a compressor, the transformation of air from atmospheric pressure into air at higher pressure (up to 414 bar) is determined by the laws of thermodynamics [3]. Rise in pressure equals to a rise in heat and compressing air creates a proportional increase in heat [8]. Boyle's law explains that if a volume of a gas (air) halves during compression, then the pressure is doubled. Charles' law states that the volume of a gas changes in direct proportion to the temperature. These laws explain that pressure, volume and temperature are proportional; change one variable and one or two of the others will also change, according to this equation: (P1 V1) / T1 = (P2 V2)/T2 [3]. Air which is having a compressible property will make it as a fuel. Energy can be stored in air by compression and store in reservoirs, aquifers, or caverns. The stored energy is then released during periods of peak demand by expansion of the air. Compressed air storage could serve for electric utility load levelling or for storing electrical energy generated from solar or wind energy. The overall recovery efficiency is estimated to be about 65 to 75 %. The energy stored in the air could be utilized to drive a compressed air engine whose shaft would then drive a generator, pump or a vehicle [8]. In normal engines the charge enters from the inlet valve known as suction stroke then it is compressed by the piston due to crank rotation which is the compression stroke, then sparking takes place through the spark plug, the fuel ignites and combustion process takes place known as expansion stroke and finally the combustion product are let out of the engine by the exhaust stroke [10]. Here air is initially taken up from the atmosphere, and then it is compressed with the help of a compressor and sent to the engine cylinder. The compressed air is the source of energy that is stored in a high pressure cylinder. Basically this cylinder is re-filled by a compressor. Piston is assumed to be at top dead centre (TDC), the inlet valve is closed permanently and initially exhaust valve also remains closed. The compressed air gets filled in the clearance volume and when a small rotation is given to the crank this piston starts to slide down, the compressed air tends to expand and pushes the piston downwards. The piston moves from TDC to bottom dead centre (BDC) in one stroke. Now the exhaust valve opens and due to pressure difference the air filled in the volume of the cylinder moves out and piston moves up from BDC to TDC. In this manner one cycle gets completed in two strokes again the same process takes place and output is obtained [10]. The tanks used in an air compressed motor can be discarded or recycled with less contamination than batteries. The tanks used in a compressed air motor...
have a longer lifespan in comparison with batteries, which, after a while suffer from a reduction in performance. Refuelling can be done at home using an air compressor or at service stations. Reduced vehicle weight is the principle efficiency factor of compressed air vehicle [11]. In addition, as a form of energy, compressed air represents no fire or explosion hazards; as the most natural substances, it is clean and safe and regarded as totally green [12]. Compressed air vehicle are more suitable for low speed, short range and flammable environment. The moped which was designed yielded top speed of about 18 mph and could go 7 miles before its air pressure ran out [12]. Figure 1 shows the representation of the compressor air vehicle and figure 2 shows the schematic diagram and working of cycle on temperature–entropy diagram of the same [13]. Figure 3 shows the pressure volume diagram of the compressor air engine.

![Figure 1 Representation of the compressor air engine [13]](image1)

![Figure 2 Temperature entropy diagram of a compressor air engine [13]](image2)

![Figure 3 Pressure volume diagram of a compressor air engine [13]](image3)
The air is passed into the compressor to increase the temperature and pressure. The compressed air is supplied into the cylinder to push the piston to undergo expansion stroke. The pressure and temperature drops during this process. Finally the air is thrown out of the cylinder. In the cylinder two strokes exits which is expansion and the exhaust, previous process exists inside the compressor. Suction and the expansion process is isothermal process. Figure 4 shows the various parts of Air compressed engine which runs by compressed air.

II. Related Work

Łukasz Szabłowskia et.al [1] presented a dynamic analysis of the compressed air energy storage in the car. The analysis was used to determine those processes most relevant to achieving highest possible efficiency. D.Ravi [6] analysed the thermodynamic efficiency of a compressed-air car powered by a pneumatic engine and considered the merits of compressed air versus chemical storage of potential energy. It was concluded that pneumatic-combustion hybrid is technologically feasible, inexpensive and could potentially compete with hybrid electric vehicles. Saurabh Pathak et.al [5] discussed environmental friendly properties of air, and concluded it as one of the future fuels which will run the vehicles. So this paper makes an effort to determine the potential advantages and disadvantages of the compressed air technology. Hemant Kumar Nayak et.al [7] explained how the manufacturing of air compressed vehicles would be environment friendly as well as put the favourable conditions for the cost. This study shows the comparison of different properties related to CAV and FE (Fuel Engines). Abhishek Lal [8] designed and performed a dynamic analysis of a light weight single stroke compressed air engine it does not required any of the fossil fuels like petrol, diesel, CNG, LPG, hydrogen etc. to run engine and no power is required to start up engine only compressed air valve is to be opened. It works on compressed pressure air and hence is pollution free and 100% eco-friendly. Mohammad Masood [9] carried out experimental analysis on the modified engine to find out its performance characteristics like brake power, mechanical efficiency, overall efficiency, air to Air ratio, volumetric efficiency, cost analysis etc. Though the efficiencies were low as the frictional forces were high for the proto designed engine, however the concept can be applied on a professionally designed engine to improve its performance. Arjit Mourya et.al [10] explained how the engine takes in the compressed air instead of using traditional fuels such as petrol diesel etc. Here this compressed air engine takes the intake of air from the vertically above the piston head. The design of the camshaft has been changed to alter the timing of the valves. Experimentally a speed of 60kmph was achieved by the use of this engine which is better than other works produced on the same topic. It is also efficient as the pollution caused is zero. Results suggested that it is efficient than electrically operated vehicles as they can be charged instantaneously and amount of compressed air can last for a longer time which is not the case with electrically operated vehicles. Hence this engine can prove to be very successful and sustainable in future. Anirudh Addalav [11] described a double acting pneumatic cylinder which is operated as a slider crank mechanism which converts the linear reciprocation of the cylinder piston rod into oscillatory motion of the driver crank about the pinion shaft. This paper concluded that pneumatically operated vehicle has low weight, easy circuits, takes less time for refuelling and requires less maintenance. Prof. Kalpesh Chavda et.al [13] reviewed on compressed air engine for the design and development of single cylinder engine which can be run by the compressed air. Four strokes single cylinder engine (bikes/moped) can be run on the compressed air with a few modifications that are the main objective of the study. Franco Antony et.al [14] built a pneumatic hybrid vehicle in which the vehicle is being powered up by an internal combustion engine and an air engine; output is being taken up as desired. Results showed that the pollution and fuel consumption of the internal combustion engine vehicles can be minimized by the use of the pneumatic hybrid vehicles.
III. Methodology

Pneumatic cylinders or air cylinders are mechanical devices which use the power of compressed air to produce a force in a reciprocating linear motion or cylinders which converts pneumatic power into mechanical power [12]. Compressed air forces the piston to move in the desired direction. Because air is expandable substance, it is dangerous to use pneumatic cylinder at high pressure so they are limited to 8 bar (gauge) pressure [12]. Consequently they are constructed from lighter material such as aluminium (Alloy) and brass. Because gas is compressible substance, the motion of pneumatic cylinder is hard to control precisely. The force exerted by the compressed air moves the piston in two directions in a double acting cylinder. The fluid pushes against the face of the piston and produced force. The force produced is given by equation (1)

\[ F=PA \]  

(1)

The velocity of piston and rod depends upon the flow rate of fluid. The volume of fluid per second entering the cylinder must be the change in volume per second which is given by equation (2) [12].

\[ Q = A \times V \]  

(2)

The network obtained from the p-v diagram is the network produced in the cylinder as measured by an indicator diagram, the power based there on is termed indicated power (IP) [3]. It is represented by equation (3).

\[ IP \leq P_{mp}L A N X 2 \]  

(3)

The product of the moment arm R & the measured force F is termed the torque of the engine & is usually expressed in Nm. Torque, T is the uniform or fluctuating turning moment, or twist, exerted by tangential force acting at a distance from the axis of rotation [3]. For an engine operating at a given speed and delivering a given power, the torque must be fixed amount, or the product of F and R must be the constant (T=FR). The equation for break power is given by the equation (4).

\[ BP= 2\Pi nt \]  

(4)

Mechanical efficiency represents the output after the assembly of all linkages. It gives how much efficiently the system works after incurring various losses. Equation (5) represents the mechanical efficiency.

Mechanical efficiency= \( BP/IP \)  

(5)

For this project first 4 stroke HONDA 160 cc engine was acquired. Working of the engine was studied to see how and what modification can done so that the engine can converted into a compressed air engine. On examination it was understood that supply high pressure air through the spark plug port is possible. Since in a normal 4 stroke engine, combustion of the fuel pushes the piston down it was decided to let in high pressure air to do the mechanical work of pushing the piston down. The carburettor was removed and exhaust and then purchased a pipe of 0.5mm and a suitable connector. One end of the pipe was connected to the outlet of an air compressor and the other end was connected to the inlet (spark plug port) of the engine. Air was supplied slowly and it was realized that at least 7 bar of pressure required to push the piston down with a good speed. To pulsate the pressure a Solenoid valve was used which supplies and cuts off air at every revolution of the flywheel. It was needed to convert the 4 stroke engine into a 2 stroke engine where air exits with every complete revolution. Hence the cam was taken out and was decided to make a similar cam profile such that the exhaust opens every revolution. To run the 24v solenoid valve two 12v batteries was procured and connected them in series. A sensor was made to sense the timings hence the possibility of a reed switch was looked at. On using the reed switch a lot of backpressure was developed and gave the engine speed but not much of torque. Hence possibility of a limit switch was looked at with a roller end which proved highly effective and helped to produce enough torque to run the engine.

To place the engine a chassis was selected. On searching a quad bike chassis is used. To reduce weight few parts were removed. Engine mounting was made to hold the engine in the chassis. Suitable tyres were placed and adjustments were made to make the chassis lighter in weight. The sprocket connecting the chains to the sprocket on the driving shaft had to be modified to fit the shaft our engine. On testing of the chassis it was not feasible to move the air compressor along with the quad bike, hence it was opted for a compressed air cylinder housing around 13 litres of air and able to give out a pressure of 10 bar. A tank was procured and a pressure regulator to regulate the pressure. The tank was placed inside the chassis and closer to the engine to minimize the time taken for the exhaust gas to escape. Testing and trials were done and modifications were done accordingly to run the quad bike smoothly on compressed air.
Figure 5 shows the steps involved in building an air compressed vehicle. It begins with the problem definition. Each and every component is designed and optimum material selection is carried out. Compressor is assembled to the cylinder which supplies the air inside to run the engine [6].

Figure 5 Methodology in design and fabrication of a compressed air vehicle

IV. Design and Construction

Working model of compressed air vehicle consists of various elements. Appropriate design and the material selection hold the key for obtaining the final output. HONDA GX 160 motorcycle engine has been used for modification into compressed air engine. There are several structural change required to be done to run the engine with compressed air. The parts like the spark plug, carburetor, exhaust pipe and fuel tank that was not of any use for the compressed air engine was removed hence reducing the weight and load on the engine. Inlet supply from the compressor/storage tank was supplied through the spark plug port using a connector as shown in figure 6. The existing 10 mm cam shaft was in a manner that the exhaust port opens only in the fourth stroke of the cycle. Hence the cam was modified such that the eccentricity has been changed to a 180 degree profile such that the exhaust valve opens in the second stroke itself. Both the exhaust and inlet cams are symmetric about the centerline of the cam shaft. Figure 7 shows the valve timing where a series of trials was done to get the right valve timings. The right valve timings are when the inlet opens and the exhaust valve closes completely when compressed air is supplied and opens up when the piston is moving from BDC to TDC and also ensuring there is no backpressure. The cam and the sprocket were placed accordingly. The trial basis of a single stage compressor with an operation pressure of 8 bar and 60 litre tank was used to supply compressed air. After trials and due to the low pressure supplied and immobility, the compressor was replaced with a compressed air storage tank of 13 liters and operating pressure of 150 bar. A pressure gauge was attached to cylinder to regulate the pressure which is shown in the figure 8. A solenoid valve shown in figure 9 is an electromechanically operated valve. The valve is controlled by an electric current through a solenoid. It operates at 10 bar at 24 V. The valve procured was a 3/2 valve. To provide a pulsating pressure a reed switch is connected to the solenoid valve. At every revolution the reed switch supplies and cuts air supply to the engine. The reed switch is actuated by the magnet present on the fly wheel. Roller/Limit switch is a switch operated by the motion of a machine part or presence of an object. They are used for control of a machine, as safety interlocks, or to count objects passing a point. A limit switch is an electromechanical device that consists of an actuator mechanically linked to a set of contacts. When an object comes into contact with the actuator, the device operates the contacts to make or break an electrical connection shown in figure 10. Supply is given to the solenoid valve using two 12 V batteries connected in series. Positive terminal of battery is connected to “1” of limit switch and “4” to the solenoid. The dead of the solenoid is connected to the negative of the battery. Chassis Fabrication: A quad bike chassis was procured to mount the air...
engine. Necessary fabrications were incorporated to fit the engine in the chassis. Suitable tyres was selected and fitted into the existing chassis for better surface contact and reduction in load to increase the power to weight ratio few parts of the chassis were cut out. A thorough cleaning and rust removal process using sand paper was done. Two new chains were procured and connected together to fit from the drive shaft sprocket to the rear axle. Since the air engine was smaller it had to be mounted onto a platform. A mounting base was made using steel plates. Four steel plates were procured and were cut 20mm in length. The base plates were welded together using electrode arc welding process and a strong mount was formed. Figure 11 shows the Quad Bike Chassis or the air compressed vehicle assembly.

![Figure 6 Inlet Supply](image6)

![Figure 7 Setting timing](image7)

![Figure 8 Pressurized air tank](image8)

![Figure 9 Solenoid Valve](image9)
After the construction of the compressed air vehicle, mechanical efficiency of the entire system is determined. Air is compressed and made to pass into a compressor. High pressure and temperature air is passed into a cylinder. Piston is pushed downwards with a velocity. And the total volume of air inside a cylinder with respect to time is a function of velocity.

**Table 1 Calculation of various parameters inside the cylinder**

<table>
<thead>
<tr>
<th>Sr No</th>
<th>Area of cross section ( \text{m}^2 ) of the cylinder (Bore)</th>
<th>Pressure (Bars)</th>
<th>Fluid Force (N) against the piston</th>
<th>Time taken for air to fill in the cylinder (s)</th>
<th>Velocity of the piston (m/s)</th>
<th>Volumetric flow rate ( \text{m}^3/\text{s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( 1.96 \times 10^{-3} )</td>
<td>3</td>
<td>589</td>
<td>2</td>
<td>0.025</td>
<td>( 4.90 \times 10^{-5} )</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>981</td>
<td>1.5</td>
<td>0.03</td>
<td>7.84 \times 10^{-5}</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>1374</td>
<td>1.25</td>
<td>0.04</td>
<td>( 9.80 \times 10^{-5} )</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>1963</td>
<td>1</td>
<td>0.05</td>
<td>( 1.176 \times 10^{-4} )</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>2552</td>
<td>.75</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1 shows the details of various parameters inside a cylinder. Figures 12 and 13 show that with the increase in the fluid pressure there is a rise in the force acting on the piston also there is a rise in the velocity of the piston. Indicated mean effective pressure is the average pressure acting on a piston during power stroke of its cycle. By considering the length of stroke is 100 mm, bore diameter 50 mm and the speed of rotation is 350 rpm.

### Table 2 Calculation of power and mechanical efficiency

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Indicated mean effective pressure</th>
<th>Torque (N-m)</th>
<th>Indicated power (IP) (kW)</th>
<th>Brake power (BP) (kW)</th>
<th>Mechanical Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>5.89</td>
<td>0.686</td>
<td>0.215</td>
<td>31.46</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>9.81</td>
<td>1.143</td>
<td>0.359</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>13.74</td>
<td>1.60</td>
<td>0.503</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>19.63</td>
<td>2.286</td>
<td>0.719</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>25.52</td>
<td>2.972</td>
<td>0.935</td>
<td></td>
</tr>
</tbody>
</table>

Figure 13 Variation of velocity of the piston vs fluid pressure

Figure 14 Variation of mean effective pressure vs indicated power

Figure 15 Variation of brake power with torque

Table 2 shows the calculations of various powers with the change in torque and mean effective pressure. Figure 14 shows that there is an increase in indicated power with the rise in mean effective pressure and Figure 15 shows that with the increase in torque there is a rise in brake power. By considering both indicated and brake power, mechanical efficiency is calculated which is equal to 31.46 %. Results are validated with the results obtained from JP Yadav et.al [3], and it shows that results are similar.
VI. Conclusions

On running the engine it was noted that on heavy load the engine couldn’t provide enough torque to move the buggy. On increasing the pressure to about 10 bar the buggy started moving at about an average speed of 5 km/hr. The compressed air cylinder tank of capacity 13 liters and with operating pressure of 150 bar could run the engine on a full run. It’s important to remember that while vehicles running on only compressed air might seem like a distant dream, but they still have public interest due to their environmental friendly nature. Efforts should be to make them light, safe, cost effective and economical for driving. Electric-powered cars and bikes already available on the market put a strong competition to compressed air car not only in terms of cost but also their environment friendly role. The technology still looks distant but that has not deterred inventors from working on it. The engine comprised of an air tank of 13 liters which could hold air just enough to run the engine for limited time period. Developments can be made to make a higher capacity tank. The tank could be made of carbon fibre so on impact it is able to withstand the force and pressure hence making it safe. The engine we selected was a 160cc engine which couldn’t generate much torque and speed. A higher capacity engine capable of 300 cc would be appropriate to achieve good performance from the compressed air engine.

Cam modifications were done by trial and error. The cam needs to be designed on proper design methods hence to achieve better performance. The engine was placed on an existing chassis. The chassis selected was not in line with the selected engine. Thus the engine had difficulties to carry such a heavy load. For a future scope the chassis must be designed in a way such that it is light and the engine is able to carry the load. This type of engine is the future with the ability to use air from the surroundings. Producing no pollution and with a good scope for the future. Further analysis of cylinder and piston can also be carried out by using velocity and acceleration diagram. Finite element method can also be used to analyze the parameters inside the cylinder.

Nomenclature

\[ F = \text{Force acting on the piston, N} \]
\[ P = \text{Pressure, N/m}^2 \]
\[ A = \text{Area of cross-section of the cylinder, m}^2 \]
\[ Q = \text{Volumetric flow rate, m}^3/\text{s} \]
\[ IP = \text{Indicated power, kW} \]
\[ BP = \text{Brake power, kW} \]
\[ P_{\text{mean}} = \text{Mean effective pressure, bars} \]
\[ L = \text{stroke length, m} \]
\[ N = \text{Speed of rotation, rpm} \]
\[ T = \text{Torque, N-m} \]

VI. References