Modification of 4-Stroke S.I. Engine to a Compressed Air Engine for a Light Utility Vehicle

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Abstract. The paper presents experimental investigation of a 100-cc four-stroke air-cooled SI engine modified to be driven by compressed air. The engine was modified from a conventional four-stroke to a two-stroke engine by designing a new cam system driven by the crankshaft. Variations in pressure were noted and the engine was tested at different engine speeds and inlet pressure for analyzing several performance parameters such as torque, efficiency and power output. This technology has a long way to go, but for light utility vehicles it can be the game changer. It can trim down our current demand for fossil fuels to some extent and alleviate the problem of global fuel crisis. The major intent of this study is to explore the compressed air engine technology and its viability as a transportation option by enhancing various performance parameters.

1. Introduction
Recent times have called for a search for alternative sources of energy, and reduction in carbon emissions in the automotive sector because of rapid depletion of fossil fuels, high fuel prices, and harmful emissions from IC Engines. The automotive sector has high dependence on the fossil fuels despite the availability of new technologies such as Electric powered Vehicles, Hydrogen Fuel Cell, and Solar Energy. But due to certain factors ranging from high cost to complex mechanisms, these technologies have not been implemented in mass produced vehicles effectively. In case of compressed air technology, cost and complexity are not issues to worry about. Instead it makes the engine even simpler than conventional IC engines. A Compressed-air engine is a pneumatic actuator that extracts useful work by the expansion of the pressurized air. Compressed-air vehicle is driven by an air engine which utilizes compressed air stowed in a pressurized container onboard. Despite of using the chemical energy of the fuel by igniting the air-fuel mixture and drive the piston by means of hot expanding gases, the Compressed Air Vehicles draws power from the potential energy of compressed air.

This technology is relatively very environment-friendly compared to the other sources used in the current automotive sector. The only carbon footprints left behind using this technology are mainly from the way the air is compressed. Since, there is no combustion taking place, there are zero tailpipe emissions. The only thing coming out of the exhaust is air. Compressed air can power a vehicle individually or as an auxiliary system alongside some other power source. The technology combined with other compatible technologies such as Regenerative Braking can minimize the urban pollution and revolutionize the way people travel [1]. In USA, one-fifth of the total emissions is caused by the personal vehicles and create a substantial amount of air pollution. With light utility vehicles deployed...
with compressed air technology, the general public could reap the benefits of a vehicle with zero air pollution. Moreover, the huge amount of money spent on fuel can also be saved and put to a better use [2].

The automotive companies such as MDI (Motor Development International) developed a conceptual vehicle named Air Pod which uses compressed air as the chief power source [3]. In addition, compressed air is also used as a secondary power source in conventional Internal Combustion engines to improve efficiency. The Group PSA developed a concept called Air Hybrid which used conventional IC engine alongside compressed air technology, and regenerative braking which converts vehicular kinetic energy to the potential energy of the compressed air during braking. This approach enables the optimum usage of the fuel which increases IC engine fuel efficiency and cuts emission by a great extent [4]. An Australian company, Engine Air, handled by Angelo Di Pietro, developed an air rotary engine, and implemented it in various concepts including car, bike, and go-cart claiming that the engine is very efficient.

Numerous studies assessing the potential of compressed air engines have been carried out in the past. For instance, Huang et al., [5,6] performed experimental investigations on 100 cc 4-stroke IC engine supplied by Taiwanese motorcycle manufacturer KYMCO and installed that engine on a motorcycle which could operate at speeds fit for urban driving. Shen et al., [7] powered an SYM 125-cc Motorcycle via an air motor and eliminating unnecessary components such as fuel tank, carburetor, battery, and exhaust pipe. Ashraya Gupta et al., [8] modified a 2-stroke engine to run on compressed air and further enhanced the engine performance by optimizing various parameters of the compressed air engine.

In these studies, an SI engine is chosen over the CI engines due to its compact size, light weight, and high RPM. CI engines on the other hand are heavy because high amount of pressure is applied on the walls of the cylinder due to its higher compression ratio which is around 16:1 to 20:1 as compared to SI engine which is around 10:1. Thus, higher temperature resistant and heavy materials are used for building the CI engines thereby making it heavy and disadvantageous for implementing in the compressed air vehicle. Thus, a 4-Stroke SI engine is more suitable for the compressed air technology.

With few modifications, removal, and addition of parts, the engine was customized to be appropriate to run on compressed air.

Figure 1. Photographic Image of Engine used for the testing.

2. Experimental Setup
2.1. Engine Modifications
A 100-cc Four-Stroke SI engine manufactured by Bajaj Auto, an Indian motorcycle manufacturer, was used and tested on compressed air. Before running the engine on compressed air, few modifications were made to make it compatible with the compressed air. Firstly, unnecessary components such as carburettor, exhaust pipe, spark plug, and Ignition System were removed as they find no application in a compressed air engine.

Table 1. Engine specifications.

| Engine          | Air Cooled, Four-Stroke SI |
|-----------------|----------------------------|
| Fuel Type       | Petrol (before modification) |
| Manufacturer    | Bajaj Auto                 |
| Displaced Volume| 102 cc                     |
| Stroke          | 58.8 mm                    |
| Bore            | 47 mm                      |
| Compression Ratio| 9.5:1                      |
| No. of Cylinders| 1                          |
| No. of Valves   | 2                          |
| Inlet Port Diameter | 20 mm                  |
| Exhaust Port Diameter | 16 mm                |

After removing the unnecessary components as stated above, the engine was transformed from a 4-stroke engine to a 2-stroke engine. This was done by designing a new camshaft for opening the valves at different timings. The stock camshaft had two different cam lobes, one for opening the inlet valve while the other for opening the exhaust valve. The newly designed camshaft is a double lobe camshaft which means there is an additional cam lobe present on the opposite side of the previous lobe as shown in the figure 2.
The newly designed camshaft opens each valve twice in a complete 4-stroke cycle. In other word, it can be interpreted that the cycle is repeating itself after every two strokes. Thus, in one complete revolution of the crankshaft, both the valves open once resulting in one power stroke and one exhaust stroke, eliminating the compression stroke and intake stroke. The camshaft was designed in such a way that it increases the valve lift by one mm which results in the increase of air intake.
Figure 4. P-V diagram.

Figure 5. Intake/Power stroke and exhaust stroke.
2.2. Layout

The layout of the complete experimental setup after the various modifications is as follows:

Figure 6. Experimental setup.

1. Compressor
2. Compressed Air Cylinder
3. Stop Valve
4. High Pressure Regulator
5. Low Pressure Regulator
6. PTFE Hose
7. High-Pressure Flow Rate Sensor
8. Solenoid Valve
9. 12V Batteries
10. Modified Single Cylinder Engine
11. Dynamometer

The air from the compressor was kept in a high-pressure tank which act as a reservoir. The compressor used in the experiments was the NPHPC-100 model manufactured by Nimpra Equipments Pvt Ltd. The storage tank plays a prominent part in the efficiency of compressed air vehicle technology because the range of the vehicle is reliant on the amount of pressurized air stored. The tank also affects the weight of the vehicle, therefore, the materials used for building the tanks should be chosen wisely. Recent trends have also suggested that using Kevlar or Carbon-fibre can reduce the weight of the tanks to a great extent without compromising its strength [9,10,11].
Figure 7. Photographic image of compressor and storage cylinder (tank).

For the flow of compressed air from the tank, PTFE hoses were used due to their properties of outstanding chemical resistance and extensive range of thermal resistance with working temperatures being between -70 °C to 260 °C. They also have a very low coefficient of friction from 0.02 to 0.2, and resistant to aging and weather conditions [12]. The pressure of compressed air was adjusted using a high-pressure regulator and a low-pressure regulator and then released into the inlet port of the engine. The air then entered the cylinder through the opening of the inlet valve when the piston reaches around 20° before TDC.

The cam system driven by the crankshaft mechanism which is used to cause the inlet and exhaust ports to open, was reserved for quick reaction rate. However, the valve could not withstand the high pressure, and leakage was observed which resulted in dropping the efficiency of the compressed air engine. To overcome this, a 24V DC Normally Closed Solenoid Valve was used. The solenoid valve is an electromechanical activated valve to regulate the stream of fluids. The solenoid valve is highly reliable and offers fast switching [13,14].

Figure 8. Photographic image of 24V DC normally closed solenoid valve.
Figure 9. Photographic Image of 12 V 2.5 Ah Batteries used for operating the solenoid valve.

This valve was timed in accordance with the inlet valve i.e. at IVO the solenoid valve allows compressed air to enter the cylinder. The solenoid valve was timed using the Infrared Sensors which could detect the position of the piston. Two 12V 2.5 Ah batteries connected in series were used to supply the required current to open the solenoid valve when the signal is received from the Infrared Pair which consists of an infrared emitter and an infrared sensor. Both the emitter and receiver are of the same rating [15].

3. Analyses and Results
Using the outcomes of the earlier performed studies on various setups, the injection timing of the compressed air was fixed at 20° BTDC. The engine was started with the kick starter which was retained from the previous setup when the crank angle was not in sync with the solenoid valve. RPM was found out using a Digital Infrared Photo Tachometer. RPM variations with respect to the pressure input were observed. The supply pressure was varied using the pressure regulators and the external load was adjusted using Rope break dynamometer. High pressure flow sensor was also equipped to measure the flow rate of the compressed air entering the engine cylinder.

The power output and torque output from the compressed air engine were observed and noted at different pressures extending from 5 bar to 9 bar. The power output, torque output, flow rate and efficiency characteristics at different RPMs and working pressure are shown in the figure 9-12 respectively.

It was noted that the power of the engine gradually increases with the increase in rotational speed and attains a zenith value after which it starts to decrease abruptly. The maximum power of 0.9 KW was observed at around 1300 RPM and at a pressure of 9 Bar. The engine’s power output was also limited due to the limited valve lift movement.
The torque output was maximum at the initial RPMs and started decreasing slowly as the engine speed started to increase. The maximum torque with a value of 10.3 Nm was observed at 400 RPM and pressure of 9 bar. Thus, at the lowest rotation speed and the highest supply pressure the maximum torque can be achieved.

The flow rate of the compressed air was measured using a High-Pressure Flow Sensor at different pressures and engine speed.
The efficiency of the engine was observed and it was noted that the maximum efficiency was achieved at the lowest working pressure and low engine speeds. The efficiency at 5 bar supply pressure was found out to be extreme. High source pressure increases the power output but brings a considerable drip in the efficiency.

**Figure 12.** Flow rate vs Rotation Speed (RPM) Graph.

**Figure 13.** Efficiency vs RPM graph.
4. Conclusions
In this study, experimental analyses of a modified 100-cc single cylinder 4-stroke engine were performed.

1. The work presents the power output and torque output inspection at varying supply pressure. It can be interpreted from the results that the engine can be operated well in the tested band of pressure i.e. from 5 to 9 bar.

2. The pressure can also be increased further at the expense of decreased efficiency. The output power achieved was lower than the conventional IC Engine using gasoline. However, the torque output was greater than that observed in the IC engine.

3. The power output was restricted because of the inadequate motion of the intake valve which was obstructing the compressed air flow. The overall performance parameters could be enhanced more by implementing better intake and exhaust valve mechanisms. This could further improve the efficiency as well and the engine could be operated at higher pressures.

4. Since, the energy output and range of a CAV largely depends on the extent of energy stored in the storage tank, the vehicles design necessitates the use of fuel with high energy density. However, the compressed air is a poor energy carrier with very low energy density compared to other conventional fuels.

5. The low energy density per volume of the compressed air creates significant challenges in making of compressed air vehicles but using the technologically advanced high-pressure tanks made of Kevlar or carbon-Fibre could help mitigate the problems [16,17].

6. It is important to mention that, although research has been carried out using this technology, it has got a long way to go to be implemented in mass produced vehicles.

![Figure 14. Energy Density of compressed air and various other transportation fuels](image)

5. References

[1] Christopher Lampton "How the Air Car Works" 27 October 2000. HowStuffWorks.com. <https://auto.howstuffworks.com/fuel-efficiency/vehicles/air-car.htm> 29 October 2018.

[2] F. Wicks, Maleszweski, J., Wright, C., and Zarybnicky, J., “Analysis of compressed air regenerative braking and a thermally enhanced option,” 37Th Intersoc. Energy Convers. Eng. Conf. (20139):406– 411, 2004, doi:10.1109/IECEC.2002.1392063.
[3] https://www mdi lu products
[4] https://www groupe psa com/en/newsroom/automotive-innovation/hybrid-air/
[5] Y. Wang, J. You, C. Sung, and C. Huang, “The Applications of Piston Type Compressed Air Engines on Motor Vehicles,” Procedia Eng., vol. 79, no. 1st ICM, pp. 61–65, 2014.
[6] C.-M. Liu, J.-J. You, C.-K. Sung, and C.-Y. Huang, “Modified intake and exhaust system for piston-type compressed air engines,” Energy, vol. 90, pp. 516–524, 2015.
[7] Y.-T. Shen and Y.-R. Hwang, “Design and implementation of an air-powered motorcycles,” Appl. Energy, vol. 86, no. 7, pp. 1105–1110, 2009.
[8] A. Gupta, H. Kathpalia, H. Aggarwal, and N. Kumar, “Performance Based Optimization of Intake and Injection Parameters of an Advanced Compressed Air Engine Kit.” SAE International, 2017.
[9] http://cair wikia com/wiki/Compressed_air_tank
[10] X. Yin, Y. Lin, and W. Li, “Operating Modes and Control Strategy for Megawatt-Scale Hydro-Viscous Transmission-Based Continuously Variable Speed Wind Turbines,” IEEE Trans. Sustain. Energy, vol. 6, no. 4, pp. 1553–1564, 2015.
[11] B. S. S. Verma, “Latest Developments of a Compressed Air,” vol. 13, no. 1, 2013.
[12] http://www tubes international com/catalogue_pdf/hoses_compensators/ptfe_hoses
[13] https://www fluidcontrols co uk/what-is-a-solenoid-valve/
[14] https://tameson com/solenoid-valve-types.html
[15] C. Rao Seela, D. V. Rao, and M. V. Rao, “Performance Analysis of an Air Driven Engine Modified from SI Engine,” Res. Artic. Int. J. Curr. Eng. Technol. Accept., vol. 3, no. 4, 2013.
[16] M. Q. Wang, “GREET 1.5 - transportation fuel-cycle model - Vol. 1: methodology, development, use, and results.” Argonne Nationa Lab., p. 218, 1996.
[17] D. Linden et al., “Linden’s Handbook of Batteries,” 2004.
[18] A. Papson, F. Creutzig, and L. Schipper, “Compressed air vehicles: Drive-cycle analysis of vehicle performance, environmental impacts, and economic costs,” Transp. Res. Rec., no. 2191, pp. 67–74, 2010.