Investigation and implementation of compressed air powered motorbike engines

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Over the last decades, fossil fuel resources have become very limited due to their tremendous use. Our dependence on fossil fuels has brought many environmental complications, but vehicles using compressed air as a fuel are still considered a dream. The compressed air engine (CAE) is receiving attention worldwide because it has the advantage of being renewable and has zero exhaust emissions. Motorbike engines have the highest percentage emissions of any fuel operated engines. Currently, in Egypt, there are more than 3 million motorcycles (motorbikes and covered three-wheeled motorbikes called tuktuk) powered by fossil fuels. This paper provides an overview of air power engine for motorcycles, called air bikes. The objective is to modify the four stroke petrol engine into a CAE by replacing the spark plug by solenoid valve and using the infrared modules for piston timing. A prototype of an air powered motorbike engine is implemented by modification of an 150 cm³ Dayun petrol engine. The modified CAE speed is 300 rpm at 8 bar air pressure with 7.8 Nm torque and 245 watt power. The efficiency of the CAE reaches 9.6%. Yet, due to low-pressure value utilization, the performance of the investigated CAE is still so poor that it clearly has a minor impact in motive power and hinders its commercialization.

KEYWORDS
air fuel, compressed air engine, motorbike, renewable energy, solenoid valve

1 INTRODUCTION

Internal combustion engines have been used in automobiles and motorbikes for numerous decades. Fossil fuel is used to produce the required vehicle power but it is the main cause of environmental pollution and global warming.1 These factors lead scientists to search for alternative renewable energy sources such as compressed air as recognizable solutions.2

Nomenclature: A, Piston area, m²; D, Cylinder bore diameter, m; F_s, Side thrust force, N; F_f, Friction force, N; F_c, Connecting rod force, N; G, Air mass flow, Kg/s; L, Length of the connecting rod, m; L_p, Length of piston skirt, m; M, Mass of the piston, rings, pin and small and end of the connecting rod, Kg; n, Crank speed, rad/s; P, Air pressure of cylinder, Pa; P_b, Bearing pressure, Pa; P_atm, Atmospheric pressure, Pa; r, Crank radius, m; R_DS, Bore to stroke ratio; S, Stroke of the cylinder, m; U_p, Average piston speed, m/s; V_p, Engine displacement, m³; V_c, Clearance volume, m³; V, Air volume of cylinder, m³; y, Piston velocity, m/s; y, Piston displacement, m; λ, Ratio of crank and link; θ, Crankshaft angular position, rad; β, Connecting rod angle, rad; τ, Output Torque, N.m; η, Coefficient of friction.

Subscripts: PCB, printed circuit board; CA, compressed air; CAE, compressed air engine; ICE, internal combustion engines; IR, infrared module; IVO, intake valve opening; IVC, intake valve closing; MDI, motor development international; NG, natural gas.

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Besides environmental protection, Shafiee et al.\(^3\) stated that oil and gas reserves can be reduced in 2042; this enhances the competition in the field of renewable energy vehicles. Compressed air is used individually as a fuel and it is directly fed into the engine. Compressed air piston is an actuator that produces a convenient work and power by expanding the compressed air. When the air cools, it expands, which leads to the formation of ice that causes troubleshooting of engine and reduces its efficiency.\(^4\)

Yet, the efficiency of output energy and power of the CAE is restricted that limits its popularization.\(^5\) Advantages of CAE are long lifespan, low cost, and safe maintenance. There is no combustion, so it is zero-polluting engines. There is no possibility of knocking results in smooth working of engine, no need for installing cooling system and no need for installing complex fuel injection systems. One of the most important reasons for using air compression instead of electricity is safety. In applications where equipment is overloaded, electrical equipment poses a safety hazard. Compressed air can be used under many conditions, such as on wet floors or in high humidity areas. Compressed air is more flexible and easier to use in remote areas. Compressed air engine has many advantages that make it comparable with other types of engine. To develop the compressed air engines (CAEs), motor development international company designed and created a set of novel air engines.\(^6\)

Nowadays, the whole world is worried about reducing the pollution of environment,\(^7\) and the rate of exhaustion of fossil fuel resources is increasing day after day and their combustion products are causing climate problems.\(^8\) The compressed air technology is necessary, which the compressed air is easily available, nontoxic, and can be effectively used as a fuel.\(^9\) The compressed air technology was analyzed by using two-stroke single cylinder engine. It is found that the air-powered engine technology is cheaper in cost and maintenance without causing any environmental pollution.\(^10\) Louis C. Kiser in 1925 tried to convert his vehicle that is powered by gasoline to run by compressed air. Lee Barton Williams in 1926 has invented the leading air car.\(^11\) Guy Nègre\(^12\) has developed an engine that could become one of the biggest technological advances of this century. Guy delivered a compressed air-driven vehicle, which is safe, quiet, has a top speed of 110 km/h, and a range of 200 km.

The performance of a two-stroke engine, by using compressed air as a fuel, was investigated and the results were 0.89 kw of power and 9.91 Nm of torque can be obtained by using air pressure ranging from 400 kpa to 800 kpa as a fuel with air consumption 1050 L/min at 1600 rpm.\(^13\) Performance optimization of a single-cylinder CAE was executed, simulation of mathematical model using MATLAB and illustration of experimental setup were done to obtain results, which showed that the efficiency of this compressed air engine was improved by 28.15%.\(^14\) Many researchers, after investigations and several trials, claimed that the compressed air engines will dominate in the future due to its power, cost, availability, maintenance, durability, and greenhouse emission gasses advantages.\(^15\)-\(^20\) The development is achieved by the enhancement of CAE performance,\(^21\) novelty of design,\(^22\)-\(^24\) integrating with renewable energy,\(^25\) adaptation of simulation and modeling techniques,\(^26\) reworking on the experimental work,\(^27\),\(^28\) new modifications,\(^29\) new transformation by rotary valve\(^30\) and cam with crankshaft,\(^31\) new application,\(^32\) and prefabricating and testing of CAEs.\(^33\)

Finally, this research can be dramatically applicable in Egypt, where there is a huge number of motorbikes and tuktuks (covered three-wheeled motorbikes), especially in remote areas, which has no infrastructure and a shortage of the fossil fuel supply. In some remote areas in Egypt, tuktuk is used mainly for transportation, in short distances that have unpaved roads infrastructure where there is no other way of transportation. People who use this way of transportation cannot afford the price of petrol fuel, cause an excess use of it, and assist in environmental pollution with high percentage. Actually, this research, using compressed air motorbike engines, can solve all these problems beside long lifespan, low cost, safe maintenance, no combustion, no pollution, less global warming, and less hazardous.\(^5\) Since the efficiency and output energy and power of the CAE are restricted beside the limited velocity and covered distance at low available compressed air pressure, this type of mobility is matched with these remote areas of Egypt. After modifications and availability of high compressed air pressure, these modified engines can replace the conventional internal combustion engines.\(^15\),\(^19\) In this paper, four-stroke single cylinder petrol Dayun engine was modified to two-stroke CAE. The modifications briefly were done by removing the spark plug from the cylinder head, providing a pulsed pressure control valve at the place of the spark plug using 5/3 solenoid valve, providing a suitable connector at the cylinder head, removing the pushrods, and connecting the solenoid valve to the cylinder head using infrared (IR) timing control system.

## 2 TECHNICAL DESCRIPTION

The motorbike engine is Dayun 150 cc worked by petrol fuel (gasoline) as a nominal internal combustion engine, as shown in Figure 1A (CAD code using Solidwork 2016) and Figure 1B (real photo). This engine is modified to work by compressed
air as a fuel. The major components of CA system are compressor, air tank, engine, solenoid valve, battery, nonreturn valve, throttle valve, pressure gauge, K-type thermocouple, electrical wires, and IR timing technique. The working principle and air flow with command signals were illustrated in the schematic Figure 2, in addition to the real photo of the engine auxiliary components.

Piston-type compressor is recommended because it is commonly used in high power machine that requires a high starting torque. Compressed air is supplied intermittently instead of continuously so that the air consumption is much less that of the rotary compressed engine. Its low air consumption rates, longer duration, and longer range performance had made it the best choice. The CAEs principle of operating mechanism is classified into two types; contact type depends on cam and follower mechanism and noncontact type depends on solenoid valve technique.

In this study, four-stroke piston-cylinder petrol engine is chosen for the experimental tests. The objective is to modify a four-stroke engine that works with gasoline fuel to a two-stroke engine that works with compressed air. The name of “two stroke” came from the unneeded operation of compression because the air already used is compressed. Two-stroke operations are the expansion stroke and the exhaust stroke.

The modification of the camshaft operation must be very accurate to get the valves opened and closed at a specific angle. Because it cannot be sure to get the modification on the camshaft accurately, solenoid valve modification was used. Moreover, solenoid valves are more accurate to control the opening and closing because the losses between the stages are nearly zero. Solenoids offer fast and safe switching, high reliability, long service life, low control power, and compact design but its small flow areas cause a pressure drops. In this project, 5/3 way double acting pneumatic compact solenoid servo-valve was used due to its availability in local market. Closing one of the valve openings is required to become 4/3 to match the engine operation. Figure 2 shows the compressed air system schematic drawing and its components, arrangements, and connections, and it shows the connection of IR solenoid valve timing mechanism with engine.
3 | MATHEMATICAL MODEL

The volume of the cylinder at any crank angle can be described as follows:

\[ V = V_c + \frac{\pi}{4} D^2 \cdot y \]  

\[ y = r \left[ 1 - \cos \theta + \frac{1}{\lambda} \left( 1 - \sqrt{1 - \lambda^2 \sin^2 \theta} \right) \right] \tag{2} \]

\[ \lambda = \frac{r}{L}. \tag{3} \]

The piston area can be described as follows:

\[ A = \frac{\pi}{4} D^2. \tag{4} \]

The relationship between the cylinder pressure \( P \) and the output torque \( \tau \) is function of the engine geometry, \( ^{14} \) ie,

\[ \tau = [(P - P_{atm}) A - F_f] \cdot r \cdot G(\theta) \tag{5} \]

\[ G(\theta) = \frac{\sin (\theta + \beta)}{\cos \beta} = \sin \theta + \sqrt{\frac{1-\lambda}{\lambda}} \cos \theta \tag{6} \]

\[ F_f = \eta F_{st} \tag{7} \]

\[ F_{st} = P_b \cdot D \cdot L_p. \tag{8} \]

The piston equation of motion and speed can be described by\( ^{14} \)

\[ M \frac{dy}{dt} = \begin{cases} -F_{cr} \cos \beta + |(P - P_{atm})| \cdot \frac{\pi}{4} D^2 - F_f & y \neq 0 \\ 0 & y = 0 \end{cases} \tag{9} \]

\[ F_{cr} = \frac{F_{st}}{\sin \beta} \tag{10} \]

\[ U_p = \left[ \frac{4 \cdot V_p \cdot R_{DS}}{\pi} \right]^{\frac{1}{3}} \cdot \frac{n}{30} \tag{11} \]

\[ S_r = 2r \tag{12} \]

\[ R_{DS} = \frac{D}{S_r} \tag{13} \]

\[ V_p = \frac{\pi}{4} D^2 \cdot S_r \tag{14} \]

\[ \cos \beta = \sqrt{1 - \lambda^2 \sin^2 \theta}. \tag{15} \]

4 | MODIFICATION OF PETROL ENGINE TO COMPRESSED AIR ENGINE

The experimental work was performed to convert the motorbike internal combustion engine to work by compressed air as a fuel. The CAE needs some auxiliary components to complete the proper function.

4.1 | Auxiliary components

Compressor used in this study is AIR-TEC that compresses max 8 bar and holds up air to 100 liter with a capacity of 3 horsepower, solenoid valve is CONSON 1.5 to 10 bar 5/3 way double acting pneumatic compact with 12 volt DC and 4.8 watt and the battery is HIS with 12 volt and 18 ampere.
| Engine type | Single cylinder, four-stroke, air-cooled |
|-------------|----------------------------------------|
| Start type  | Electric & kick                         |
| Engine displacement (cc) | 150 cc |
| Ignition system | CDI                                   |
| Bore        | 0.062 m                                |
| Stroke      | 0.0495 m                               |
| Clearance volume | $2.23168 \times 10^{-5} \text{ m}^3$ |
| No. of gears | 5                                      |
| Cylinder Arrangement | Single cylinder                      |
| Maximum power | 8.5 kw @7500 rpm                       |
| Maximum torque | 11.5 Nm@6000 rpm                      |
| Fuel tank capacity | 13 L                                 |

**TABLE 1** Dayun engine specifications

4.2 | **Engine specifications**

The engine is Dayun made in China and its specifications with technical descriptions are shown in Table 1.

4.3 | **Engine modifications**

As shown in Figure 3A, the place of spark plug is directly above the piston. Therefore, the solenoid valve, which is installed instead of the spark plug, is considered the best choice. After removing the spark plug from the cylinder head, it was discovered that the depth of the entry of the spark plug was large for the solenoid valve to be installed. The solution was to connect the entry of the solenoid to the entry of the removed spark plug with an appropriate special coupling, as shown in Figure 3B.

The camshaft is connected to the crankshaft by mechanical mean. The camshaft has pushrods that synchronize the movement of the cams to the movement of the valves connected to the rocker shaft. The pushrods and rocker shaft were dissembled so there would be no connection between the cams and the valves.

It was not executable to work with the output of gearbox due to the speed reduction that takes place that lowers the rpm, so the angles of the gears differ from the angles of the crankshaft, which make the angles matchless with solenoid valve.

The crankshaft was not visible directly but there was a place in the engine that can be opened and the dynamo shaft appeared. A nut was visible outside the dynamo, which synchronizes with the rotation of the crankshaft. Special key with some modifications was used to calculate the angle of the crankshaft and the crank speed. The key was connected to the nut and the handle (arm) of the key was cut. The key was connected to the nut by a coupling with bearing. Figure 4 shows the crankshaft nut before modification and fixation of special tool and, after fixation, it also shows the photos of the used special key and the used coupling with bearing.

5 | **SOLENOID VALVE TIMING MECHANISM**

The adjustment of the timing of the solenoid valve operation is related to the angle of the crankshaft. The signals of the solenoid are as follows: to open the intake valve at 0°, close the intake valve at 35°, open the exhaust valve at 175°, and, finally, close the exhaust valve at 355°. One of the proposed solenoid valve timing methods is encoder but it is very
Before modification   Special key  Coupling & bearing   After modification

FIGURE 4  Crankshaft output visualization

expensive and was not available in the local market. The following methods were tested firstly by 2800 rpm drill to avoid any testing failures of the engine.

5.1  Limit switches

With high rotational speeds, each limit switch will have to take 47 orders in one second. Therefore, the limit switches are useless because the ability of the switch cannot handle that much of various orders and will not feel the difference between them.

5.2  Specially designed mechanical mechanism

The mechanism was designed to transfer electricity between two upward opposite bearings, which represents the intake gate, and two opposite downward bearings, which represents the exhaust gate that has a rotating wood disc between them with sectors of metal. Each face of the disc is a mirror to the other. The bearings were chosen to reduce friction. To make sure that the bearing is touching the disc all the time, a spring was used. The aluminum pieces that connected with a bolt were attached to the disc at both sides representing the crankshaft angles. Each side has two pieces of aluminum; the first piece of aluminum represents the intake angles and the second represents the exhaust angles. Each couple of bearing is connected to a gate of solenoid valve. When the bearings contact the aluminum piece, the electricity is transferred and the gate was opened; but when the bearings contact the wooden part of the disc, the electricity is cut off and the gate was closed. The disc gets its motion directly from the crankshaft.

Figure 5 shows that, when the engine starts its motion, the disc starts to rotate and the aluminum pieces at the two sides of the disc pass between the couple of bearings, which is responsible for the opening of the solenoid intake gate. The disc continues to rotate until it reaches the end of aluminum piece and the couple of bearings got isolated by the wood disc and the intake gate closes. This operation is repeated for the exhaust gate. At the testing process, it was discovered that the mechanism works efficiently till 150 rpm. When rpm increases, mechanism vibration arises and causes some problems that prohibited the operation with that mechanism.

5.3  IR modules (applied to the studied system)

Figure 6 shows the IR modules that are programmed as follows. First, module gives the signal to open intake. Second, module gives the signal to close intake. Third, module gives the signal to open exhaust. Fourth, module gives the signal
to close exhaust. The IR modules operation must have a designed electronic circuit that consists of IC, which is small processor or the brain of the electronic circuit, as showed in Figure 7. The IR modules record the signals; the signals were transferred through the circuit wires to the IC processor. The IC processor transfers the signals to the solenoid valve to perform its function.

A spinning piece of wood, attached to the shaft representing the crankshaft angles, cuts the previous four modules to initiate the valve operation. Each IR module has a different angle to give a determined response. The spinning piece of wood adjusted such that, when it reaches certain design angle, the solenoid valve opens. When it reaches subsequent angle, the valve closes the other two angles, repeating the sequence but in opposite direction and so on alternately. During working on the IR timing system, there was an interference between each opposite IR module as they were activating each other. The solution was to separate the opposite IR modules on both sides of the wooden sheet.

6 | OPERATION OF THE CAE

The crankshaft was adjusted at 0°, the supply pressure of the tank was 8 bar and IR was adjusted. The kick start was pushed by hand for applying initial torque to start the engine; the crank rotates; and the piece of wood attached at the end of the crankshaft will rotate, which cuts off the first IR module responsible for opening the solenoid valve.

A compressed air was pushed into the engine; meanwhile, the crankshaft still rotates until it reaches 35°; then, the second IR module was cut off, which sends the signal to the IC processor and to the solenoid to close the valve. The crankshaft keeps rotating till it reaches angle 175°, which opens the solenoid valve in opposite direction. The valve was closed at angle 355° and the cycle keeps repeating itself as long as there was a sufficient amount of supply pressure tank, as shown in Figure 8.

At start, the piston moved from the top dead center to the bottom dead center as a first stroke (power stroke); the intake was opened; and the exhaust was closed. Just before the bottom dead center, at angle 35°, the intake was closed to decrease the amount of compressed air consumption and permit the pressurized fluid to expand. This isentropic expansion of the piston produces the required power according to the inflow air pressure during the intake.

At the exhaust stroke, the intake was closed; meanwhile, the exhaust was opened at 175° angle. The piston moves this stroke to eject the expanded air from the cylinder. The exhaust was closed at 355°, which is just before the piston reaches TDC, which results in a compression process of the remaining air used for building up the limited pressure. This technique helps the incoming pressure (if the incoming pressure value was insignificant) to move the piston with sufficient power but, at the same time, results in decreasing of the piston output work.
Simulation of the mathematical model of the CAE was performed by using software MATLAB 8. The simulation was performed under some assumptions such as; the air follows ideal gas laws with no leakage, the air flow is a stable one-dimensional, the viscous friction force is ignored and the exhaust air pressure is atmospheric.

Due to the output power and output torque indicate the performance of the CAE, the studying of the variation of cylinder pressure with cylinder volume (P-V) under range of supply tank pressure was studied as shown in Figure 9. The maximum supply air pressure during the simulation is assumed 10 bar due to this is the highest pressure that the available small size air compressors in Egypt local market can provide.

The output power of CAE can be calculated by the area within P-V diagram to determine the work output. Figure 9 shows, as the compressed air pressure increases the area under the curve increases hence the output power increases. There is a small difference between the work produced at 8 bar and 10 bar tank pressure, so from technical and economic points of view and the availability in Egypt local market 8 bar compressor is chosen.

Finally, the output power equals the work times cycles per second. Figure 10 shows, as the compressed air pressure increases the engine output work increases.

Figures 11 and 12 show simulation graphs of theoretical variation of output power and output torque of CAE at range of supply tank pressure that extended from 8 bar to 10 bar and at rotation speed of 300 rpm. Figures 11 & 12 show at 8 bar air pressure the engine output torque is 7.8 Nm and the output power is 245 watt. The engine required high torque at the start of the operation, so the gasoline engine torque is higher than the CAE torque nearly about 30% and the output power of the gasoline engine is higher than the CAE power nearly about 97%. The figures show when the supply tank pressure increases, the output power and the output torque increase at the same rotation speed and when supply tank pressure increases, the pressure of air at the end of expansion increases.

It can be concluded from the later figures that the CAE produces small output power and output torque at 8 bar supply tank pressure. The behavior of CAE that operates at supply tank pressure of 8 bar during full operating cycle of the
piston operations was simulated to show the variation of cylinder volume and pressure with crank angles as shown in Figures 13 and 14.

Figures 13 and 14 show that, at the beginning of the intake process, the intake valve opens at crankshaft angle 0°, and the exhaust valve stays close, whereas the piston moves from the top dead center (TDC) toward the bottom dead center (BDC). During this process, the incoming compressed air pushes the piston downward, producing the power stroke, so the cylinder volume increases at constant supply pressure. The intake valve closes at 35° before the piston reaches the BDC to reduce the air consumption, and thus changing the process from a constant pressure expansion to an isentropic expansion. At the start of the exhaust process, the exhaust valve opens at 175°, whereas the intake valve remains close. The piston moves from the BDC toward the TDC to discharge the compressed air from inside the cylinder.
The exhaust valve is closed at 355°, which is before the piston reaches TDC, which results in an isentropic compression process. The work that is required to compress the air in the cylinder reduces the total work output of the entire engine cycle. The cycle keeps repeating itself as long as there was a sufficient amount of supply pressure tank.

After studying simulation graphs acquired during one engine cycle at supply tank pressure of 8 bar and engine speed 300 rpm, it was concluded that the CAE produces 7.81 Nm output torque and 245.3 watt output power.

The experimental setup is to measure the variation of the engine rotation speed with cylinder pressure variation at different times. The engine rotation speed measured by tachometer (model UT371) while the cylinder pressure is measured by pressure gauge. The air flow rate is measured by flow meter (GENie FLO model, 0.1 hyphen; 5 LPM range and ± 5% accuracy). Figure 15 shows when the supply tank pressure increases the rotation speed of CAE also increases and the minimum pressure to run the 150 cc CAE is 6.5 bar. The maximum speed is 300 rpm at supply tank pressure of 8 bar. The operation time of the engine is 90 sec, measured by stopwatch, but in the last 10 sec as a result of decreasing the cylinder pressure and time.
| Items of comparison | Dayun engine “Compressed air” | Dayun engine “Gasoline” |
|---------------------|-------------------------------|------------------------|
| Max. RPM            | 300                           | 7500                   |
| Max. torque (N·m)   | 7.8                           | 11.5                   |
| Max. Power (Kw)     | 0.245                         | 8.5                    |
| Emissions           | Zero emissions                | NOx, SOx, COx & others |

Table 2: Comparison between Dayun engine compressed air and gasoline

pressure to approximately 6.6 bar a sudden drop in engine speed is recorded. Experimental measurements for the temperature of exhaust air of CAE with K-type thermocouple showed that the average exhaust air temperature was 24°C, which is colder than the ambient air and help in reducing the global warming. CAE probably give rotation speed and output power as high as conventional internal combustion engine at high compressed air pressure about 250 bar.35

Table 2 shows a comparison between the traditional Dayun internal combustion engine operated with gasoline and the modified Dayun engine operated with compressed air as a fuel. Due to the CAE operated under low pressure of 8 bar, the output power is considered very low. The torque is accepted compared to the original engine, the CAE under high pressure about 250 bar the output power is 11.4 kwatt higher than gasoline engine.35

8 | UTILIZATION OF NATURAL GAS STATION AS COMPRESSED AIR CHARGING STATION

The schematic drawing illustrates a natural gas station shown in Figure 16A, which is widely distributed in Egypt. Natural gas is being used as a type of fossil fuel for certain vehicles; however, the total cost of using natural gas as a fuel is high due to the cost of the extraction, transportation, compression power, and the profit.

Compressed air can be used as an alternative of natural gas, the total cost of using compressed air by original station compressors is much less compared to the natural gas. The only cost that people will have is the cost of compressing the air. Figure 16B shows a modified nature gas station as a compressed air station.

9 | COST ANALYSIS OF CAE SYSTEM

From the cost analysis of the CAE shown in Table 3, it has low cos; therefore, as a result, the whole vehicle will have low price. That is why it is highly recommended from economical point of view. The cost of modified engine is $580.8. The cost of the modified engine includes the price of air compressor, which can be avoided if it is available in stations, and it also includes the cost of gasoline engine and electric battery.

FIGURE 16 Modification of natural gas station as compressed air charging station. A, Natural gas station; B, Modified natural gas station as a compressed air station
### TABLE 3  Cost analysis of compressed air engine

| Item                          | Number | Price ($) | Total ($) |
|-------------------------------|--------|-----------|-----------|
| Single cylinder engine        | 1      | 222.2     | 222.2     |
| Engine base                   | 1      | 25        | 25        |
| Infrared module               | 4      | 1.9       | 7.78      |
| Electronic circuit            | 1      | 16.7      | 16.7      |
| Solenoid valve                | 1      | 10        | 10        |
| Nonreturn valve               | 1      | 6.1       | 6.1       |
| Gauge pressure                | 1      | 1.9       | 1.9       |
| Throttle valve                | 2      | 0.8       | 1.7       |
| Air hoses                     | 15     | 0.3       | 5         |
| Battery                       | 1      | 7.2       | 7.2       |
| Engine electrical components  | 1      | 8.3       | 8.3       |
| Air fittings                  | 1      | 0.3       | 5         |
| Machining (CNC-plasma-turning)| 1      | 47.2      | 47.2      |
| Air compressor                | 1      | 216.7     | 216.7     |
| Total                         | 10     | 580.8     |           |

## 10 | CONCLUSIONS

This work modified the four-stroke petrol engine into the CAE (working by compressed air instead of gasoline as a fuel) to solve the problems of fossil fuel depletion and greenhouse gas emissions. Prototype of the air powered motorbike engine is acquired and investigated through the modification of 150 cm³ Dayung gasoline engine by replacing the spark plug with automated control solenoid valve used for intake and exhaust of compressed air.

1. Engine after modification can work under compressed air of pressure 8 bar to produce 7.8 Nm torque and 245 watt power. At 8 bar pressure, the engine maximum speed reaches 300 rpm.
2. The power efficiency of CAE is 9.6%.
3. The engine speed is slightly increased to 320 rpm after removing the nonreturn valve.
4. The limit pressure, which can drive the engine, is 6.5 bar, but when the orifice area of the throttle valve is increased, the engine operation reaches 4 bar.
5. The CAE performance can be enhanced by speeding up the valve response and enlarging its motion.
6. The temperature of exhaust air is lower than the ambient air temperature, so no polluting gasses are released. Therefore, the designed engine is eco-friendly, pollution free, and economical.
7. Due to the utilization of low compressed air pressure, the performance of the investigated CAE is poor, so that it clearly has minor impact in motive power and hinders its commercialization. Presumably, a much higher pressure could provide some degree of energy storage and increases the engine power and efficiency.

This work helps to advance the vehicle fuel, engine, power, and gas emission with available cost. In the future, the experimental work will proceed at higher compressed air pressure with different types of engines using different field tests. Moreover, different computational simulation techniques can be used to be validated with experimental results and help in completing the correct vision.

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How to cite this article: Nabil T. Investigation and implementation of compressed air powered motorbike engines. *Engineering Reports*. 2019;1:e12034. [https://doi.org/10.1002/eng2.12034](https://doi.org/10.1002/eng2.12034)