An Overview of Compressed Air Engine Technology

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Abstract – *Compressed Air Engine (CAE) technology has several advantages such as; a zero-emission, low transport cost, small size, low weight, low maintenance cost, high power density and long life use which make it strong competitor with electric vehicle technology in transport sector.*

In this study, the ideal thermodynamic and performance of CAE are introduced and compared with the measured results at different working conditions. It has been notice the CAE performance is influenced by supplied pressure and rotational speed. CAE thermal efficiency is influenced by injection duration and supplied pressure. The maximum measured efficiency is notice to be less than 30% at all working conditions while the predicted efficiency can be higher.
The measured and the predicted ideal indicated power were compared at different working condition and it gave an acceptable agreement even if the ideal thermodynamic model was used. The prediction can be improved it a real engine model is used.

Key Words: Compressed air energy, CAE, thermodynamic model, thermal efficiency, measurements.

1. INTRODUCTION

Pneumatic drive systems for vehicles are attracting more and more attention in research. As one of the potential technologies for achieving zero emissions [1,2], a compressed air power plant can be combined with a conventional internal combustion engine (ICE) to form a hybrid system [3,4]. A hybrid propulsion system can be identified as a propulsion system for a vehicle that passes between an internal combustion engine using fossil fuels and an emission-free propulsion system such as an electric propulsion system, hydraulic system or a pneumatic system [5]. A hybrid powertrain is currently one of the most viable solutions to improve fuel economy and reduce emissions at a relatively low investment cost compared to an electric powertrain that uses lithium-ion batteries. A hybrid powertrain consists of two powertrains including an internal combustion engine and an auxiliary powertrain with a clean energy source such as a battery or a compressor pack. The hybrid transmission enables a conventional combustion engine with fossil fuels to work under improved conditions with lower fuel consumption and lower pollutant emissions [6]. This study aims to present a simplified mathematical model that university students and young researchers can use to study the performance of a Compressed Air Engine (CAE) under various operating conditions. It was also clarified how to build a platform to test the performance of the engine in the laboratory when the flow rate and the inlet air pressure differ. Which necessitated a comprehensive review that was not addressed by researchers, research challenges and strategies for potential future developments on the application of compressed air energy technology in the vehicle propulsion system.

2. COMPRESSED AIR POWERTRAIN

2.1 Compressed Air Engines (CAE) Development

Simple, safe and cost-effective, pneumatic powertrains have been widely used as a power source for locomotives for more than half a century, before the invention of the fossil fuel internal combustion engine (ICE) [7]. The use of compressed air in transportation began to decline in the 1930s due to the emergence of highly efficient fossil fuel ICEs. After the Second World War, the dramatic reduction in the price of fossil fuels encouraged the commercialization and development of petrol and diesel engines for vehicles or locomotives, leading to the disappearance and replacement of compressed air engines off the road. However, research interests and technological advances in the compressed air propulsion system reappeared in the 1970s due to concerns about the energy crisis and environmental issues [8].

In 1976, Ray Starbard [9] invented a pneumatic truck in Vacaville, California. In 1979, Terry Miller [10] designed a spring-powered car and demonstrated that compressed air was the ideal energy storage medium. Inspired by the work of Terry Miller [10], many studies were conducted in the following decades. Interest in the pneumatic vehicle was stimulated by the announcement of a prototype for commercial production. In 1992, Guy Negre [11] proposed a compact design air vehicle. As indicated in the design, a typical vehicle can run 200 kilometers using 300 liters of compressed air (300 bar) stored in carbon fiber or fiberglass tanks. He estimated that it takes about 2-3 minutes at a price of 1.5 euros to fill the air tank. In 1993, Terry Miller jointly developed an air-powered engine with Toby Butterfield and named the car after the Spirit of Joplin's Air Car. In 1979, as America found itself embroiled in an energy crisis, Missouri-based engine designer Terry Miller [12] built a car that ran on an abundant, zero-emission fuel source—air. Miller streamlined the design for his Air Car One. Pressure generated by the release of compressed air from onboard tanks drove the car's engine but Miller's vehicle was never commercially produced.

2.2 CAE Working Principles

In a CAE, the energy is normally changed over by the motor into mechanical energy through the extension of packed air in the chamber. Figure 1 shows the functioning system of a typical pneumatic engine.

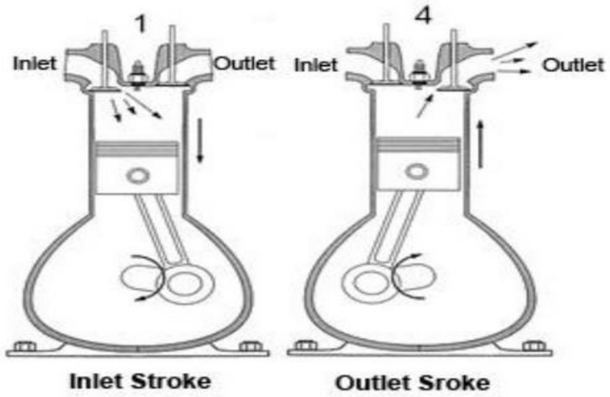

Fig -1 : Working process of a reciprocating piston compressed air engine.

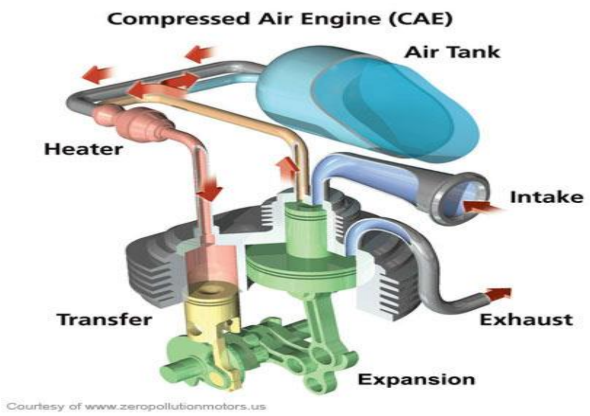

Fig – 2 : compressed air engine Working Principles.

The construction of a CAE cylinder is like that of a customary inner ignition motor aside from that the pneumatic motor doesn't have a fuel injector or sparkle plug. The admission valve ordinarily opens when the cylinder moves to the top flawlessly focused (TDC), and packed wind streams into the chamber from the air tank. After the admission valve is shut, the compacted air caught in the chamber keeps on growing until the cylinder arrives at the base flawlessly focused (BDC). The exhaust valve opens after the development interaction, and compacted air is siphoned out of the chamber with the vertical development of the cylinder. Most of studies on a pneumatic motor have been founded on a responding cylinder structure during the previous decades.

Liu et al. [13,14] established mathematical models for a CAE and analyzed the its working characteristics under both single-stage and double-stage expansions. Yu et al. [15] analyzed the theoretical cycle of a pneumatic motor and concluded that the motor's work output was in a linear positive correlation with the initial temperature of the expansion process, and one possible way to increase the motor's work output is to introduce a multi-stage and quasi-isothermal expansion of compressed air.

Liu et al. [16] reported the optimisation design on the theoretical cycle of the compressed air powered engine using multi-objective optimisation method, they concluded that the maximum cycle efficiency can be obtained under the engine intake pressure ratio and the compression ratio respectively at 32 and 13.

Optimal design for the trajectory of the reciprocating piston was also proposed by introducing a dual crankshaft mechanism [17]. The reenactment showed that the chamber can remain fixed before the chamber pressure rises to the affirmation pressure when the ideal chamber way is taken on. Moreover, the chamber speed can be straightforwardly dependent upon the confirmation valve\'s stream district until the in-chamber squeezing component of the engine shows up at a biggest and subsequently remains consistent after the affirmation valve is closed. J.-Q. Hu et. al. [18] played out a transient in-chamber stream field assessment of a pneumatic engine to focus on the power transport during the running framework and found that unevenness near the affirmation port can incite outrageous power hardship in compacted air. The simulation model made by [19] has been validated by an Air-Powered Engine (APE) [20]. A virtual model was made with an as of late developed valve system to focus on the novel presentation of the pneumatic powertrain and progressed valve control techniques, making responsibilities to the speculative understanding of pneumatic powertrain advancement.

Following the previous progress, the team further developed the dynamic heat transfer to investigate the temperature drop during operational conditions of the air-powered engine [21]. Additionally, a temperature compensation technology [22] was proposed to eliminate the risk of ice blocking as a consequence of the throttling effect during the flow of compressed air.

2.3 Effect of Design and working on CAE Parameters

Some new technology is developed like new design of cam for four stroke engines; also provide new technology of fabrication of compressed air vehicle. It has some advantages and disadvantages of compressed air vehicle and the experimental analysis like load calculation, power production by engine and main factor is pollution is not produced by this engine. The thermodynamics of heat exchange, mechanical and aerodynamic losses, electrical efficiencies etc. all these effects may reduce the overall efficiency to 40% or less. The speed of the engine is found to increase almost linearly with the increase in the pressures. High pressure of 9 bars the maximum speed attained was 36.5 km/hr. The engine is modified from a 4-working stroke to a 2-working stroke engine (power and exhaust) by modification of cam-gear system. At 20°c, 22-liter tank loaded with air at 8 bar used just 15.6 W of vitality. The motorcycle installed with the compressed air engine can operate at maximum speed around 38.2 km/hr and distance up to 5 km. This will be produced enough power for speeds of about 15-20 kilometers per hour Compressed air engine is not producing any harmful gases for environment as well as human body this is totally pollution free engine [23].

Saurabh Pathak, et al. [24] describes the automotive industry is now using light weight vehicles as they have better handling. Heavy vehicles produce harmful gases like SO2, CO2 which is major cause of air pollution. The CAE technology is cheaper comparatively to IC engines at lower maintenance cost. The author concludes that pneumatic technology can be tested and developed using vane type noble air turbine and their efficiency varies from 72% to 47% which is very high comparatively to IC engines and the widespread of this technology helps in controlling serious problems of global warming.

Ankit Sharma, et al. [25] analyzed different effects to various parameters on air engines such as capacity of compressor tanks, number of strokes, number of cylinders, air pressure from compressors, use of electric devices, number of inlet and exhaust port, pneumatic guns. It is found that the engine speed is 3000 rpm was obtained at maximum pressure of 8 bars and high-power gain of 0.95KW achieved at (bar at 1320 rpm. The rotating speed was found to be 715 rpm to 965 rpm whereas at high pressure of 25 bars with varying angles the speed ranges from 1191 rpm to 1422 rpm. At low pressure of 5 bars, maximum speed was 28.9 km/hr having travelling distance of 2.5 km and at 9 bars maximum speed was 36.5 km/hr travelling distance of 1.7 km.

Arjit Maurya, et. al. [26] is concerned about saving the environment and many measures are taken to reduce the pollution in environment. In compressed air technology air is taken as input from intake valve vertically above piston head and modified cam shaft is used to alter the timing of valve. Experimentally speed of 60 km/hr was achieved by the use of this engine. This engine is very efficient as it causes no combustion and therefore no harmful gases are released. The experiment which is performed shows that vehicle runs at 60 km/hr and weight was 18.5 kg which slightly affects the efficiency of engine.

An experimental analysis of a compressed air engine is presented by Qihui, and Maolin [27]. A prototype CAE system is set up to obtain performance of the CAE. The output torque, power and efficiency are obtained through experimental study. The results show that the prototype of CAE has a good economic performance under low speed, the performance of the CAE is mainly influenced by the rotation speed and supply pressure and when the supply pressure is 2 MPa, the maximum output power is 1.92 kW; the maximum output torque is 56.55 N·m, and the maximum efficiency is 25%.

Addala and Gangada [28] examined the performance of a car which takes air as the working medium. Compressed air car is affordable and have a performance rate whose power to weight ratio stands up to 0.0373kW/kg. For arriving at a fair power to weight ratio, it has been considered possible factors which would result to minimize the weight of the car such as a 3-wheeled vehicle was designed, and the entire chassis was fabricated with 1inch angular frames.

Sharma and Singla [29] presented a modified proto type of a horizontal, single cylinder low speed to run on compressed air. From the presented results, it can be seen that the indicated power is increasing for increase of load, as load is increased, the speed falls down, to maintain it constant injection pressure has to be increased, and as the injection pressure has to be increased, the indicated mean effective pressure gets increased; hence the indicated power is increased upon the application of the load. Though the applied load was small, however, the developed power was in proportion to the applied load. As load was applied the speed was reduced, to maintain it constant, the inlet air pressure has to be increased. As shown injection pressure is increased. In the present case the speed was maintained constant as 600 rpm. As the output speed was less the brake power was significantly lower. The mechanical efficiency is increasing with the increase of output power. At lower output it was very low.

Swapnil and Kailas [30] studied the compressed air driven vehicle, the engine used in this project is being subjected to different modifications like, Cam-shaft modification, new set of gears for camshaft and different conclusion has been drawn from the presented results, Engine speed (RPM) versus inlet pressure; as the inlet pressure increases, also engine speed increased linearly, also, as the engine torque versus inlet pressure; as the pressure increases, torque on crankshaft increased linearly, and engine torque versus engine speed; as the engine speed increases, the engine torque increased linearly.

Huang et. al. [31] presented a theoretical (using a simplified thermodynamic models) and experimental investigations of 100 cc internal combustion engine running on a compressed air at pressures ranging from 5 to 9 bar (absolute pressure). It has been shown that the highest power output of 0.95 kW was obtained at 9 bar and 1320 rpm, the highest torque of 9.99 N·m occurred at the same pressure, but at 465 rpm, the outlet pressure increased from 1.5 bar at 500 rpm to 2.25 bar at 2000 rpm, the temperature inside the cylinder decreased from room temperature to 17 °C was observed, the air consumption (flow rate) of used air engine is low, at approximately 1050 L/min, which limits its power performance, causing problems of lubrication and sealing between the piston and cylinder. It has been also shown that the efficiency of the compressed air operation is approximately 13% at 5 bar supplying air pressure while the rotation speeds is below 1500 rpm and an approximately 2.25 bar exhaust air pressure occurs when operating at 9 bar supplying air pressure and 2000 rpm.

Mahendrakar and Chandan [32] have been modified the four-stroke engine to work on a six stroke, the first four stroke for gasoline and the last two for compressed air. It has been shown that use of pressure energy (Compressed Air) and Gasoline improve the Brake Thermal Efficiency (BTE) to 34% and overall efficiency of 68%, reduce the use of fossil fuel, decrease in cylinder temperature and reduce the residual of the exhaust gasses which improve the volumetric efficiency.

Design and analysis of CAE is presented by Lal, [33], it has been stated that weight of the engine is reduced to great extent that leads to, high power to weight ratio, Power loss due to inertia of the moving parts is reduced, start-up power is not required to run engine, and Exhaust air causes no harm to environment as it is cold and clean.

According to the above analysis, the compressed air engine (CAE) will be emphasized in the future. In this paper, an air-powered engine of a renewable energy vehicle is introduced. To lay a foundation for the optimization of CAE, a physical model of CAE is set up. To obtain performance of the CAE, a prototype CAE system is set up. And the physical model of CAE is verified by experiments. The contents of this paper are organized as follows: the introduction to CAE is represented in section 1; the engine modification, experimental procedure and assumptions are described in section 2; the experiment results are shown and analyzed in section 3; a comparison between the ICE power and the CAE power is presented in section 4, and the conclusion is stated in section 5.

2.4 Background Summary

- The main advantage of the CAE is that there is eco-friendly and running on a fuel that is freely available. no need of hydrocarbon fuel, improvement is carried out with thermodynamic analysis, stress analysis and energy losses may decrease.
- Various parameters are considered while designing CAE like temperature, energy density, requirement of input power, and energy release. There is strong competition between electric powered and CAE vehicles market which gives the priority to compressed air car in terms of cost and environmental purpose. Single cylinder CAE can be used as alternate for IC engine in future
- Exhaust of harmful gases is at very low temperature than IC engine which solve problem of heating of engine. Zero emission of harmful gases, this concept can also be used in stationary application.
- Power and engine speed affected by compressed air inlet pressure, travelling distance depends on the capacity and the pressure of the air tank, the maximum vehicle speed is 60 km/hr and maximum thermal efficiency is 25%.
- The CAE technology is lower maintenance cost comparatively to IC engines.

3. THEORETICAL AND EXPERIMENTAL CHARACTERIZATION OF CAE

3.1 Indicated Power Characterization of CAE

Based on the theoretical background of ICE [1], the ideal thermodynamic process can be shown as Figure 3, intake process and exhaust process are considered constant pressure process, and expansion process is considered adiabatic process.

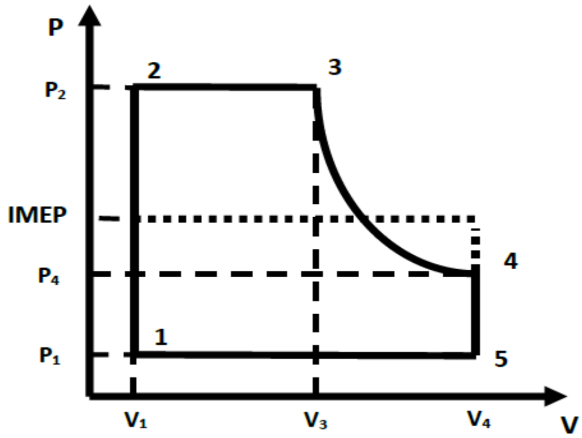

Figure -3: The ideal thermodynamic process of CAE.

V1, is the clearance volume, V4 is the total swept volume (cylinder volume), V3 is the volume related to flow discharge from compressed air tank related to 100 Degree of crank angle [1].

The theoretical work is calculated by plotting the P-V diagram and calculating the area under the curve, and it is given as follows.

$$W_{1-3} = \sum_{i=1}^{3} \text{PdV} \quad (1)$$

$$W_{1-3} = P_2(V_3 - V_1) \quad (2)$$

and

$$W_{3-4} = \frac{P_2 V_3}{1-k} \left[\left(\frac{V_4}{V_3}\right)^{1-k} - 1\right] \quad (3)$$

and

$$W_{4-1} = P_1(V_1 - V_4) \quad (4)$$

Which can be presented as

$$W_{Total} = W_{1-3} + W_{3-4} + W_{4-1} \quad (5)$$

=

$$P_2(V_3 - V_1) + \frac{P_2 V_3}{1-k}\left[\left(\frac{V_4}{V_3}\right)^{1-k} - 1\right] + P_1(V_1 - V_4)$$

where, Wtotal is the theoretical work done, P2 and V2 represent the supply pressure and volume, respectively, at which the air push down the piston downward movement, V1 is the clearance of cylinder, P4 and V4 are the pressure and volume, respectively, up to which the maximum expansion of air takes place, and P5 is the pressure at which the piston discharges the air to the environment. Equation 4, can be simplified as;

$$W_{Total} = IMEP \ (V_4 - V_1) \quad (5)$$

Where IMEP is the indicated mean effective pressure, which can be calculated using equations (4) and (5) as;

$$IMEP = W_{Total}/(V_4 - V_1) \quad (6)$$

For a single cylinder engine, the Indicated Power (IP) in watts can be calculated using equation (3) as;

$$IP = W_{Total} \, N/60 \quad (7)$$

It can be also calculated using equation (6) as;

$$IP = IMEP \ (V_4 - V_1) \, N/60 \quad (8)$$

3.2 Experimental Characterization of CAE

The test rig [1] as shown in Figure (4) consists of a 2 stroke, single cylinder compressed air engine and its full specification can be found in Appendix (A), The CAE equipped with all measuring devices as well as the inlet flow electronic control unit. The electronic unit [1] is used to control the electrical signal of the solenoid valve, to control the close and open-air passage. The solenoid valve that shown in Appendix (B) is used to control the compressed inlet air only while the original inlet and exhaust valves are used as discharge valves. The compressed air is supplied for suppling Air unit which, is specified in Appendix (C).

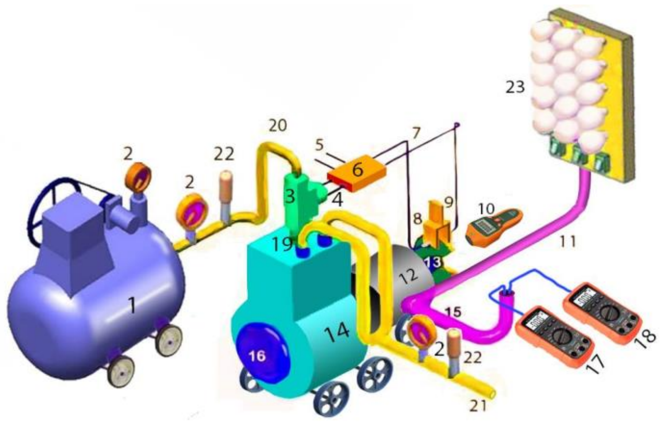

Figure - 4: Layout of the compressed air engine test rig [1].

1) Compressed air tank, 2) pressure sensor, 3) solenoid valve, 4) Signal output,5) Power Source (24 volt), 6) ECU, 7) Input signal, 8) LDR holder ,9) LDR, 10) Tachometer, 11) Timing disc, 12) Generator, 13) Output shaft, 14) Engine,15) Output cable to measure power,16) Flywheel, 17) Ammeter, 18) Voltmeter, 19) Inlet air and 20) Pneumatic hose, 21) air outlet, and 22) temperature sensor.,23) Electric load.

4. RESULTS AND DISCUSSION

4.1 Theoretical Results

The ideal thermodynamic process is presented at inlet pressure of 8 bar in Figure 5. Based on the presented data, the IMEP is estimated using equation 7, and the P-θ diagram is also is presented in Figure 6.

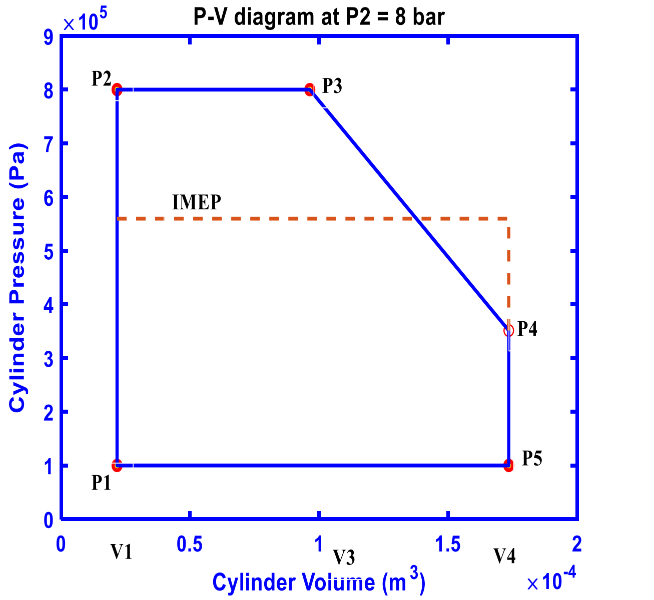

Figure -5: The ideal thermodynamic process of CAE at P2=8 bar.

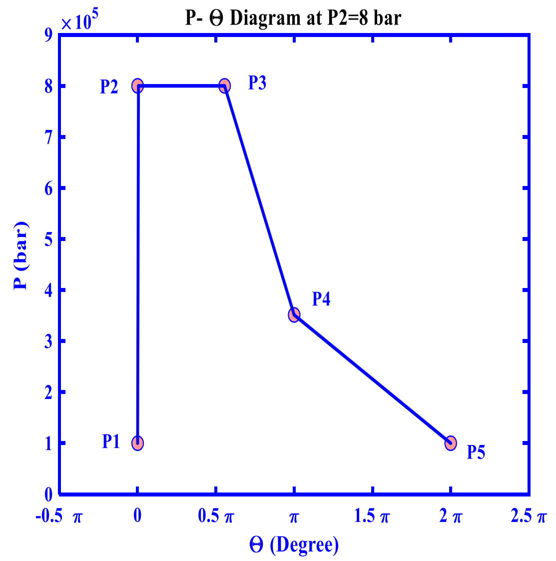

Figure -6: P- θ of Ideal CAE at P2=8 bar.

Engine IP at inlet pressure of 8 bar are calculated using equations 8, 9 are presented in Figure (7). It can be seen that they are identical for the ideal thermodynamic process, and they are linearly increasing with engine speed. The effect of inlet pressure on the predicted IP is presented in Figure (8).

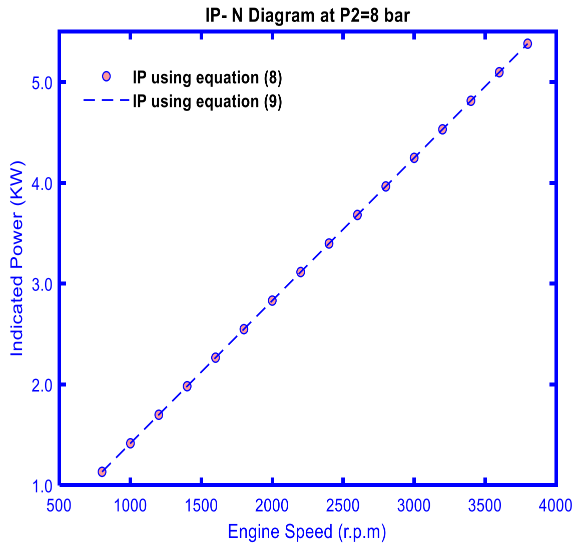

Figure -7: IP versus engine speed of CAE at P2=8 bar.

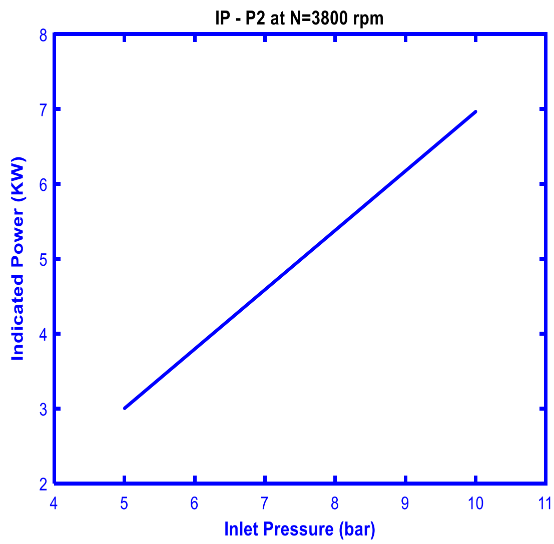

Figure -8: IP of CAE versus inlet pressure at engine speed 3800 rpm.

4.2 Experimental Results

Based on the measured results using the presented test stand in section 3.2, the acquired flow rate of the CAE at different rotation speeds and supplied air pressures are presented in Figure 9. The relation between the measured Brake Power (BP) versus engine speed is presented in Figure 10, Based on work done by Singh Avinash [34] and Richard Wagner [35], the friction power (FP) is estimated and presented on Figure 10. Figure 11 also, presents the variation of the measured IP at different engine speed which, is calculated as follow:

$$IP = BP + FB \qquad (9)$$

Likewise, if we measure or calculate the work or power lost through friction,

$$FP = FMEP\,(V\_4 - V\_1)\,N/60 \qquad (11)$$

Where FMEP is the friction mean effective pressure (FMEP). Patton and Sandoval [41, 42] decomposed overall engine friction into functional groups that are still commonly recognized and used today:

- Crankshaft bearings (including connecting rod bearings) and seals
- Pistons (including piston skirts and piston rings)
- Valve train (Camshaft bearings and seals and camshaft followers)
- Accessories (oil and coolant pumps)
- Pumping (intake and exhaust flows)

The following correlations, representing each of the functional groups above, are from Patton and Sandoval [41, 42] all FMEP units are in kPa:

4.2.1 Crankshaft (CS) friction:

$$FMEP_{cs} = 1.22x10^5\left(\frac{D_b}{b^2 sn_c}\right) + 3.03x10^{-4}\left(\frac{N D_b^3 L_b n_b}{b^2 sn_c}\right) + 1.35x10^{-10}\left(\frac{D_b^2 N^2 n_b}{n_c}\right) \qquad (12)$$

All Symbol' definition can be found in [41, 42].

4.2.2 Piston friction (including skirt, ring tension and ring pressure)

$$FMEP_p = 294\left(\frac{\bar{U}_p}{b}\right) + 4.06x10^4\left(1 + \frac{500}{N}\right) + 6.89\left[0.88r + 0.182r^{(1.33 - 2k\bar{U}_p)}\right] \qquad (13)$$

where $k = 2.38x10^{-2}$.

4.2.3 Valve train friction (including cam, cam followers and valves):

$$FMEP_v = 244\frac{N n_b}{b^2 sn_c} + C_{ff}\left(1 + \frac{500}{N}\right)\frac{n_v}{Sn_c} + C_{rf}\left(\frac{N n_v}{sn_c}\right) + C_{oh}\left(\frac{L_v^{1.5} N^{0.5} n_v}{bsn_c}\right) + C_{om}\left(1 + \frac{500}{N}\right)\frac{L_v n_v}{sn_c} \qquad (14)$$

4.2.4 Accessories (including oil and coolant pumps and alternator):

$$FMEP_a = 8.32 + 1.86x10^{-3}N + 7.45x10^{-7}N^2 \qquad (10)$$

4.2.5 Pumping friction:

$$FMEP_{i/o} = (p_a - p_i) + 4.12x10^{-3}\left(\frac{p_i}{p_a}\right)^2\left(\frac{\bar{U}_p^2}{n_v^2 r_i^4}\right) + 0.178\left(\frac{p_i}{p_a}\bar{U}_p\right)^2 + 4.12x10^{-3}\left(\frac{p_i}{p_a}\right)^2\left(\frac{\bar{U}_p^2}{n_v^2 r_e^4}\right) \quad (16)$$

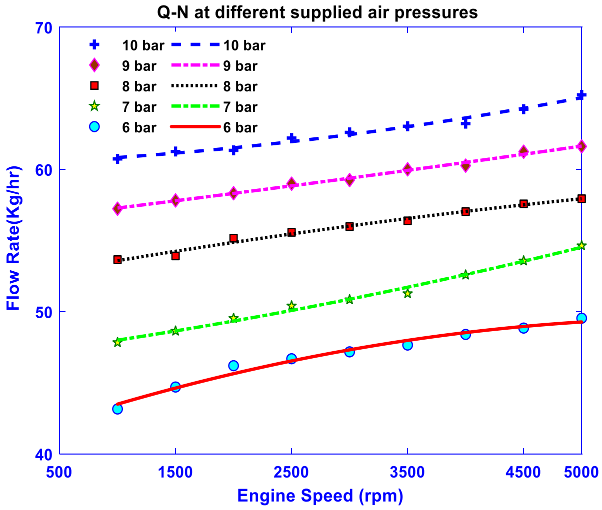

Figure -9: The acquired flow rate of the CAE versus rotation speeds at different supplied air pressures.

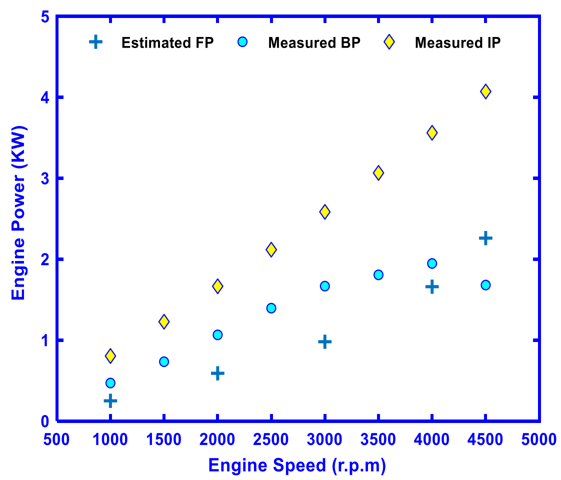

Figure -10: Measured IP, BP, and FP versus engine brake power at inlet pressure 8 bar.

4.3 Predicted and Measured Results

The predicted IP using equation 9 is compared with the measured results at the same working condition of in let pressure and working speeds in Figure 11. It can be notice that they are in the same trend, quiet close to each other and the different between them is coming from the difference between ideal and the actual working process of the CAE and there is an urgent needs to model a real CAE.

(11)

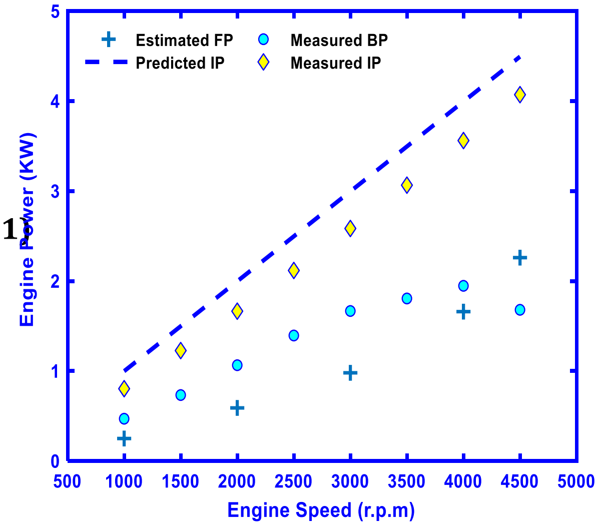

Figure -11: Predicted and measured IP versus engine speed at inlet pressure 8 bar.

5. Efficiency Analyses

The CAE is applied to transform compressed air energy into mechanical energy. The energy efficiency of CAE can be defined as follows [27, 36],

$$\eta = \frac{P_{out}}{\mathrm{P}} \times 100 \quad (12)$$

where, Pout is the output power, P is the available energy of the compressed air can be calculated as follows

$$P = P_2 V_3 \, ln\left(\frac{P_2}{P_5}\right) \quad (13)$$

where p5 is the atmospheric pressure, and p2 is the pressure of the supply air.

$$\eta = \frac{P_2(V_3 - V_1) + \frac{1}{1-\mathrm{k}} P_2 V_3\left[\left(\frac{V_4}{V_3}\right)^{1-k} - 1\right] + P_5(V_1 - V_4)}{P_2 V_3 \, ln\left(\frac{P_2}{P_5}\right)} \quad (19)$$

Employing Lagrange's multiplier, the optimum value of efficiency will be acquired when

$$\frac{\delta\eta}{\delta V_3} = 0$$

Differentiating Equation (18) with respect to V_3

$$\left(\frac{V_4}{V_3}\right)^{-k} = \frac{P_5(V_4 - V_1)}{P_2 V_4} + \frac{V_1}{V_4} \quad (14)$$

In piston-type CAE, V4 represents the maximum volume of cylinder, V1 represents the clearance volume of cylinder, V3 represents the volume of intake air. V3 can be optimized by Equation (19).

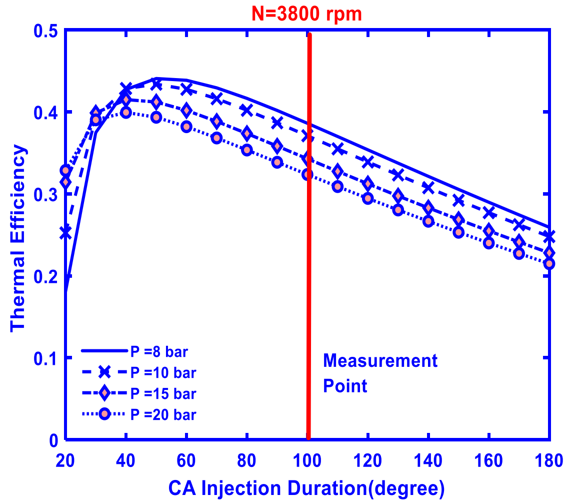

Figure -12: Thermal efficiency versus CA injection duration at different inlet pressure.

As shown in Figure (12), the CAE thermal efficiency is influenced by the injection duration (i.e.V_3) as well as the supplied pressure. The maximum measured efficiency was notice to be less than 30% at all working conditions.

6. *Conclusions*

In this paper, the thermodynamic characteristics and efficiency analysis of a CAE were introduced. To obtain the CAE performances, a prototype of CAE was prepared and adopted in test bench. The output power, torque and efficiency were obtained through experimental study. The conclusion can be summarized as follows:

- The performance of the CAE is mainly influenced by the supply pressure and rotation speed.
- The CAE thermal efficiency is influenced by injection duration and supplied pressure.
- During the measurements, the injection angle was electronically controlled using ECU connected to solenoid valve and the used injection angle was 100 degree.
- The proposed CAE engine has a good economic performance under medium speed.
- The measurements were done at different supplied pressure at Theta=100 degree of crank angle and the maximum efficiency is varied according to supplied pressure and it is theoretically 32 % at 20 bar while during the measurement it did not reach 30% at all working conditions.
- The performance of a real CAE modeling is still going on.

7. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work presented in this paper.

8. Acknowledgement

Technical support during the preparation of the test stand and the measurements from Mohamed Zakaria, who is working at EG Ministry of Education, Zagazig Technical Education Sector, is highly acknowledged

Nomenclature

A_v, A_{vc}	Valve Curtain Area	$(m2)$
$bmep$	Brake Mean Effective Pressure	(Pa)
b	Cylinder Bore	(M)
C	Intake or Exhaust Discharge Coefficient	
D_v	Valve Diameter	(m)
$Fmep$	Frictional Mean Effective Pressure	(Pa)
h_d	Displacement Height	(m)
h, H	Lubrication Gap Height	(m)
$imep$	Indicated Mean Effective Pressure	(Pa)
l_{cr}	Connecting Rod Length (center to center)	(m)
L_v	Valve Lift	(m)
$\dot{m}_b$	Blowby Mass Flow Rate	$(\frac{kg}{sec})$
$\dot{m}_e$	Exhaust Mass Flow Rate	$(\frac{kg}{sec})$
$\dot{m}_i$	Intake Mass Flow Rate	$(\frac{kg}{sec})$
MEP	Mean Effective Pressure	(Pa)
$\dot{Q}_c$	Rate of Combustion Heat Added	(W)
$\dot{Q}_T$	Rate of Heat Transfer from Charge to Cylinder	(W)
r	Compression Ratio	
s	Piston Stroke	(m)
V_c	Clearance Volume	(m^3)
V_d	Displacement Volume	(m^3)
V_T	Total Cylinder Volume	(m^3)
U_p, V_p	Piston Velocity	$(\frac{m}{sec})$
θ	Crankshaft Displacement	$(crankshaft^{\circ})$

General

P	Power	(W, HP)
P	Pressure	(Pa)
$\dot{q}$	Mass-Specific Rate of Heat Transfer	$\left(\frac{W}{kg}\right)$
Q	Heat Energy	(J)
R	Specific Gas Constant	$\left(\frac{kJ}{kgK}\right)$
R	Universal Gas Constant	$\left(\frac{kJ}{kg-molK}\right)$
t	Time	(sec)
T	Temperature	(K)
V	Velocity	$\left(\frac{m}{sec}\right)$
ρ	Density	$\left(\frac{kg}{m^3}\right)$
$\vec{S}$	Surface Unit Normal Vector	(m^2)
U	One-Dimensional Fluid Velocity	$\left(\frac{m}{sec}\right)$
U	Flux Variable	$\left(\frac{kg}{m}, \frac{kg}{sec}, N\right)$
W	Work	(Joule)
$\dot{W}$	Power	(W)
μ	Dynamic Viscosity τ Shear Stress	$\left(\frac{Ns}{m^2}\right)$
τ	Shear Stress	$\left(\frac{N}{m^2}\right)$
τ	Torque	$(Nm, ft-lb)$

Subscripts:

b	Blowby
b	"Burned"
c	Charge
e	Exhaust
i	Intake
p	Products
r	Reactants
u	"Unburned"

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Appendix A: Engine Specifications

Engine type	2 stroke, single cylinder
Bore/ Stroke (mm)	68/45
Capacity (CC)	163 cc
Engine Max. power	3200 Watt @3800 rpm
Generator Max. power	2466.2 Watt @3800 rpm

Cooling system	Air cooled
The oil tank	0.6 litter
The power factor (Pf)	0.77

Appendix B: Specification of Electric Solenoid Valve

Product features	Details
Model	SLp-20E4
pressure	0.5-16 bar
Port size	G 3/4 inch
Current Type	DC
Supply Voltage	24 volt
Body materials	Brass
Number of Ways	2-Way
Solenoid Operation Mode	N/C (normally closed)
Operation Type	2-way 2-position direct lift
Wattage	13 Watt
Orifice Diameter	16 mm

Appendix C: Specifications of the Air Components

Item	Specifications
Compressor	- Pressure 0 – 10 bar - Power 1.5kw
Tank	- Capacity 100L
pressure gauge	- range 0 to 12 bar
Connectors	- Thread is BSPT R1/2 (British standard piping thread). - The outer diameter is 21.5mm - the inner diameter is 12mm.
Pneumatic hose	- Φ8:12mm and length of 1/2m
Valves	- Power: Manual - Working Temperature: 20:100Co - Working pressure: 25Bar - Size: 1/4":4" - Structure: Ball

Figure -13: Compressed air systems.

Figure -14: Photograph Experimental setup of the compressed air engine.

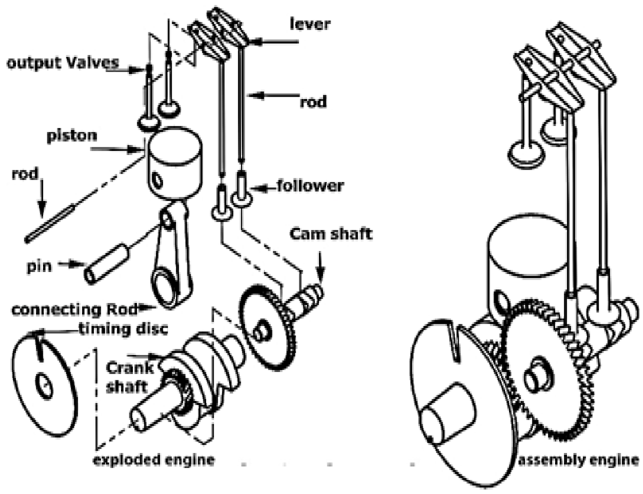

Figure -15: Schematic Experimental setup of the compressed air engine.