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# PERFORMANCE EVALUATION OF A SINGLE CYLINDER COMPRESSED AIR ENGINE: AN EXPERIMENTAL STUDY

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**Abstract:** The quest to reduce dangerous environmental emissions has led to the research and use of alternate and renewable energy sources. One of the major contributors to the dangerous environmental emissions is the automotive industry. The world is, therefore, quickly moving towards hybrid and electric vehicles. An alternate pollution-free automotive engine is a compressed-air engine, which is powered by compressed air and is more efficient than the electric engine since it requires less charging time than a traditional battery-operated engine. Furthermore, the tanks used in compressed-air engines have a longer lifespan in comparison to the batteries used in electric vehicles. However, extensive research is required to make this engine viable for commercial use. The current study is a step forward in this direction and shows the performance analysis of a single-cylinder compressed-air engine, developed from a four-stroke, single-cylinder, 70 cc gasoline engine. The results show that compressed-air engines are economic, environmental friendly and efficient.

**Key words:** internal combustion engines, compressed air engines, engine analysis, single cylinder engine

## 1. INTRODUCTION

Engines, of both combustion and non-combustion types, are used to convert energy into useful mechanical motion. Combustion engines convert the energy of the burning fuel, viz. expansion of the high-pressure and -temperature gases produced during the burning of fuel, to mechanical work. The combustion process, besides producing mechanical work, generates and releases environment-polluting emissions, such as unburned hydrocarbons, carbon dioxide, nitrogen oxides, volatile organic compounds, particulate matter and so on [1]. The environmental challenges posed by combustion engines used in passenger cars have forced the automotive industry to look for environmental alternatives, such as compressed-air engines [2]. A compressed-air engine is powered by compressed air stored in a tank. Instead of creating an air–fuel mixture and burning it in the engine to drive pistons with the expansion of hot gases, compressed-air engines use the expansion of compressed air to drive their pistons. Hence, air-compressed engines have the inherent benefits of pollution-free character and economy in terms of fuel and lubrication (since ignition procedure is completely eliminated and a wide range of motor oils can be used for lubrication purposes for a longer period) [3]; moreover, there is no need for a separate air-conditioning system (the exhaust air can be used for air conditioning) [4].

The first compressed-air vehicle was developed for a locomotive by Bompas in England in 1828. There were two storage tanks between the frames, with conventional cylinders and cranks. The first documented compressed-air vehicle in France was built by the Frenchmen Tessie and Andraud of Motay in 1838. A compressed-air-run car was tested on a test track at Chaillot on 9 July 1840 and it worked well. A similar vehicle was made by Barin von Rathlen in 1848 and was driven from Putney to Wandsworth (London) at an average speed of 12 mph. During the 1850s, a French engineer called Julienne drove a self-made compressed-air car at Saint Denis in France, driven by air compressed at 350 psi. He used it in coal mines. In 1874, the famous Simplon tunnel was dug by using compressed-air locomotives and the cold exhaust of the engine was used for ventilation in the tunnel. Louis Mekarski built a standard-gauge self-contained tramcar, which was tested in February 1876 on the Courbevoie-Etoile Line of the Paris Tramways Nord (TN), which impressed the President and Minister of Transport Maurice de McMahon [5,6,7].

Various companies are financing the research, development and deployment of compressed-air locomotives. Overoptimistic reports indicating 'awaiting production' date back to at least 1999. For instance, an air car manufactured by the French company Motor Development International (MDI) made its public debut in South Africa in 2002, and it was predicted that production will start 'within 6 months' in January 2004. But until January 2009, the air car never went into production in South Africa. But the company started its production in France in 2009. And currently, MDI's air car is common on the roads of Paris, Orleans, Marsille and Lyon. Tata Motors, in collaboration with MDI, planned to develop a car, named AIRPod, which would run on compressed air and could travel 140 km. Tata planned to launch this car in 2020, but it has yet not been launched, although the first phase of the project has been completed successfully. The production model of the

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AIRPod will have a maximum speed of >65 km/h [8,9]. However, more work is still needed in various areas related to compressed-air engines [10].

Compressed-air engines have been well studied, but their potential has not been understood enough to encourage mass production. Furthermore, less work is available on the description of its construction for academic developers and on the conversion of fuel engines to compressed engines. The current study was carried out to convert a four-stroke 70 cc petrol engine, which is cheap and easily available, to a two-stroke compressed-air engine. The redesigning and performance analysis has been presented here with the aim of understanding the potential and capabilities of a small compressed-air engine. The study will give confidence to researchers to carry out more research on compressed-air engines in collaboration with the automobile industry to pave the way for the development of vehicles run on such engines and reduce environmental challenges [11]. Furthermore, the novel idea may also encourage more research to study the prospects of converting existing fuel engines to compressed-air engines.

## 2. MATERIALS AND METHODS

For the conversion of a four-stroke engine to a two-stroke compressed-air engine, a single-cylinder four-stroke gasoline-operated 72 cc engine was used; its other important details are provided in Tab. 1 [12]. This particular engine was selected as it is cheap and easily available and has better relative performance parameters. A new operating cycle was devised, including a series of mechanical modifications and experimental verification, as explained in the ensuing paragraphs, in order to successfully achieve the aims and objectives [13].

**Tab. 1.** Important details of the 4-stroke engine

| Property | Value |
|---|---|
| Bore length, cm | 4.7 |
| Stroke length, cm | 4.12 |
| Cylinders, n | 1 |
| Compression ratio | 8.8:1 |
| Displaced volume, $cm^3$ | 71.82 |
| Clearance volume, $cm^3$ | 9.23 |
| Total volume of cylinder, $cm^3$ | 81.05 |
| Surface area of piston, $cm^2$ | 17.34 |

### 2.1. Cycle/mechanical/electrical modifications

A typical single-cylinder four-stroke gasoline engine operates on a standard Otto cycle, in which air at atmospheric pressure is introduced into the cylinder during the suction stroke, which is then compressed in the compression stroke with the sole purpose of raising the pressure of the introduced air. However, in a compressed-air engine, since the injected air is already at a high pressure, the compression stroke is no more needed. Furthermore, since no ignition is required inside the engine, the carburettor and spark plugs were removed from the engine [14]. The compressed-air cycle engine thus consists of only two strokes, namely intake/expansion and exhaust, to utilise the energy of the compressed air to the maximum. During the intake/expansion stroke, compressed air is injected into the cylinder and allowed to expand to move the piston down to the bottom dead centre (BDC) from the top dead centre (TDC). In the exhaust stroke, the air is expelled out of the cylinder.

#### 2.1.1. Modification in Air Intake Circuit

Air must be injected into a compressed-air engine through the inlet that does not leak and that tolerates high pressure. To achieve this in the modified engine, compressed air is injected into the cylinder through an unorthodox opening (spark plug port) [15] during the intake/expansion stroke, while both inlet and outlet valves are closed; the air expands in the cylinder to move the piston down to the BDC. During the exhaust stroke, when the piston approaches the TDC, both inlet and outlet valves open one after another to let the expanded air out of the cylinder, as shown in Fig. 1. Therefore, the spark plug was replaced by a specially designed nozzle that is fixed in the threaded port of the spark plug. The fabricated nozzle and its port are depicted in Fig. 2.

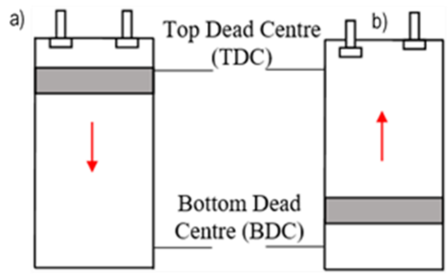


**Fig. 1.** Strokes in a compressed air cycle engine: a) Intake/expansion stroke; b) Exhaust Stroke

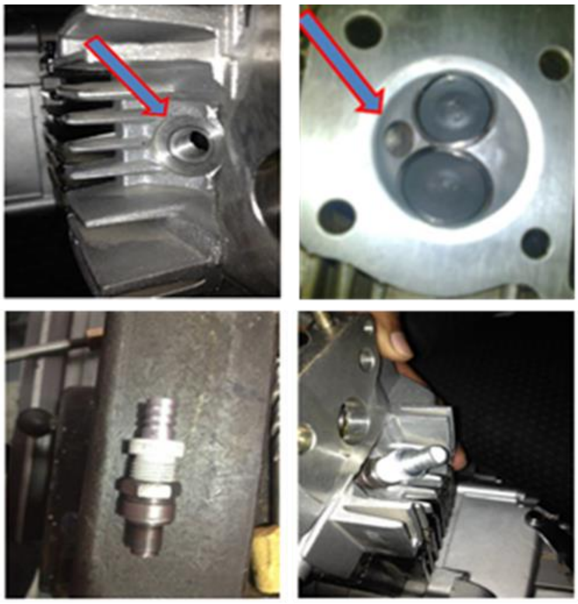

**Fig. 2.** Spark plug port and fabricated nozzle

#### 2.1.2. Cam Crank Ratio

The sprockets at the end of the cam shaft and crank shaft are connected by a timing chain in the original engine. For the two-stroke operation of the compressed-air engine, the diameter and number of teeth on the cam sprocket must be equal to those of the crank sprocket to allow one revolution of the cam shaft during one complete revolution of the crankshaft. To achieve a 1:1 ratio, the crank sprocket was removed and the new sprocket was fabricated. Similarly, a new chain was designed using CAD software, which was fabricated and adjusted accordingly to allow for the change in length of the chain due to the change in the crankshaft sprocket [16]. The camshaft and crankshaft assembly and the modified crankshaft sprockets are shown in Figs. 3 and 4, respectively. The new dimensions of the chain and sprockets are given in Tab. 2.

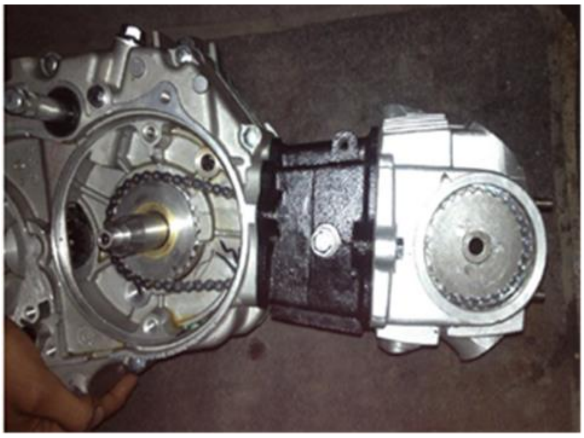

**Fig. 3.** Crankshaft and camshaft assembly

**Fig.4.** Modified crankshaft sprocket

**Tab. 2.** Modified cam-crank dimensions

| Property | Value |
|---|---|
| Distance – sprocket centres, cm | 18 |
| Teeth on camshaft sprocket, n | 14 |
| Teeth on crankshaft sprocket, n | 14 |
| Radius of camshaft sprocket, cm | 4 |
| Radius of crankshaft sprocket, cm | 4 |
| Length of chain, cm | 61.5 |
| Pitch, mm | 17.8 |

### 2.1.3. Cam Lobe Positioning

The chain was wrapped in such a way to achieve the desired cycle, the piston must be at the TDC at the instant when both valves just close. However, in a four-stroke petrol engine, the piston is at the TDC at the beginning of the intake stroke and expansion strokes, and the cam position also varies accordingly. A graphical description of the cam positioning is shown in Fig. 5. The cam parameters and cam displacement are given in Tab. 3 and Fig. 6, respectively [17].

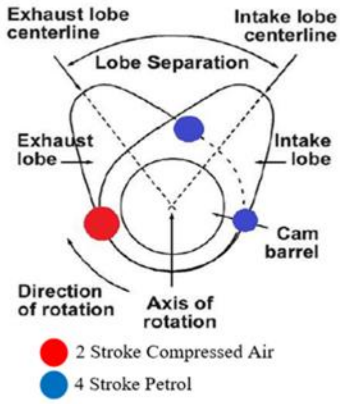


**Fig. 5.** Position of top dead centre (TDC)

**Tab. 3.** Cam parameters

| Property | Value (mm) |
|---|---|
| Base diameter | 21.1 |
| Lobe lift | 4.9 |
| Lobe height | 26 |

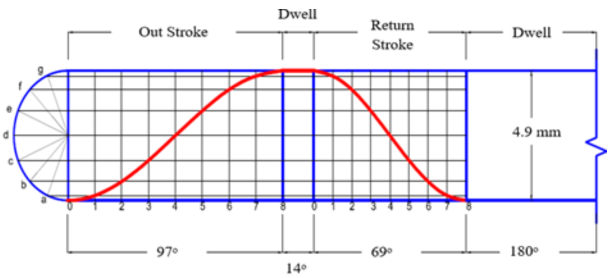


**Fig. 6.** Adjusted cam lobe displacement

### 2.1.4. Compressed Air Injection Control

The capacitor discharge ignition (CDI) box of the engine, along with other major electrical components – as shown in Fig. 7, was used to control the timing of injection of compressed air into the cylinder at the correct time (piston at the TDC) [18]. The inbuilt timing of the CDI was not altered; rather, mechanical modifications were made in a way that satisfies our operating cycle, described in Section 2.1. A solenoid valve was connected with the CDI through an electric circuit (Fig. 7), which controls the opening and closing of the valve with a pulse. This was done to stop the continuous supply of compressed air. The piston regains its position due to the crank mechanism operating within. Thus, the air injection angle was synchronised with the operating cycle; the cam profile is shown in Fig. 6 for reference.

– Solenoid valve: To synchronise the power stroke of compressed air with the piston's position.
– Relay switch: To control the timings of the solenoid valve.
– Switching transistor: To amplify the current from the CDI,

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which is not enough to operate the switching relay.
– Resistor: To prevent excess flow of current to the transistor.
– Catch diode: To prevent damage to the switching transistor by capturing the reverse voltage from the solenoid and routing it to the battery.

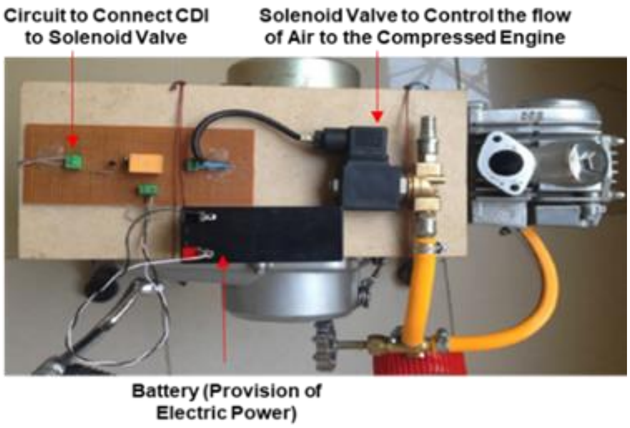


**Fig. 7.** Electrical circuit for compressed air injection timings

### 2.2. Thermodynamics Performance Analysis

A detailed theoretical analysis of the thermodynamic performance was performed, based on the design parameters, to obtain the expected efficiency of the compressed-air engine. The important design parameters and the calculated performance parameters of the thermodynamic analysis are given in Tab. 4 [19].

**Tab. 4.** Calculated thermodynamic performance parameters/ design parameters

| Parameter | Value |
|---|---|
| Pressure at the beginning of compression, bar | 1.01352 |
| Pressure at the end of compression, bar | 6.2 |
| Pressure at the end of expansion, bar | 3.67 |
| Volume of free air, $m^3$ | 0.37 |
| Volume of air at the end of compression, $m^3$ | 0.103 |
| Volume of air at the end of expansion, $m^3$ | 0.255 |
| Temperature before compression, ˚C | 16 |
| Temperature after compression, ˚C | 216 |
| Temperature after expansion, ˚C | 16 |
| Specific heat, kJ | 63.62 |
| Polytrophic constant | 1.406 |
| Length of connecting rod, mm | 72.45 |
| Area of piston, $m^2$ | 0.001734 |
| Work done during compression, kJ | 63.723 |
| Work done during expansion, kJ | 28.88 |
| Efficiency | 45% |
| Force available on piston, N | 1,075 |
| Torque, Nm | 77.88 |
| Revolutions per minute, rev/min | 719.3 |
| Angular velocity, rad/s | 75 |

## 3. RESULTS AND DISCUSSION

### 3.1. Experimental Verification

A cylinder with a capacity of 50 L and a maximum pressure of 8 bar was used, with the engine installed on a specially designed test bench as shown in Fig. 8. The filling time of the cylinder using a compressor is 2.7 s. The compressed-air engine was operated at a pressure of 5.44 bar (80 psi) successfully at an average speed of 700 rev/min (recorded using a tachometer). The engine stopped running when the pressure in the tank reduced to 2.44 bar (30 psi).

The potential of the compressed-air engine was analysed, based on the values of the parameters applied and calculated during the experimental analysis. The average pressure used for the calculation was 5.9 bar, for which the results are given in Tab. 5.

A tachometer was used to measure the speed of the engine; the angular velocity was derived from it. A pressure gauge was attached at the outlet of the solenoid valve to monitor the inlet pressure, as shown in Figs. 7 and 8. Available force and torque were calculated with the help of gauge readings, and standard formulas of automotive engineering were used [20] for the calculations.

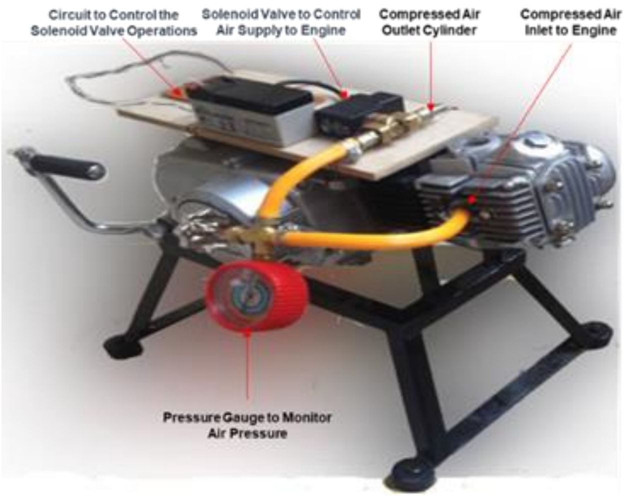


**Fig. 8.** Test bench used to test the compressed air engine

**Tab. 5.** Results of experimental analysis

| Parameter | Value |
|---|---|
| Force, N | 1,016 |
| Torque, Nm | 73.69 |
| Angular velocity, rad/s | 73.3 |

### 3.2. Economic Analysis

Despite numerous factors affecting the economy of a fuel, a preliminary comparative analysis was conducted on a 70 cc internal combustion (IC) engine idling at 700 rev/min. The study shows that, for a given mileage, using compressed air reduces the cost by nearly three times as compared to petrol [21]. The salient features of the study are given below [22]:

- The value of fuel consumption for a 70 cc IC engine is ~0.4 L/h under idle operating conditions.
- During our experiment, compressed air at 8 bar was used in a 50 L tank. The engine was kept running for around 2 min.
- With the help of thermodynamic analysis, it can be estimated that, to keep the engine running for 1 h, 1 m3 of compressed air at 30 bar is required.
- Cost of production of 1 m3 of compressed air at 30 bar is 0.2 USD.
- Currently, 1 L petrol costs nearly 0.9 USD in Pakistan.

## 4. CONCLUSIONS AND RECOMMENDATIONS

The compressed-air engine is economic and pollution free. By redesigning a small single-stroke petrol engine to a compressed-air engine, the current study has demonstrated the simplicity of the design of a compressed-air engine, its cost-effectiveness and potential. The study is expected to give confidence to researchers working on compressed-air engines and to pave the way for the development of vehicles run on such engines to reduce the fuel crises and environmental challenges; however, more research is needed in this field to utilise the technology with commercial viability [10]. Some of the areas recommended for further research, specifically in relation to the current study, are highlighted below:

- A more professional approach to the designing of such engines.
- Testing on a multiple-cylinder engine.
- Studying lightweight reinforced air storage tanks to render it possible for the engine to be used in the automotive industry.

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