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Compressed Air Engine: A Bridge for Sustainable Development

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ABSTRACT

Researchers all over the world have been striving hard to find a sustainable solution to the future energy requirements. In this context, an engine using compressed air might very well prove to be an effective solution. In the present study, a 4 stroke engine was modified to run on compressed air and a specially designed "articulated connecting rod" has been used, which has the provision of dwelling at the top dead center. This would make the injection of compressed air a constant volume process inside the cylinder contrary to conventional engines. In the proposed design, compressed air was supplied through a distribution system in time sequence into separate cylinders of the engine by solenoid-actuated valves located in spark plug holes. A valve actuator, which modified the time interval over which compressed air was admitted into the cylinder, in accordance with engine speed, was also incorporated. The proposed engine was theoretically compared with an ideal Otto cycle in terms of its efficiency and power generated. The results were found to be acceptable to put the proposed engine into actual practice with ample scope left for future work.

Key words: Compressed air, renewable energy, valve actuator, distributor system, solenoid valves

INTRODUCTION

Air pollution is one of the most serious problems facing modern humanity and as is well known, one of the greatest contributors to air pollution is the automobile engine. In the vast majority of automobiles now operating, the motive power is obtained through operation of an internal combustion engine with gasoline or diesel as the fuel. The internal combustion engine is not noted for its efficiency in obtaining useful work from the energy available through combustion and as a result, many unburnt hydrocarbons are exhausted into the air. Gases such as carbon monoxide and nitrogen dioxide are harmful to animal and plant life, thereby contributing to a breakdown in the ecology of this planet (Yancey, 2002). As a result, internal combustion engines for powering motor vehicles have been under attack and facing severe criticism. Steps have therefore been taken to increase the combustion efficiency and filter exhaust from these engines with a view to save the atmosphere through more efficient and cleaner burning. The relative success of such operations has, however been slow and limited due to many problems which arise.

Thus, efforts are being made to substitute the existing energy wasteful and contaminating internal combustion engines for an energy saving and ecologically superior compressed air engine. However, design in this area has been somewhat limited because of the reduced power output from such engines and their somewhat inefficient and complex operation (Shofner, 2009).

The present invention provides a specific apparatus for operating an engine using the expansion of compressed air as the motive power and thus, eliminates the usual pollutants exhausted from an IC engine. Moreover, this apparatus can even adapt a pre-existing internal combustion engine for operation on compressed air.

Thus, it was an object of the present study to provide a reliable method for ready adaptation of standard internal combustion engine for operation with compressed air. Another object of this study was to provide an apparatus which would deliver a constantly increasing amount of compressed air to an engine as the speed of the engine increases. A further object of this study was to provide an apparatus which would create pressures high enough above the piston in order to give ample power output and also generate more uniform torque on the crankshaft of the engine. Another objective of the study was to compare the IC engine and compressed air engine from a thermodynamic point of view and compare their efficiencies under similar operating conditions.

LAYOUT OF APPARATUS

The engine was similar to a conventional 4-stroke IC engine in basic construction except that mechanically operated intake valves were replaced by injectors, which were operated by means of valve actuators and use of an articulated connecting rod. In the present study, a V-8 engine was used. In the following text, "( )" represents the parts/components shown in the figures. Figure 1 shows an overall layout of the entire system with all the components labelled. These diagrams only show the components for one cylinder of the engine block. The same configuration was replicated for other cylinders as well, making a complete V-8 engine (Delano, 1984).

The engine employed a compressed air tank (1) to store compressed air at high pressure. Refuelling of this tank can be done at home or at service stations by means of an air compressor. A main supply line, (2) transported the air withdrawn from the tank further. In this line, a key-operated solenoid valve and (3) was placed which served as a selective shut off valve to start and stop the engine. After this, the main supply line delivered compressed air to the main injectors (Naveenchandran *et al*., 2011).

This line had a throttle valve (4) arranged downstream which was connected to a mechanical linkage which in turn, was operator-actuated by means of accelerator pedal (5). Line 2 then entered into the distributor (6). The pipe running morph through the distributor had a plurality of holes, which were equal to the number of cylinders in the engine, along its length. From the distributor, each hole lead a separate line to convey compressed air to each cylinder of the engine. In this manner, line 2 ultimately terminated into a solenoid-actuated valve or injector (9) which was

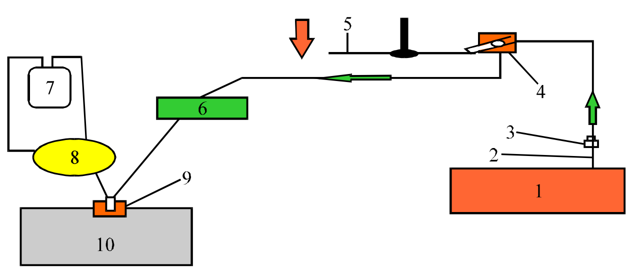

Fig. 1: Overall layout of entire compressed air engine system

screwed into a tapped hole in the cylinder (10) usually provided for spark plug in IC engines. The injector was electrically energized by a valve actuator (8) through wires.

VALVE ACTUATOR FOR INJECTOR

Figure 2 shows the front view of the valve actuator full in section. Figure 3 represents the transparent top view of the valve actuator. The valve actuator received electrical power from a battery through a wire (3). The wire was attached to a central post (1) by a nut (2). The post was connected to a conducting plate (4) arranged in a housing (15) for valve actuator.

Within the housing, a shaft (12), driven by the crankshaft of the engine was present. This shaft was driven at the speed of the engine by a suitable gearing mechanism. To the shaft, a curved insulating element (11) was secured by a screw for co-rotation with the shaft. The screw was screwed into a tapped hole in the insulating element so that a tab at the end of the screw engaged a groove provided in the shaft. In this way, the insulating element rotated positively with the shaft. However, the insulating element was made of a flexible material and was shaped in such a manner

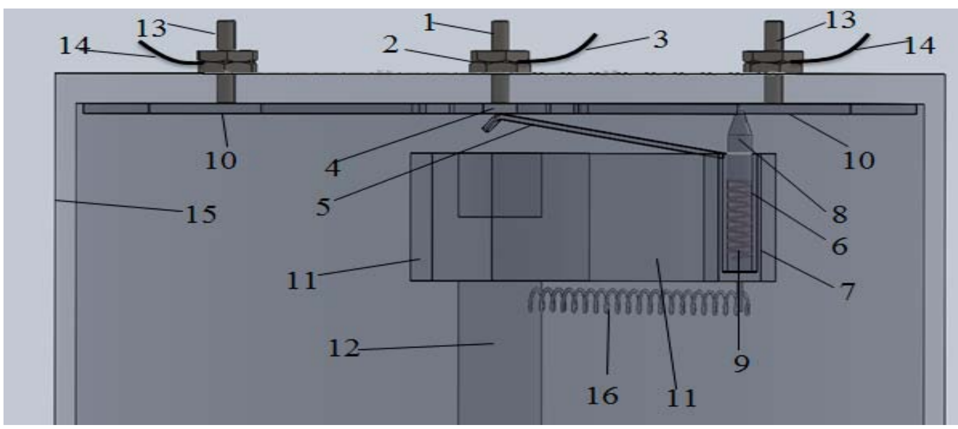

Fig. 2: Front view of valve actuator full in section

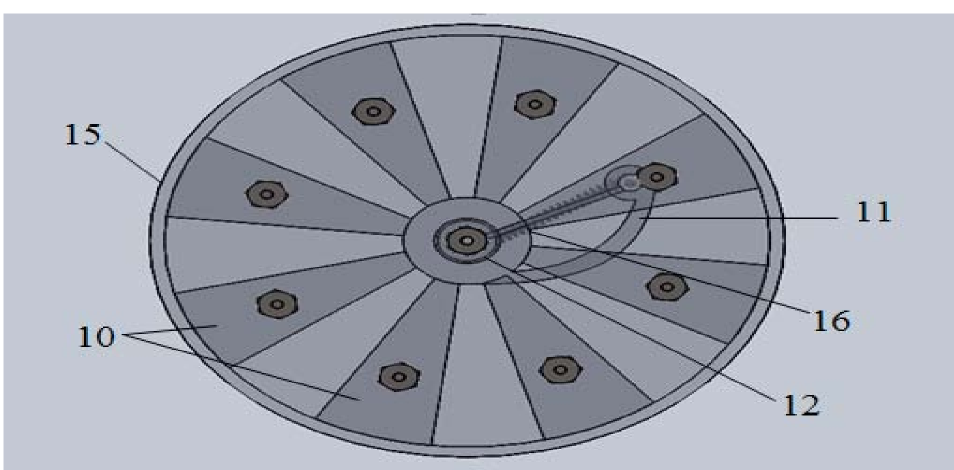

Fig. 3: Transparent top view of valve actuator

that the outer end of the insulating element was permitted to pivot outwards, under the influence of greater centrifugal forces, with increase in speed of the shaft. A spring (16) connected between the second end of the insulating element and the shaft pushed the second end of the element towards the centre of the housing (Crouse and Anglin, 2004).

Here, series of equally spaced contacts (10) were arranged on the upper inside of the housing. The number of contacts were equal to the number of cylinders in the engine. The number of degrees covered each of the radial contacts gradually increased as the distance from the centre of the housing increases. These radial contacts were electrically connected to separate posts (13). One of the wires (14) which actuated the valves was secured to each of these posts.

A contact piece (5), with its one end in constant contact with the conducting plate (4) located centrally within the housing, was also used. Its other end engaged a conductive sleeve (6) arranged in a bore (7). A contact element (8) was arranged in the conducting sleeve, in constant contact with the sleeve. The bore was generally arranged parallel to the shaft, near the second end of the curved insulating element. The contact was biased by a spring (9) towards the upper inside of the housing for selective contact with each of the plurality of radial contacts (10) which increased in arc length towards the outer peripheral surface of the housing.

In operation, as the shaft rotated, the curved insulating element (11) also rotated with it. Electricity flowed along a path through the wires (3), down through the central post (1) to the conducting plate (4). From here, the current passed through the conducting sleeve (6) and the contact element (8) and was ultimately delivered to the radial contacts (10). Then, current went to each of the electrical valves which were activated and opened in proper timed sequence to admit compressed air to each of the cylinders to drive the piston in the downward stroke.

Now, when the rotational speed of shaft increased, the second end of insulating element moved outwards radially, due to increased centrifugal forces. Thus, the number of degrees of rotation over which the contact element remained in contact with each of the radial contacts on the upper inside of the housing increased, thereby, allowing each of the valves to remain open for a longer period of each engine cycle. This in turn, allowed more compressed gas to enter in the respective cylinders to further increase the speed of the engine. Conversely, as the speed of the engine decreased, the insulating member rotated in a circle of smaller radius, because of smaller centrifugal forces acting on it. Thus the effective contact time with each of the radial contacts decreased, resulting in a decrease in injection time for compressed air into the cylinder. In this way, the amount of compressed air that was used during idling of the engine was at a minimum whereas the amount of compressed air which was required to increase the speed of the engine to a level suitable to drive the vehicle on a highway was readily available.

ARTICULATED CONNECTING ROD

Figure 4 shows the different parts of the proposed connecting rod. Instead of a conventional connecting rod, a kinematic link called the Articulated Connecting Rod was employed (http://www.aircarcompressedairtechnology.com/mdi-tech-eng.php). This assembly consisted of three links namely A, B and C. The link A was directly connected to the gudgeon pin of piston. The link B had its one end attached to link A while the other end was attached to a fixed base. The link C was fixed to link B at or near its middle, on one side and the crankshaft on the other side. This assembly had the provision of dwelling at the top dead centre for particular degrees of crankshaft rotation. Angle of dwell of the piston depended on the position of the fixed base for the link B. The angle of dwell had values of 30°, 45° or 60°.

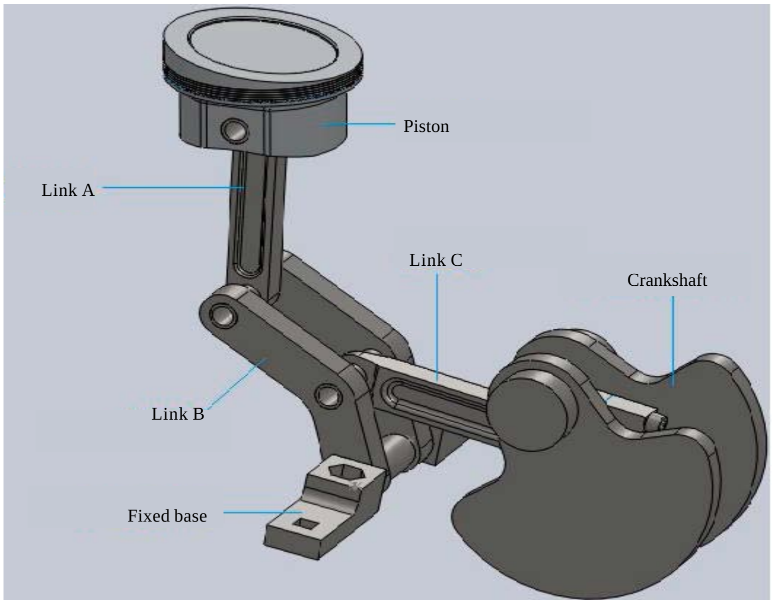

Fig. 4: Articulated connecting rod assembly

With increasing angle of dwell, the swept volume in cylinder decreased. As a result, compression ratio decreased causing a fall in the output power of the engine. Thus, we can say that the power of the engine was inversely proportional to the angle of dwell for this link. During operation, link A reciprocated with the piston, link B oscillates and link C rotated the crankshaft. Dwelling period of the piston resulted in a practical constant volume above the piston. This gave enough time for injected air to develop a significantly high pressure which was then used to drive the piston. Also a more uniform torque was applied to the crankshaft than in a classical system.

MODIFIED WORKING CYCLE

Compressed air was injected into each cylinder of the engine block when the piston was at TDC, through the injectors (9) (Fig. 1). This was an isochoric process since the piston would dwell at TDC due to the presence of articulated connecting rod (http://www.aircarcompressedairtechnology.com/mdi-tech-eng.php). This high pressure air then drove the piston in each cylinder downwards to rotate the crankshaft and in turn, expanded rapidly and cooled down. The expansion process continued till the piston reached BDC. This was followed by expulsion of air through a mechanically operated exhaust valve (as in conventional IC engine), as the piston moved from BDC to TDC.

THEORETICAL ANALYSIS OF PROPOSED ENGINE

Otto cycle: Referring to Fig. 5 for the pressure-volume curve of a typical Otto cycle:

(a) P_1= 1 bar T_1= 300 K (atmospheric conditions)
Using the ideal gas equation
Pv= RT, where, R= universal gas constant = 287 J/kg/K (Yusof *et al*., 2009)
$\Rightarrow v_1$ (specific vol.) = 0.861 $m^3\ kg^{-1}$
Also, V_1 (clearance vol + swept vol)
= $8.7266\times10^{-4}\ m^{-3}$ (standard value assumed)

(b) Taking a compression ratio r = 10 (standard value assumed) (Heywood, 1988)

$\Rightarrow V_2$ (clearance vol) = 8.7266×10^{-5} m^{-3} and $v_2 = 0.861$ m^3 Kg^{-1}

As PV = k

$\Rightarrow P_2 = 29.5$ bar

Using the ideal gas equation

Pv = RT

$\Rightarrow T_2 = 885$ K

(c) $v_3 = 0.861$ m^3 kg^{-1} and $P_3 = 40$ bar (standard value assumed) (Heywood, 1988)

$\Rightarrow$ T_3= 1200 K

(d) $v_4 = 0.861$ m^3 kg^{-1}

$\Rightarrow$ $P_4 = 1.35$ bar and $T_4 = 405$ K

Now, η_{Otto}= 1- $1/r^{\gamma-1}$ = 66.11%

Three-stage compressor: Compressor used for supplying high pressure air is a 3-stage compressor with inter-coolers employed after each stage except the final one where no after-cooler was used. Referring to Fig. 6 for the pressure-volume curve of a three stage compressor with intercooler.

Let the polytropic index for each compression process be n = 1.3

(a) P_1 (inlet pressure) = 1 bar

$T_1 = 300$ K (atmospheric conditions)

P_6 (delivery pressure) = 37 bar

Let the pressure drop in inter- cooler arranged after each stage be y = 5%.

Now, for minimum work condition; (Cengel and Boles, 2008)

P_2/P_1= $[P_6/(1\text{-}y)^2\times P_1]$

$\Rightarrow P_2$= 3.45 bar

As P_3= (1-y) x P_2

$\Rightarrow P_3$=3.27 bar

Similarly, $P_4 = 11.3$ bar and $P_5 = 10.7$ bar

Now, Work required to be done by the compressor per unit mass of high pressure = w_c

$w_c = 3RT_1n/(n\text{-}1)$ x $[\{P_6/(1\text{-}y)^2 \text{ x } P_1\}^{(n-1)/2n}\text{-}1]$ (Cengel and Boles, 2008)

$\Rightarrow w_c = 370.076$ kJ kg^{-1}

Also, $T_6 = T_5 (P_6/P_5)^{n-1/n}$ where, $T_5 = 300$ K

$\Rightarrow T_6 = 400$ K

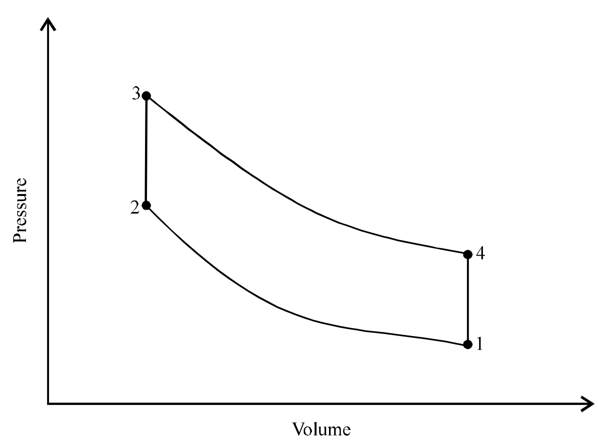

Fig. 5: P-V Diagram of the Otto cycle

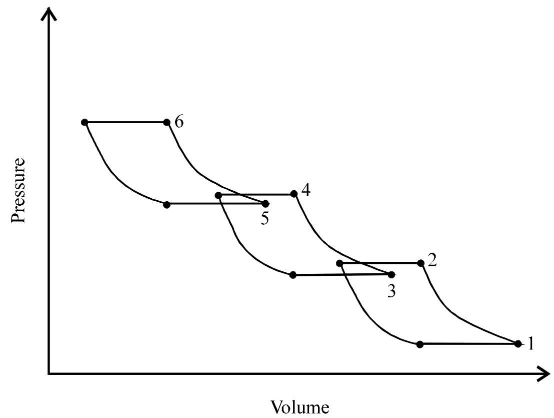

Fig. 6: P-V Diagram of a three stage compressor with intercooler

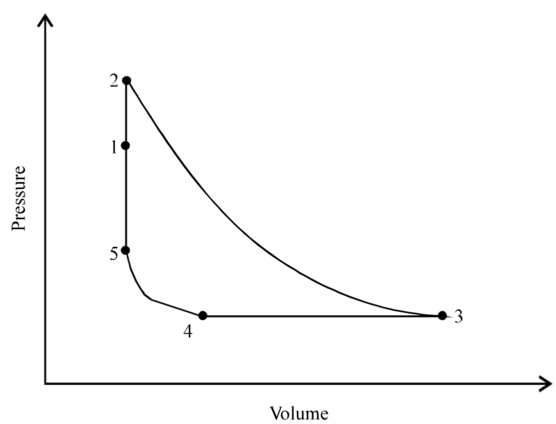

Fig. 7: Process Cycle of Proposed Engine, (1-2) Isochoric injection of high pressure air during the period the piston dwelled at TDC, (2-3) Polytropic expansion of air from high to low pressure, (3-4) Isobaric exhaust of low pressure air, (4-5) Polytropic compression of air retained in clearance volume, (5-1)Isochoric mixing of air initially present in engine with the intake high pressure air, thus raising the pressure of the clearance volume (Heywood, 1988)

Proposed engine: Referring to Fig. 7 for the pressure-volume curve of the proposed engine cycle. Let the poyltropic index for expansion and compression process be, n = 1.3.

(a) V_1= 8.7266 x 10^{-5} m^{-3} P_1 = 37 bar T_1 = 400 K (delivery conditions of compressor)

$\Rightarrow v_1 = 0.031\ m^3\ kg^{-1}$

$\Rightarrow m_1 = 2.81\ g$

(b) $V_2 = V_1 = 8.7266\times10^{-5}\ m^{-3}$ P_2 = 40 bar

Taking the mass flow rate of compressed air through the valve injectors= 23.27 g sec^{-1} (http://www.cleanairpower.com/pdf/VC-SP-Gas-Spec_updateNov08.pdf).

Thus, mass of air injected into the engine in 30° dwell period of piston = 2.9×10×^{3} g (assuming the crankshaft to have a mean rpm of 4000).

$\Rightarrow m_2 = 2.813$ g

$\Rightarrow T_2 = 432.4$ K

(c) $V_3 = 8.7266\times10^{-4}$ m^{-3} $m_3 = m_2$

$\Rightarrow v_3 = 0.31$ m^3 kg^{-1}

As $PV^{\square} = k$

$\Rightarrow P_3 = 2$ bar and $T_3 = 216$ K

(d) Let $V_4 = 2.836\times10^{-4}$ m^{-3} and $P_4 = P_{3,}$ $v_3 = v_{4,}$

$T_3 = T_4$

$\Rightarrow m_4 = 0.915$ g

(e) $m_5 = m_4$ $V_5 = V_1$

$\Rightarrow P_5 = 9.256$ bar and $T_5 = 307.6$ K

Now, Work done by engine per cycle = W_E

$W_E = [(P_2V_2 - P_3V_3)/(n-1) - P_3(V_3 - V_4) - (P_5V_5 - P_4V_4)/(n-1)]$ (Heywood, 1988)

$\Rightarrow W_E = 383.8$ J

W_C = Total work required per cycle in compressor = $w_c\times$mass = 370.076 kJ kg^{-1} $\times$ $(m_2 - m_5)$ = 702.4 J

Thus, efficiency of engine $\eta_{Engine} = W_E/W_C = 54.6\%$

RESULTS AND DISCUSSION

The effectiveness of the technique was analyzed mathematically, by comparing the thermal efficiencies through P-V diagrams of respective cycles. The thermal efficiency of the proposed cycle (54.6%) was found to be less than that of ideal Otto cycle (66.11%) under similar operating conditions. This was primarily attributed to the indirect use of energy (energy is used to compress air which in turn is used to run the engine) and the losses associated with the energy conversion processes (Creutzig *et al.*, 2009). It was also noted that for multi-stage systems, the efficiency of the proposed engine is reasonably high for it to replace IC engines (Cestero, 1987). Compressed air has a very low energy density compared to gasoline or electric batteries. This means that a large onboard storage tank is necessary to achieve a similar energy output as compared to that of an average sized gasoline tank or an electric battery. However, the small size of an air-powered vehicle limits the space available for onboard storage. This can be addressed by using high-pressure carbon fiber tanks storing air up to 300 bar. But an increase in tank pressure leads to greater energy losses in the expansion process thus limiting the benefits achieved by increasing the energy stored (Mcbride and Bollinger, 2012). Also when the greenhouse gas emissions associated with upstream processes like electricity generation, fuel extraction and processing are taken into account, compressed air vehicle underperforms both the gasoline and electric vehicles (Creutzig *et al.*, 2009). However, the compressed air engine has certain positives as well. As there is no combustion, there is no need of spark plugs and cooling system which results in reduced cost, weight, volume and vibration of the vehicle. Moreover, the low temperature exhaust obtained from the engine can be used for air-conditioning purposes in a vehicle (Chen *et al.*, 2011).

CONCLUSIONS

The compressed air engine thus, provides a viable option as a future state of technology which can replace internal combustion engines. With no harmful pollutants in the exhaust, it is evident that compressed air is indeed a renewable source of energy. Also some mechanical configurations allowing exhaust regeneration and energy recovery during braking can boost the overall economy of this engine usage. To make the air powered vehicle competitive with the gasoline and electric cars, it is to be redesigned as a hybrid with some other fuel source.

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