Optimization of Single-Cylinder Compressed Air Engine Equipped with Prechamber

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ABSTRACT
In some last decades, increasing air pollution and its consequences captivate attention of researchers from all over the world. Scientists have developed some alternate fuels to eliminate the exhaust pollutants. In this paper, idea of using compressed air as a power source in natural gas engines is presented and discussed to explore the concept of new energy vehicles. However, energy density of air and output torque of compressed air engine (CAE) is limited, which confines its application and popularization. The present research on compressed air engine mainly focused on simulation and system integration. The air engine equipped with prechamber which works as a heating device for inlet air. Prechamber pressure rise, total heat release and maximum jet velocity all increases with increasing prechamber fuel mass fraction delivered into prechamber. An in-house model of air engine equipped with prechamber has been developed using the DIESEL-RK platform. Through analysis it can be obtained that optimization of single cylinder CAE showed positive slope towards efficiency and eliminate NOₓ emission to almost zero. Furthermore, this study revealed that the idea of using prechamber with CAE provide theoretical support to researchers in development of zero-emission vehicles and to make the technology more feasible.

Keywords: single cylinder-compressed air engine; prechamber; numerical simulation; zero-emission

1. INTRODUCTION
Fossil fuels provide significant economic benefits, but increasing environmental pollution and non-renewable energy consumption by internal combustion engine vehicles (ICEVs) have arisen a series of concerns about their environmental cost. According to literature, approximately 65 % of global greenhouse gas emission is generated from fossil fuel combustion [1]. The Clean Air Act Amendment 1990, created a framework to reduce nitrogen oxide and sulphur oxide from the combustion of gasoline and diesel fuels in vehicles [2]. Today a number of electric fuels like electric battery, hydrogen cell, biodiesel, and compressed air used as energy source to power vehicles [3]. Since 20th century, compressed air has been using as energy storage in United States and Europe [4]. Because of low energy density of air and low efficiency of CAEs, they were not used for a long period of time [3]. The most prestigious development in compressed air vehicles (CAVs) in recent years is the work of Motor Development International (MDI) led by Guy Negre. One of MDI’s car, TOP (Taxi Zero Pollution) model have substantiated a mileage of 300 km at a maximum speed of 110 km/h [5]. Along with MDI, some other companies like Energine, Tata Motors, Toyota, and Honda are currently working on development of CAVs [6]. Shen et al [7], presented an idea of using compressed air to run motorcycles. Huang et al [8], introduced a new concept of using hybrid pneumatic power system (HPPS) to improve energy efficiency of air engine. Papson et al [9], characterized the potential performance of compressed air vehicles in terms of driving range, fuel cost, fuel economy and energy efficiency. Verma SS [10], summarized the working principle, latest developments, advantages and bottlenecks in using compressed air as a source of energy to run vehicles. Pandya et al [11], developed a compressed air charged vehicle. Wang et al [12], modified a four-stroke internal combustion engine (ICE) to two-stroke CAE and examined its performance parameters.
The present research focused on optimisation of prechamber with CAE to enhance efficiency and eliminate NO\textsubscript{x} emission from CAE. Results of the study can be used to analyze dynamic performance of CAE and to provide solutions for optimisation of prechamber parameters for further study.

2. WORKING PRINCIPLE OF CAE
Compressed air engine uses energy of compressed air to run vehicles. Initially, atmospheric air compressed in the compressor and then compressed air stores into an air reservoir to avoid the deficiency of compressed air throughout the cyclic process. Following are some key components of CAE [7,8]

<table>
<thead>
<tr>
<th>Sr No</th>
<th>Element</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air Reservoir</td>
<td>To store compressed air and provide when required.</td>
</tr>
<tr>
<td>2</td>
<td>Filter</td>
<td>Filter the water in the air</td>
</tr>
<tr>
<td>3</td>
<td>Pressure Sensor</td>
<td>Calculate pressure of air flow</td>
</tr>
<tr>
<td>4</td>
<td>Turbocharger</td>
<td>To increase the mass flow of air into CAE</td>
</tr>
<tr>
<td>5</td>
<td>Buffer Tank</td>
<td>To stabilize the air pressure during operation</td>
</tr>
<tr>
<td>6</td>
<td>Prechamber</td>
<td>To increase the temperature of inlet air</td>
</tr>
<tr>
<td>7</td>
<td>Air Engine</td>
<td>Utilize energy of compressed air to produce work output</td>
</tr>
</tbody>
</table>

Figure 1. Construction of Compressed Air Engine (CAE)

The present study relates to a prechamber unit of a gas engine, comprised of a prechamber device in the form of an elongated body adjusted to be placed in upper part of engine’s cylinder. A prechamber heating system is a small chamber of 6 cm\textsuperscript{3} volume. Inside the prechamber, heating is actuated by means of resistive heating of prechamber walls [13]. Wunsh et al [14], carried numerical simulation of a natural gas engine equipped with an auto-ignition prechamber. Generally, prechamber is used to ignite a lean fuel-air mixture. Here in this
study, prechamber is used as a heating device for compressed air placed in between inlet port and exhaust port. Compressed air from air reservoir directly enters into prechamber and when compressed air comes into direct contact with cylinder walls, temperature of the air increases at constant pressure which further released into engine cylinder to produce power output. The following properties were varied to conclude the overall response of CAE-

- The cylinder wall and head temperature
- The prechamber wall temperature
- The initial gas temperature

Figure 2. Prechamber model.

3. COMPRESSED AIR ENGINE MODEL

The following assumptions during analysis were made

i. The compressed air used in the system follow all ideal gas laws.

ii. The air inside the cylinder is uniform throughout the process.

iii. The airflow in and out of the cylinder is assumed one-dimensional, isentropic and quasi-steady.

iv. There is no leakage during the whole working cycle.

3.1 Energy Equation

As mentioned above, there is no leakage in the working process, charge and discharge air do not simultaneously happen. Therefore, the energy equation for the cylinder can be written as [17]

\[
C_v \frac{dT}{dt} = aA_w (T_a - T) + (C_p T_a - C_v T)Q_1 - RTQ_2
\]  

Where, \(C_v\) is the specific heat of air at constant volume, for \(m\) mass of air inside the cylinder when cylinder maintained \(T\) temperature of air at \(P\) pressure. Heat transfer coefficient of air is denoted by \(a\), and heat transfer area of cylinder is denoted by \(A_w\). \(C_p\) is the specific heat of air at constant pressure. \(Q_1\) and \(Q_2\) define intake and exhaust mass flow respectively.

3.2 State Equation

Ideal air meets the equation of state

\[PV = mRT\]  

(2)
Where, \( R \) is the gas constant of air, defined in J/KgK.

### 3.3 Torque Equation

Ideal output torque can be analysed by calculating force on the piston crank connecting rod mechanism and it can be described as [18]

\[
M = (F_g + F_j) r \frac{\sin(\phi + \arcsin(\lambda \sin(\phi)))}{\cos(\phi)}
\]

(3)

Where, \( F_g \) is the driving force of compressed air on piston and \( F_j \) is the reciprocating inertial force of the piston. \( \lambda \) is the crank ratio and \( r \) is the crank radius.

### 3.4 Energy Efficiency

The efficiency of compressed air engine is defined as the ration of output mechanical power to the input air energy [15]

\[
\eta = \frac{P_o}{P_i} \times 100\%
\]

Where,

\[
P_o = \frac{T_{av} \times n}{9550}
\]

(4)

Where \( T_{av} \) is the average output torque and \( n \) is the speed of CAE.

### 4. SIMULATIONS & ANALYSIS

Input parameters considered for air engine during simulation are shown in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore, mm</td>
<td>80</td>
<td>Intake port diameter, mm</td>
<td>16</td>
</tr>
<tr>
<td>Stroke, mm</td>
<td>88</td>
<td>Exhaust port diameter, mm</td>
<td>16</td>
</tr>
<tr>
<td>Connecting rod length, mm</td>
<td>162</td>
<td>Intake pressure, bar</td>
<td>5</td>
</tr>
<tr>
<td>Engine Speed, rpm</td>
<td>1500</td>
<td>Compression ration</td>
<td>9</td>
</tr>
</tbody>
</table>

![Figure 3. Variation of prechamber pressure with crank angle.](image)
The intake valve opened at an angle of 20° before top dead centre (TDC) and closed at an angle of -20° after bottom dead centre (BDC). The exhaust valve opened at an angle of 30° before BDC and closed at an angle of 0° after TDC. For the whole working cycle, compression ratio remains stable at 9. The simulation environment was built using DIESEL-RK platform. The simulation was done on a 4-stroke, 2 valves natural gas engine equipped with prechamber and using compressed air as a fuel gas. The input parameters of prechamber are shown in Table 3.

<table>
<thead>
<tr>
<th>Sr No</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Volume, cm³</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Diameter of nozzle, mm</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Fuel mass fraction delivered into prechamber</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>Air injection initiation, degree before TDC</td>
<td>340</td>
</tr>
<tr>
<td>5</td>
<td>Air injection duration, degree</td>
<td>40</td>
</tr>
</tbody>
</table>

As shown in figure 3, in the first instance, when injection into the prechamber initiates, pressure of air decreases slightly but as the injection into the prechamber closed, pressure showed a constant value throughout the process. It implies that heating of air done at constant pressure in the prechamber.

![Figure 4. Variation of prechamber temperature with crank angle.](image)

Figure 4 shows relation between prechamber temperature and crank angle. At 340° crank angle compressed air enters into prechamber and injection continue up to 40° crank angle. Air while flowing through prechamber heated and ejected to cylinder at a higher temperature and enhance efficiency of engine.

![Figure 5. Variation of cylinder temperature with crank angle.](image)

Figure 5 shows that at inlet of cylinder compressed air enters at high temperature, during suction, temperature of air decreases with crank rotation and increases during compression and pointed maximum temperature in
the cylinder to 738.96 K at 1500 rpm engine speed. During power stroke and the temperature decreases and during exhaust air leaves cylinder at approximately atmospheric temperature.

Figure 6. Variation of cylinder pressure with crank angle.

In Figure 6, relation between crank angle and cylinder pressure is represented. Through analysis of variation in graph pointed out some key features in following manner-

- Air enters into cylinder at 4.87 bar pressure.
- Maximum cylinder pressure is 58.09 bar which obtained at 359° of crank angle.
- Air leaves cylinder at almost atmospheric pressure.

Variation of temperature and pressure at different crank angles are shown in above figures. The present study was focused on energy efficiency of CAE and exhaust emission. Simulation results obtained after analysis demonstrated that overall efficiency of engine is about 56 % which is much better than other CAE’s efficiencies [3,15,16]. NOx emission at exhaust of cylinder was observed from figure 7 which demonstrates compressed air engine be a zero emission engine and explores the concept of future alternatives fuel vehicles. Simulation data was collected at a single speed of engine @ 1500 rpm. Total power produced by engine was 0.95 while brake torque at 1500 rpm was 6.622 N m. The whole study circulated around the optimisation of prechamber unit with turbocharger. The results observed from simulation analysis provide a new direction in the field of compressed air vehicles.

Figure 7. Variation of NOx emission with crank rotation.

5. SUMMARY

The single cylinder, 4-stroke , natural gas engine using compressed air as a fuel shows good agreement when simulated on DIESEL-RK platform. It was substantiated from the facts that exhaust gases when recycled
through turbocharger improve the efficiency of the engine. Prechamber as a heating device explore a new concept of heating in compressed air engine. Some key points regarding performance of engine are follows-
1. Prechamber intake temperatures also have a significant effect on power and torque output of the engine. As the inlet temperature of the prechamber increases, power and torque output from the engine shows a positive slope.
2. Increasing inlet temperature of air at cylinder inlet provides good momentum to air particles during expansion stroke.
3. Within a certain parametric range, when the bore diameter is 80 mm and stroke length is 88 mm, the optimal performance indicators were calculated at 1500 rpm. The single cylinder overall efficiency equals to 56 % and brake output torque was 6.62 Nm.

This research can provide theoretical support to the new compressed air engine design and optimisation.

REFERENCES