



Design and development of compressed air engine

Aplsh Kumar Mahato^{1*}, Dinanath Sharma¹, Durga Bastakoti¹, Min Narayan Shrestha¹,
Niraj Bhatt¹, Rajeshwor Koirala¹

¹ Department of Mechanical and Automobile Engineering, Tribhuvan University
Institute of Engineering, Pashchimanchal Campus, Pokhara, Nepal

*Corresponding email: aplsh.mahato102@gmail.com

Received: December 20, 2022; Revised: January 29, 2023; Accepted: February 09, 2023

doi:<https://doi.org/10.3126/joeis.v2i1.50326>

Abstract

This research aims to build an engine that uses compressed air as a fuel to provide mechanical energy to rotate a crankshaft which can be used for useful work. The specific objectives of the study are to design and fabricate a compressed air engine within a pressure range of two to five bar and to test the engine's performance in terms of angular velocity of the crankshaft, torque produced at the crankshaft, stress and displacement analysis on the base frame and efficiency of the engine. To achieve these objectives, design equations of inertial forces in reciprocating parts is used to calculate the torque produced at the crankshaft, computational tool is used to calculate the stress and displacement analysis on the base of the frame and experimentally the engine is tested to calculate the angular velocity at the crankshaft and valve timing so that crankshaft produces uniform rotational motion. It was found that, the angular velocity is directly and Arduino valve timing is inversely proportional to the pressure exerted by the piston. A force of 245.43 N is exerted by the pneumatic piston cylinder when rotated at 100 RPM producing a torque of 45 Nm at efficiency of 29.60%. The base frame exerted a maximum stress of 48 Mpa and maximum displacement of 1.9 mm, both at the location at which the crankshaft is installed. It is important to note that the results may not be generalizable to all compressed air engines and further research is needed to fully understand their performance and capabilities.

Keywords: Compressed air engine, Flywheel, Stress analysis, Torque, Valve timing

1. Introduction

Over the recent decade, the concept of ecofriendly sustainable development has been promoted realizing the environmental issues such as greenhouse effect, ozone layer depletion, acid rain, fog, haze, unconditioned pollution, and its health hazards. Hence, engineers across the globe are emphasizing the development and use of renewable energy sources rather than fossil fuels. Emphasis is being given to the use of power generating sources that contribute the minimum in desecrating the environment in its overall design process. In the coming future, petroleum crisis is likely to happen which could end the era of high-cost petroleum and open

a fierce competition market of new energy automobile. So far, the new energy automobiles such as electric vehicles, may gradually appear (Nabil, 2019).

The typical product of zero pollution vehicles usually consists of electric vehicles. However, disposal of battery becomes a major disadvantage in using electric vehicles in the long run. Though the idea of compressed air vehicle (CAV) may seem revolutionary, the prototypes have been around since the 1920s. Compressed air has been used with torpedo propulsion for many years. Zero Pollution Motors is the French company behind the car. They intend to manufacture 10,000 of the vehicles in the first year alone. They expect to sell the cars for approximately \$17,800. These cars will have 75 horsepower and will comfortably have room for six passengers. The car will be able to travel approximately 1,000 miles on one fill-up at a maximum sustained speed of about 96 miles per hour (Motor Development International, 2021). CAV takes the form of lightweight passenger cars designed for slow speed city driving. However, unlike those fuels, the efficiency of a CAV is largely dictated by the thermodynamic properties of gases with accompanying inefficiencies of compression and expansion (Yu et al., 2015). Thus, it has become a more ecofriendly and sustainable power choice. LancyCyrilBenjamin et al. (2018) has developed a dual energy engine employing the petrol and compressed air engine (CAE). The relevant research going on at the Motor Development International (MDI) has developed a CAV namely Evolution (Motor Development International, 2021). Its capacity is 3000 liters. The vehicles can travel 200 km at the speed of 96km/hr and can be charged in merely three minutes at a high-pressure air charging station. In accordance with the above analysis, CAE will be emphasized soon. Zero Pollution Motors (ZPM) is also poised to produce the first compressed air-powered car for sale in the United States by mid-2019 (Samar, 2021). Evrin et al. (2014) developed and tested fully integrated prototype systems a compressed air system with a Phase Change Materials (PCM) heat exchanger prototype. In this regard, the energetic efficiency for the system is found to be 74.0% while the exergy efficiency for system is 61.5% where the predicted driving range for systems is 140 km. Three different PCMs of polyethylene glycol, paraffin, and alkane mix are investigated for heat recovery purposes in the prototype where the paraffin option provides the best results. Furthermore, the maximum torque is found to vary between 21 and 44 Nm with changing shaft speed from 400 to 1300 rpm while the minimum torque fluctuates between 3 and 13 Nm with changing shaft speed in the same range. Supplementary battery power is 2.18 kW and the turbine work output is found to be 1.25 kW with the recovered air which provides 36% of needed heat to heat up the PCM heat exchanger. The total motor work consumed during operation is 18.36 kW which can be considered sufficient for the powertrain of a small-size city vehicle. Shkolnik et al. (2021) also reviewed the high efficiency hybrid cycle and presented model results indicating the feasibility of achieving 60% net indicated efficiency in a 1.3L 3-chamber compression ignition design.

Initially the air is compressed into a gas tank through a compressor via electricity. The compressed air is then all allowed to be flown into the engine via different arrangements. The arrangement includes, pressure gauge, solenoid valve controlled via Arduino, a pressure regulator, pipes, and fittings. The compressed air is initially allowed to pass through pressure gauge where we can note down the pressure of air inlet; then it is passed through pressure regulator to control the flow manually to solenoid valve. The solenoid valve is controlled electronically via Arduino, relay module and battery arrangement. The solenoid valve contains one inlet and two outlets for two ports of double acting reciprocating piston cylinder. For one instant, the solenoid valve opens its port, one port at a time and stops the other to flow, which causes the reciprocating motion. The interval of reciprocating motion is controlled via Arduino called the timing valve. The reciprocating motion so achieved is transferred to the crankshaft via crank and connecting rod arrangement. The crank shaft is bolted into the frame through bearing and bearing holder arrangement via nut and bolt. Now, when the compressed air is fed into the piston, it produces reciprocating motion which is converted into rotary motion of crankshaft via crank.

The general objective of this project is to design and develop a CAE and test its performance. It is also intended to find out the correlation between operating pressure and valve timing, flywheel design for a fixed operating pressure, and to control valve timing electrically using Arduino, relay and solenoidal valve. The specific objective of this project is to determine the corresponding force exerted by the piston with the applied pressure onto the cylinder, the valve timing required to obtain smooth rotational motion, the torque produced, and efficiency of the engine.

2. Materials and Methods

The goal of this project was to design, fabricate and test the performance of the engine that uses compressed air as a power source. After the feasibility study of the project, the materials required for the project were selected. First, mild steel was selected to build the frame and crank shaft. Ball bearings were selected to withstand created stress. The size and composition of materials were chosen wisely to reduce the cost without reducing the quality of work. Cast iron was used for crank shaft, body frame, connecting rod, flywheel, bolts, and nuts. In addition, bearing holder was made from mild steel while the remaining components such as solenoid valve, Arduino, relay module, pressure gauge, and tachometer were preassembled.

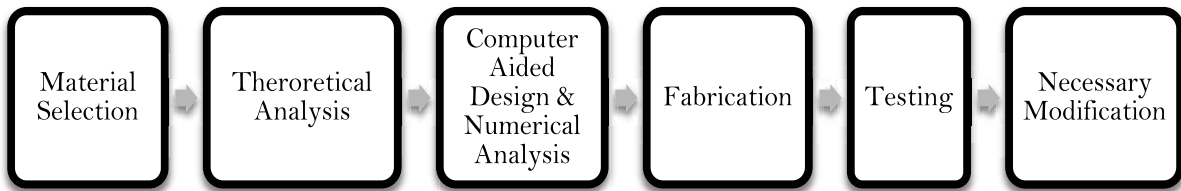


Figure 1: Steps involved in the mechanical design process

The forces developed by the pneumatic piston and cylinder at different pressure were calculated and this force formed the basis of frame and shaft design. The dimensions of the crankshaft and connecting rod were finalized based upon the displacement of the piston. An average operating pressure of five bar was taken as the basis of all the design specifications. With this, the average force developed at the piston output was theoretically calculated to be 980 N. Various Computer Aided Design (CAD) models of different dimensions were developed. Each of the models were tested in a simulation software ANSYS and SolidWorks under the same force that was calculated. The best model with proper dimensions was selected through the iteration technique. The dimensions and weight of the flywheel was calculated through theoretical designs and iteration technique in Microsoft Excel by making turning moment diagrams and maximum fluctuations for the given radius and thickness. The thickness, radius and weight were found to be 12 mm, 16 cm, 2 kg, respectively. CAE was fabricated after the calculation of various parameters and simulation. Various workshop processes like welding, drilling, grinding, cutting etc. were carried out. To build the frame, rods and pipes were welded. Drilling holes for nuts, bolts and screws was also being done. A proper bearing holder was also fabricated based on designed dimension. After the fabrication of the machine, it was tested for different conditions. The variable pressure test resulted in analyzing faulty alignments and need of proper strength in ball and bearing holder was analyzed and modification was made time and again for the proper design of the compressed air engine. The modification includes bearing holder, dimensions of shaft and flywheel, piston holder, frame modification etc.

This was the practical approach of finding out the design parameters. After the fabrication of compressed air engine, the project was made to run under various pressure ranges through pressure regulator. As the solenoid valve timing was controlled by fixed timing Arduino controlled system, the actuation of pneumatic

piston varied with pressure. So, there was a need to change the time for proper non intermitted motion of the crankshaft. The more pressure was the timing of switch on and off of solenoid valve. Thus, this phenomenon also resulted in varying rpm of the crankshaft as per the varying pressure. Data of varying pressure and its corresponding time and rpm was measured.

2.1 Theoretical analysis

This analysis is based on theoretical concepts and frameworks of inertial forces in reciprocating parts under the theory of machine and mechanism (Khurmi et al., 2007).

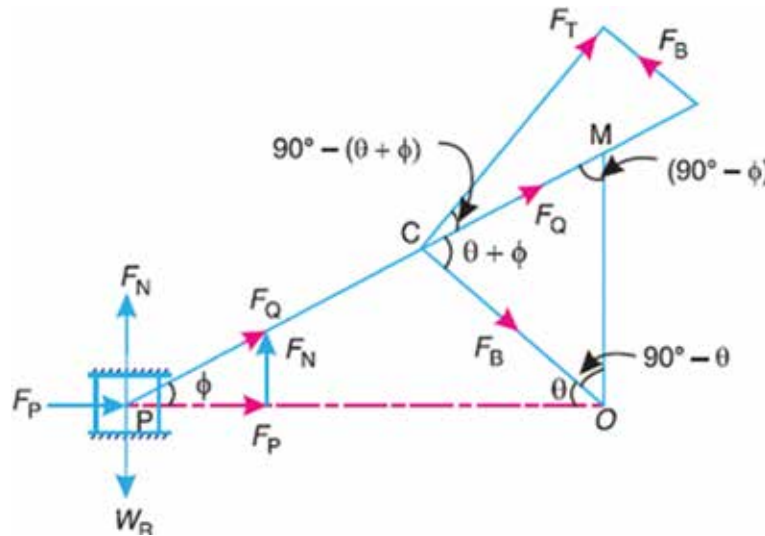


Figure 2: Forces on the reciprocating parts of an engine

The net force acting on the piston along the line of stroke is called piston effort (F_p) which is the main contributing factor for rotational motion and torque produced. Piston effort is a function of net piston load (F_L), inertial force (F_I) and frictional force (F_R) (given in Eq. 1) where F_L is a function of pressure exerted and area of cross-section at inlet and outlet of piston (given in Eq. 2) and F_I is a function of mass (m_p) and acceleration (a_p) of the piston (given in Eq. 3).

$$F_p = \text{Net load on piston} + \text{Inertia Force} - \text{Frictional Force} = F_L + F_I - F_R \quad (1)$$

$$F_L = p_1 A_1 - p_2 A_2 = p_1 A_1 - p_2 (A_1 - a) \quad (2)$$

$$F_I = m_p * a_p = m_p \omega^2 r \left[\cos \theta + \frac{\cos(2\theta)}{n} \right] \quad (3)$$

where, ω is angular velocity of the rotating part, θ is angle made along the radius of crankshaft with the line of stroke and n is the ratio of length of connecting rod to the radius of crank ($n = l/r$).

From Figure 1, the theoretical relation for the force component along the connecting rod (F_Q), force on the side of the cylinder wall (F_N), crank pin effort (F_T) and thrust on crank shaft bearing (F_B) can be given by Eq. 4, Eq. 5 and Eq. 6 respectively.

$$F_Q = \frac{F_P}{\cos \phi} \quad (4)$$

$$F_N = F_Q \sin \phi = F_P \tan \phi \quad (5)$$

$$F_T = F_Q \sin(\theta + \phi) = F_P * \frac{\sin(\theta + \phi)}{\cos \phi} \quad (7)$$

F_T is responsible for the production of the torque on crankshaft (T), also known as turning moment which can be given by Eq. 8.

$$T = F_T * r = F_P \frac{\sin(\theta + \phi)}{\cos(\phi)} * r = F_P * r * \left[\sin \theta + \frac{\sin 2\theta}{2n} \right] \quad (8)$$

Also, Torque required at the flywheel can be given by Eq. 9 as

$$T = I\alpha = \frac{mK_G^2 * \omega^2 R}{2} = \frac{m_R R^2 \omega^2 R}{2} = \frac{2\pi R^4 t \delta \omega^2}{2} \quad (9)$$

where, m_R is rotational gross mass of piston, K_G is the radius of gyration, R and t are the radius and thickness of flywheel, and δ is the material's mass density.

F_L and F_I are to be calculated based on design specification of the engine. The torque can also be calculated based on crank angle and piston effect. The pneumatic piston to withstand the range of torque produced by the crankshaft is to be selected. The pressure range of 0.5 - 2 Mpa at solenoidal valve is sufficient to withstand the working pressure. The valve timing then ranges from 160–250 ms.

Talking about the performance of the engine, one parameter is the efficiency of the engine (given at Eq. 12) which is the ratio of output energy received at the crankshaft (given at Eq. 10) to the input energy supplied at the piston (given by Eq. 11).

$$\text{Output Shaft Energy (O)} = \frac{2\pi NT}{60} \quad (10)$$

$$\text{Input Pressure Energy (I)} = P * Q \quad (11)$$

where, P is pressure of air supplied into the cylinder, and Q is the volumetric flow rate and

$$\text{Efficiency} = \frac{\text{Input Energy}}{\text{Output Energy}} = \frac{60PQ}{2\pi NT} \quad (12)$$

2.2 Modeling of components

Depending upon the design and selection, all the parts were modeled in a computer aided design software Solid works. All the parts were then assembled in the same systems. These modeled parts were taken for simulations and fabrication. This process of modeling helped in the proper manufacturing process of the tools, parts, and systems.

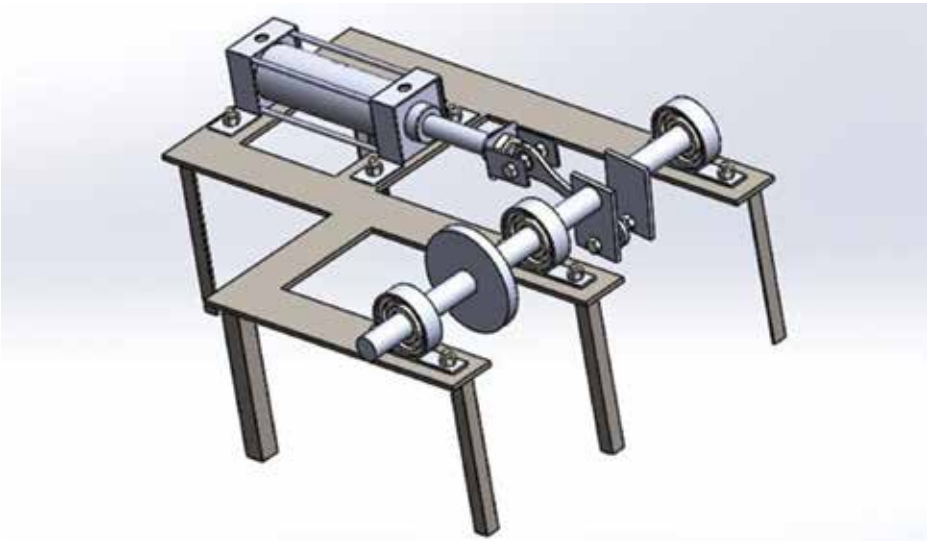


Figure 3: Modeled design of the compressed air engine

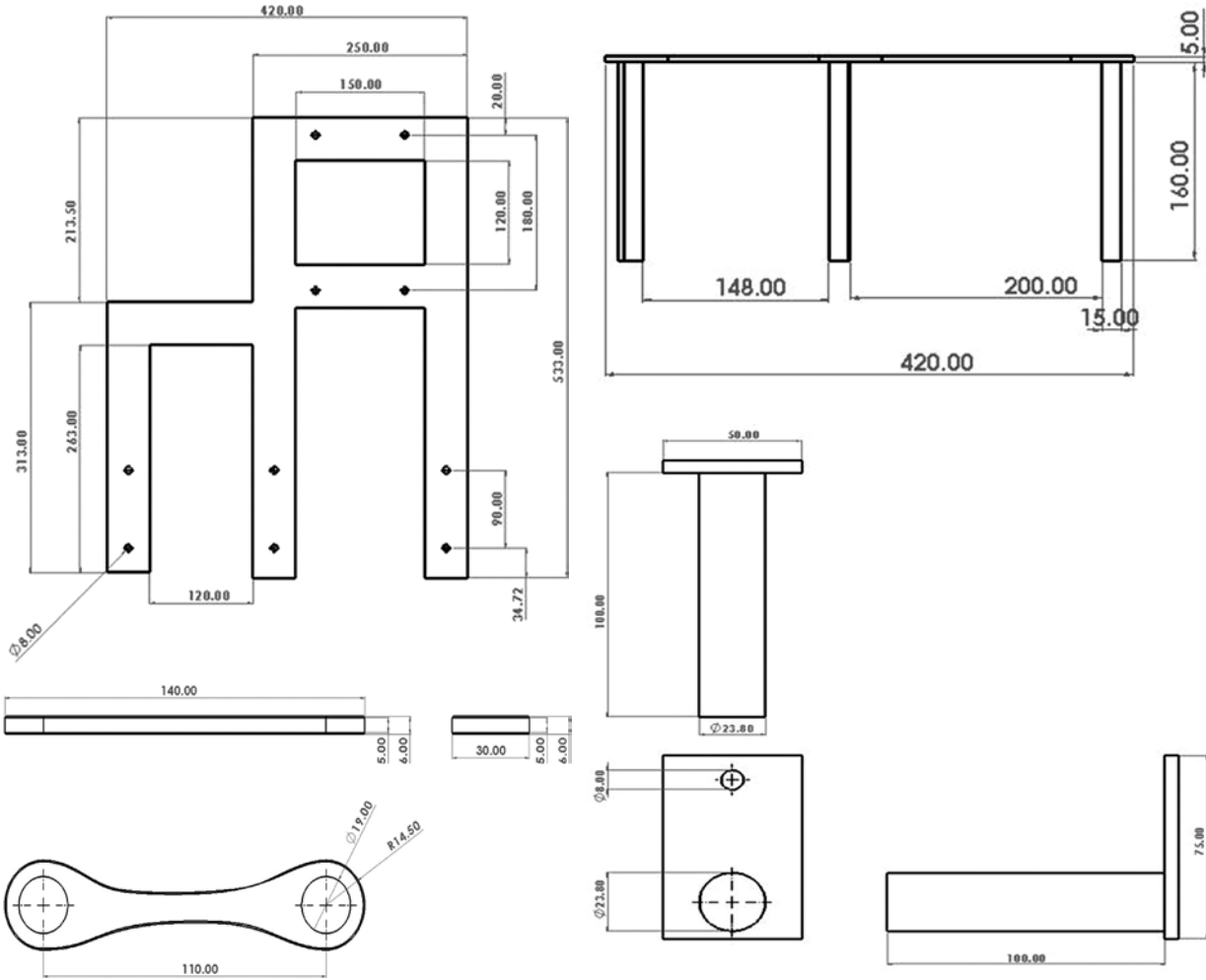


Figure 4: Detail drawing of base frame, connecting rod and crankshaft

2.3 Fabrications and testing

Depending upon the design calculations, modeling and analysis, each component and system were fabricated and assembled. The base frame, crank, crank holder, crank rod, coupler, bearing holder was fabricated with the help of lathe machining, drilling, welding and much of the manufacturing process. Systems such as solenoid valve, pressure gauge, Arduino, relay module, pipes and fittings, pneumatic cylinder was used to pre-assemble and synchronize with the engine. This designed and fabricated engine was subjected to testing and result analysis.



Figure 5: Image of fabricated and assembled system of compressed air engine

3. Results and Discussion

This section presents the findings of the study and interprets their significance. It typically includes a summary of the results, a discussion of the implications of the findings, and a comparison of the results to previous research and theories.

3.1 Theoretical result

This section refers to the outcome of mathematical analysis that are performed to explain the performance parameter of the CAE. It is used to gain a deeper understanding of the underlying principles of the compressed air fuel-based piston-cylinder engine.

3.1.1 Design constraints

This section includes physical parameters which are considered for the design of the engine.

Mass of the Piston Rod (m_R) = 0.8 kg,

Radius of the Crankshaft (r) = 0.05 m,

Length of the Connecting Rod (l) = 0.11 m, Diameter of the Piston (D) = 0.08 m, and Diameter of the Piston Rod (d) = 0.02 m.

3.1.2 Net piston effort

The cross-section area of the piston at one end and other end can be calculated with the help of diameter of the piston and diameter of piston rod. Keeping the intake pressure of the air at one end (P_1) to 4 bar and at another end (P_2) to 1 bar, the net piston load (F_p) is calculated to be 1539.335 N (using Eq. 2). From Eq. 3, for each angle made by the crank radius with the stroke of the piston, the inertial force so produced due to the reciprocating motion of the piston at 100 rpm can be plotted in Figure 1. Similarly, from Eq. 1 and Eq. 2, piston effort can also be calculated for each angle made by the crank radius with the stroke of the piston. The nature of the graph will be similar to Figure 1. From the above figure, the net piston effort of 1545 N is required for the continuous running of the engine to be concluded.

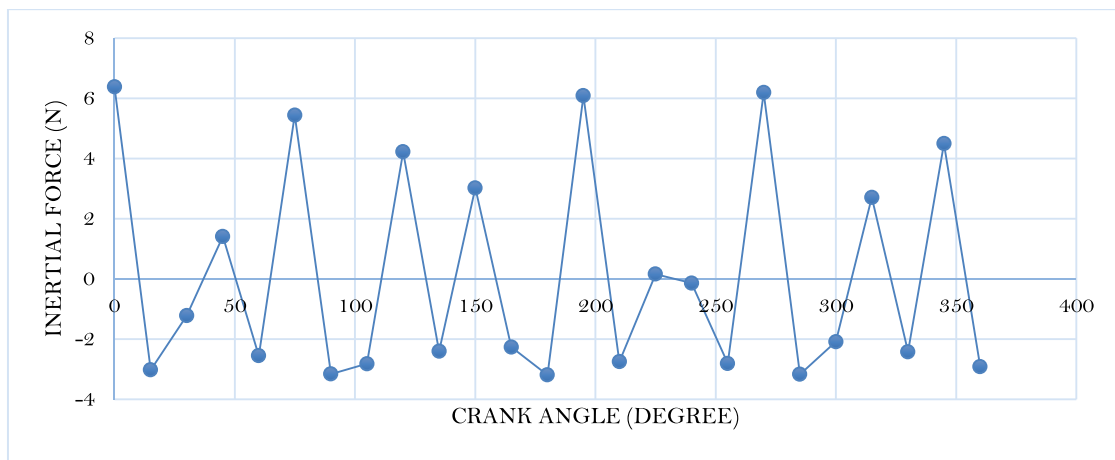


Figure 6: Inertial force of piston against each angle rotated by the crankshaft

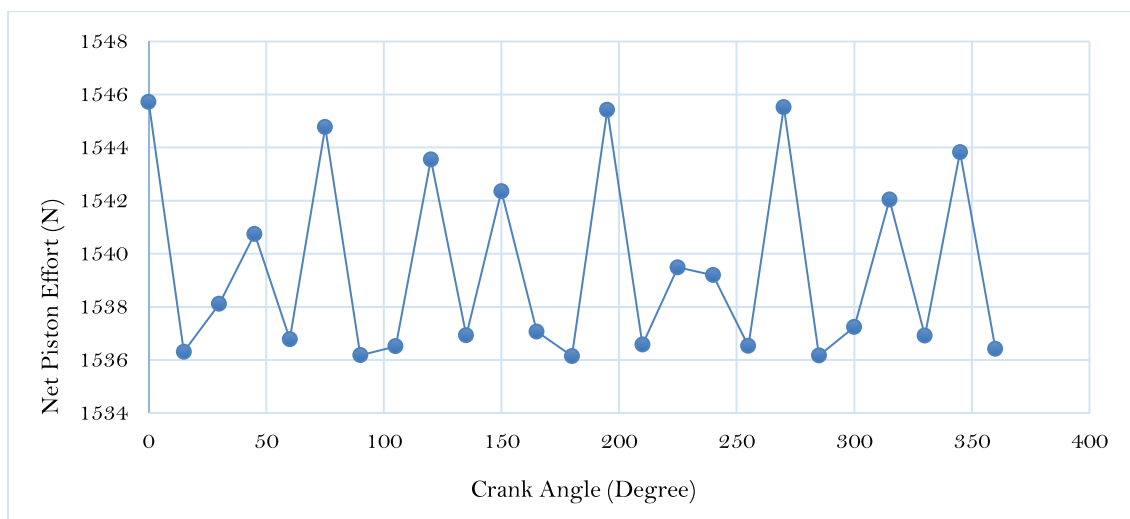


Figure 7: Net piston effort by the piston against each angle rotated by the crankshaft

3.1.3 Selection of flywheel

The parameters influencing to produce torque includes material properties, radius and thickness of the flywheel. Some characteristics analysis must be done before the section of material, radius and thickness of the flywheel. As per the net piston effort required, cast iron is selected. Figure 8 represents the torque required by the crankshaft during each revolution along its axis (Eq. 8 is used to generate the chart). For the selection of the flywheel, the torque generated by the flywheel needed to be slightly greater than the torque required by the crankshaft. Figure 9 represents the radius of the flywheel to the corresponding torque against the crank angle for each thickness of the flywheel. Figure 10 represents the radius corresponding to thickness respective to mean torque. From Figure 4 and Figure 5, it can be concluded that the radius required is inversely proportional to the thickness of the flywheel. From the above chart, a flywheel of radius 80 mm and thickness 15 mm was selected for experimentation.

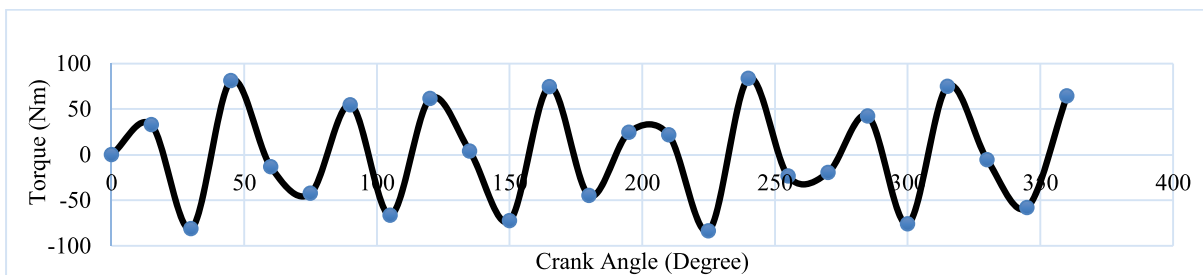


Figure 8: Torque required by the crankshaft against each angle rotated by the Cranksh

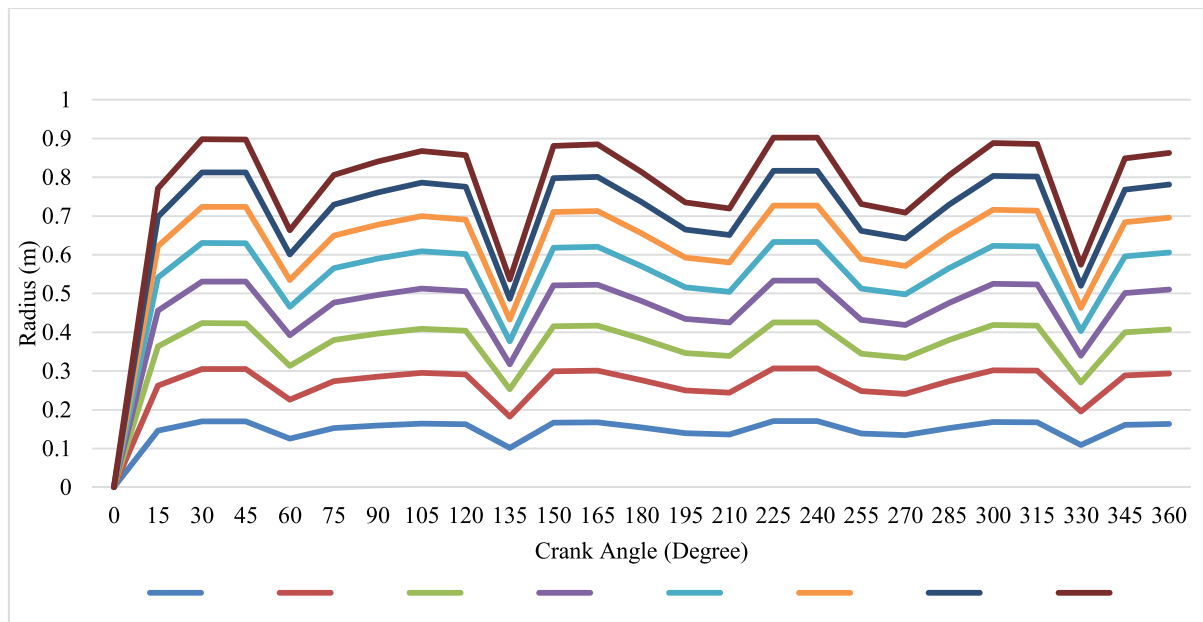


Figure 9: Radius of the flywheel corresponding to torque produced against each angle rotated by the crankshaft for each thickness of the flywheel.

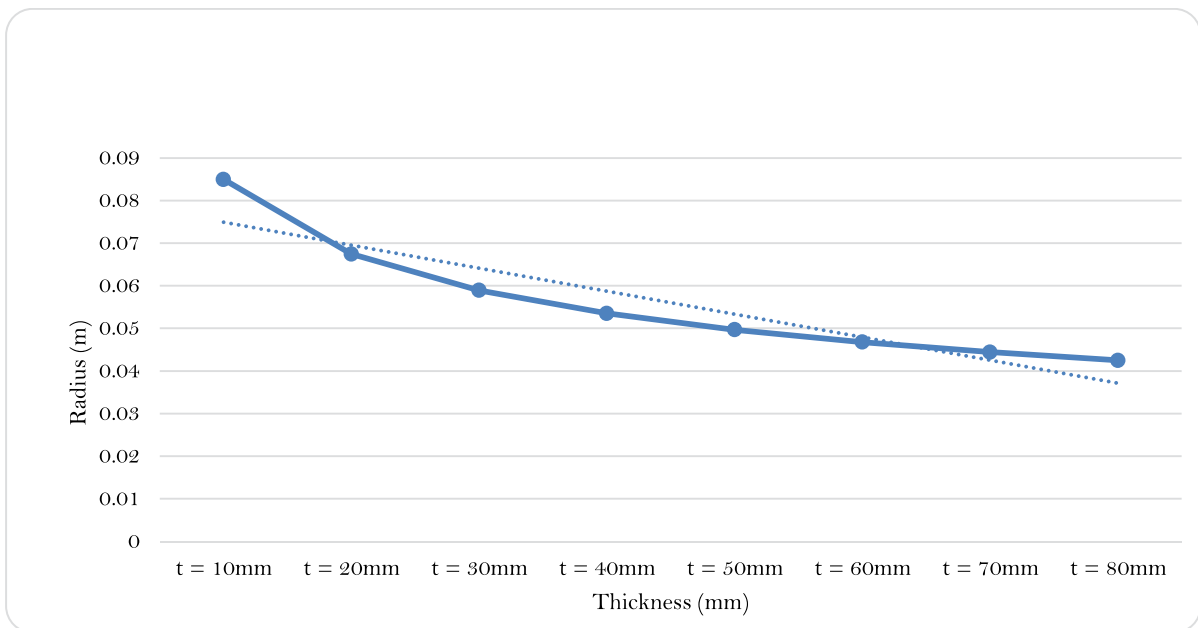


Figure 10: Radius against thickness of the flywheel corresponding to the mean torque produced

3.2 Computational results

The modeled design is simulated for stress and displacement analysis in base of the frame. The base frame is used to hold the piston cylinder and all other components. It is subjected to two conditions of load; the minimum of 245.4 N and maximum of 981.74 N. The simulations result under both the conditions are shown below. Material used is AISI 1020 steel which resembled the properties of mild steel. Total mass is found to be 98 kg through the solid works tool and surface area is found to be 0.28 m². The total number of nodes and elements are found to be 18668 and 8775 respectively. In case first, the frame is subjected to reaction force of 245.4 N which resulted in yield strength of 516e+08 N/m² and maximum deflection of 0.00018 mm. While in case second, the frame is subjected to reaction force of 981.74 N which resulted in yield strength of 516e+08 and maximum deflection of 0.00075 mm. The results from each of the simulations helped to predict that the base frame will be stable and unreformed during the testing and operation of the system. Hence the design is further taken for fabrication and testing.

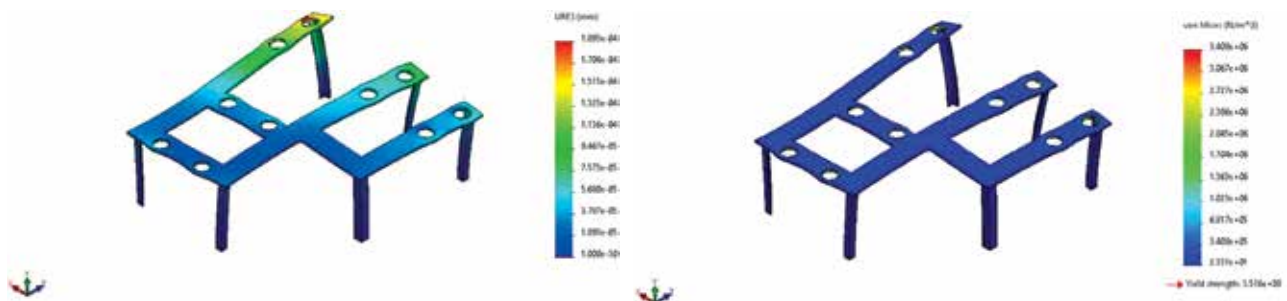


Figure 11: Stress and displacement analysis of the base frame of reaction force of 245.4 N

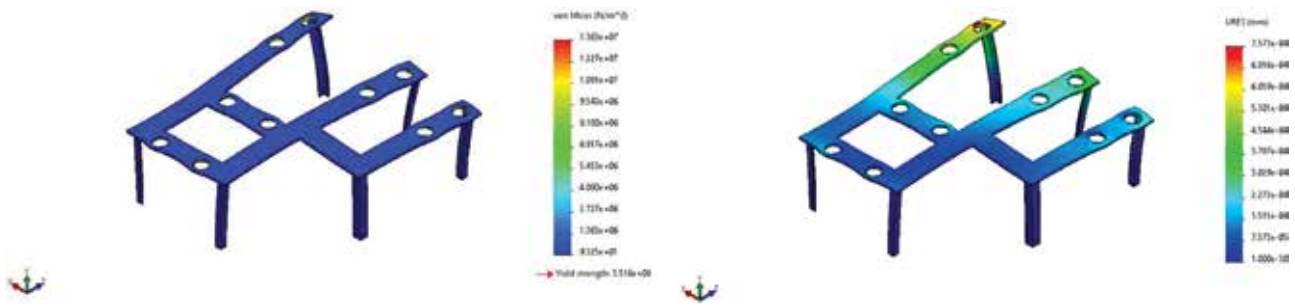


Figure 12: Stress and displacement analysis of the base frame of reaction force of 981.74 N

3.3 Test results

After the fabrication of components such as base frame, flywheel, bearing holder, crank rod, crankshaft, and coupler was done followed by assembly of the compressed air engine using solenoid valve, pneumatic piston cylinder of stroke length 100 mm, Arduino, relay module and pressure gauge, test of the engine was done under the pressure range of 1 to 5 Bar and corresponding angular velocity in rpm was measured with the help of tachometer. Arduino valve timing was also recorded from computer screen and plotted.

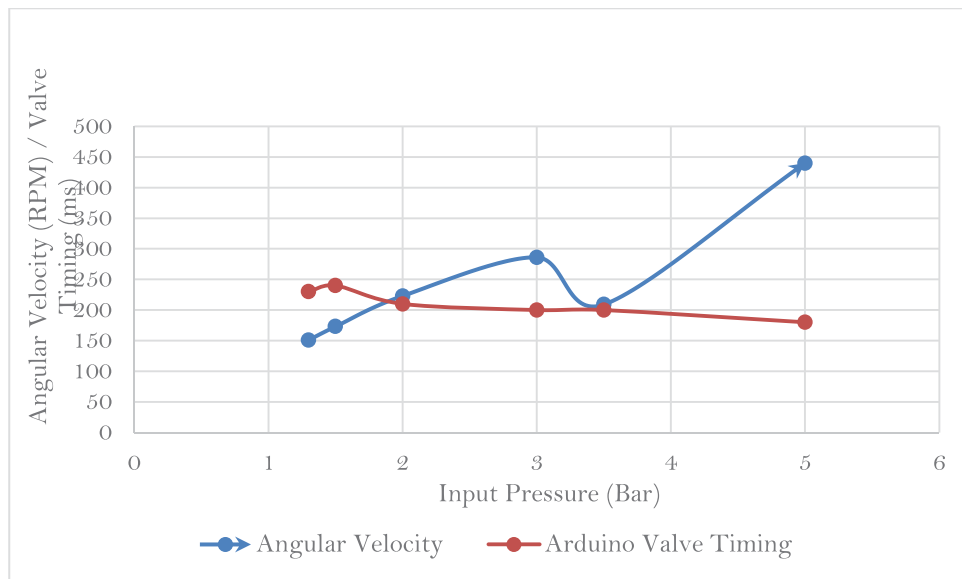


Figure 13: Intake air pressure Vs rpm of flywheel and solenoid valve timing

The designed and developed engine has specifications based on theoretical and test results. With maximum pressure of 5 bar applied on the cylinder, controlled by valve timing of 160-250 ms, rotated the crankshaft at maximum angular velocity of 250 rpm, and producing the optimum torque of 45 Nm., the force so exerted is calculated to be 981.75 N. Similarly, there are four number of bolts used to hold the piston cylinder. So, force acting on each bolt is calculated to be 245.43 N. With the testing, it was verified that the body frame is able to withstand the given load as calculated in the computational results. The volumetric flow rate was calculated to be 0.00167 m³/sec with an optimum inlet pressure of 2.5 bar. According to a research article (Nabil, 2019), engine was operated at 8 bar to produce 7.8 Nm torque with maximum rpm of 320. The variation is due to variation in input parameters of pressure and size of cylinders. They also calculated the efficiency of 9.6%

which is far less than the current result of 29.6% which results due the fact that the concept of vehicle is not included in calculation efficiency in the current project.

4. Conclusions

The CAE was first assessed analytically, and then individual mechanical components were modelled, and motion study was analyzed in SolidWorks, a CAD modelling software. Stress and displacement analysis was also carried out for the base frame of the engine in SolidWorks. Based upon the design criteria i.e. pressure range of 2 to 5 bar (maximum pressure of 5 bar), a fully functional CAE was designed, controlled by solenoid using Arduino, and performance was tested including speed vs pressure test, correlation between operating pressure and valve timing. Similarly, the flow timing of compressed gas was controlled using Arduino, relay, and solenoid valve. Similarly, the data of various operating pressure and valve timing was collected and engine was operated based on it. It was found that the angular velocity and Arduino valve timing is directly and inversely proportional to the pressure exerted by the piston respectively. An average torque of 45 Nm was obtained and total efficiency of 29.6% was obtained. Future study can be done to auto adjust the valve timing as the pressure drops. This includes the use of a pressure sensor feedback mechanism and conditional Arduino programming. CAE can be installed into CAV as per design criterion by appropriate selection of operating pressure range and torque requirements.

Acknowledgements

We owe our deepest gratitude to the Research Management Unit and Department of Mechanical and Automobile Engineering, Pashchimanchal Campus, Institute of Engineering, Tribhuvan University for supporting this project, providing us the platform and funds to conduct this research-based project.

Declaration of Competing Interest

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

References

- Nabil, T. (2019). Investigation and implementation of compressed air powered motorbike engines. Engineering Reports. <https://doi.org/10.1002/eng2.12034>
- Motor Development International. (2021, Jan, 10). Zero Pollution Motors: Airpod 2.0 Compressed Air-Powered Car. <https://zeropollutionmotors.us/>
- Yu, Q. and Cai, M. (2015) Experimental Analysis of a Compressed Air Engine. Journal of Flow Control, Measurement & Visualization, 3, 144-153. <https://doi.org/10.4236/jfcmv.2015.34014>.
- LancyCyrilBenjamine, F., Ravindran, & Suresh, N. (2018). Fabrication of Compressed Air Engine using Double Acting Cylinder. International Journal of Advance Research, Ideas and Innovations in Technology, 4, 594-596.
- Samar L. (2021, Jan 10). Compressed Air Vehicles can be a potential mode of urban transport in India. Down to Earth. <https://www.downtoearth.org.in/blog/air/compressed-air-vehicles-can-be-a-potential-mode-of-urban-transport-in-india-62987>
- Shkolnik, A., Littera, D., Nickerson, M., Shkolnik, N., & Cho, K. (2014). Development of a Small Rotary SI/CI Combustion Engine. <https://doi.org/10.4271/2014-32-0104>.
- Nabil, I., Mohamed, M., Dawood, M., & Nabil, T. (2021). Review of Energy Storage Technologies for Compressed-Air Energy Storage. American Journal of Modern Energy. <https://doi.org/10.11648/j.ajme.20210704.12>
- Khurmi, R. S., and Gupta, J. K. (2007). Theory of Machines. A Textbook for the Students of B.E. / B. Tech., U.P.S.C. (Engg. Services); Section 'B' of A.M.I.E. (I). Eurasia Pub. House, 529-540.

- Vishnuvardhan, M., Prasad, K. & Purushothaman, D. (2020). Design and experimental investigation of compressed air engine. *Materials Today: Proceedings*, 33. <https://doi.org/10.1016/j.matpr.2020.04.739>.
- Baddela, S. (2017). Compressed Air Engine. 1-05. <https://doi.org/10.9790/1684-1404070105>.
- Qihui, Y., Hao, X. & Tan, X. (2017). Comparative study on air distribution system for piston-type compressed air engine. *Advances in Mechanical Engineering*, 9. 168781401769762. [10.1177/1687814017697625](https://doi.org/10.1177/1687814017697625).
- Jandhyala, A., Varun, G. & Paliwal, R. (2004). A New Design to the Compressed Air Engine. <https://doi.org/10.1115/HT-FED2004-56010>.
- Hanan, A., Feroze, T., Arif, A., Iftikhar, H., Khan, A. & Javaid, S. (2022). Performance Evaluation of a Single Cylinder Compressed Air Engine: An Experimental Study. *Acta Mechanica et Automatica*, 16, 119-123. <https://doi.org/10.2478/ama-2022-0015>.
- Fru, N., Arnold, N. Florent, B., Armel, K., Abraham, K. & Chamberlin, N. (2022). Modeling of a Zero CO₂ and Zero Heat Pollution Compressed Air Engine for the Urban Transport Sector. *Mechanical Engineering Research*, 10, 25. <http://doi.org/10.5539/mer.v10n1p25>.
- Gawali, P., & Dhole, A. et al. (2022). Design and Fabrication of Plunger Type Compressed Air Vehicle. *International Journal for Research in Applied Science and Engineering Technology*, 10, 1455-1459. <https://doi.org/10.22214/ijraset.2022.41430>.
- Kunt, M. (2022). Modelling of Performance Outputs of a Pneumatic Piston Engine with Single Cylinder by means of Artificial Neural. *American Journal of Engineering Research*, 11, 25-31.
- Wang, L., Zhu, S., Zhang, X. (2022). Performance and economic evaluation of CO₂ (R744) air conditioning system driven by compressed air engine. *International Journal of Refrigeration*, 135. <https://doi.org/10.1016/j.ijrefrig.2021.12.026>.