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Research Article

Experimental investigations on performance improvement of multi point sequential fuel injection engine by reducing back pressure

Chandrakumar PARDHI[1], Anshul GANGELE[1], Sanjay CHHALOTRE[2], C.P. JAWAHAR[3,*]

[1]*Department of Mechanical Engineering, Amity University Madhya Pradesh, Gwalior, 474005, India*
[2]*Department of Mechanical Engineering, Sagar Institute of Science and Technology, Bhopal, 462036, India*
[3]*Department of Mechanical Engineering, School of Engineering and Technology, Alard University Pune, 411057, India*

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ABSTRACT

Substantial developments in automotive technology have led to the recent explosion in the availability of high-performance vehicles. One of the most important components of internal combustion engines for reducing fuel consumption and exhaust emissions. Exhaust back pressure, a critical engine characteristic regulates the amount of internal exhaust gas trapped in the cylinder, affecting emissions and engine performance. The present work is focused on improving the performance of a multipoint sequential fuel injection engine by reducing the back pressure. The performance tests were carried out on a Hyundai i10 engine (1200 cc, multi-cylinder, 3000 rpm maximum speed). This study includes introducing fresh jet air at various flow rates into the exhaust system to reduce the concentration of exhaust gas contaminants and provide the desired backpressure while accounting for changes in engine speed. The effect of backpressure on various engine performance parameters at different engine speed conditions has been analyzed. It is inferred from the present study that at 2000 engine rpm, the temperature of exhaust gas drops between 50°C and 90°C and there is a marginal increase in the volumetric efficiency from 4.5 to 6.25%. The engine power increased about 6 to 8.2% at this operating condition.

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INTRODUCTION

Exhaust manifolds, often called headers, collect exhaust gases from various internal combustion (IC) engine cylinders and direct them into a single pipe. The exhaust manifold›s correct sizing is crucial since it influences fuel economy and emission efficiency [1]. The exhaust pipe establishes a connection between this header and the cylinders. It plays a crucial role in multi-cylinder engines, consolidating numerous exhaust streams into a single pipe and connecting to the engine downstream [2].

The primary function of the exhaust system in automobiles is to reduce engine noise, but now, it is designed to

***Corresponding author.**
*E-mail address: cpjawahar@gmail.com, cpjawahar@alarduniversity.edu.in

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reduce noise as well as increase the reaction time between exhaust gas and the composition of the catalytic converter so that nitrogen oxides separate into nitrogen and oxygen [3]. Also, an exhaust system is essentially a lengthy tube with a fully developed boundary layer that slows the flow by rubbing against the walls; backpressure is an inevitable consequence. This results in an increase in the exhaust backpressure (EBP). Excessive back pressure can restrict the amount of fresh air entering the combustion chamber, reducing oxygen availability and potentially leading to incomplete combustion.

When the back pressure is high, the engine's performance decreases due to inefficient exhaust gas discharge. Loss of power and torque, increased fuel consumption, and increased emissions are typical outcomes of increased backpressure [4]. Due to back pressure, all the burnt gases are not discharged during the exhaust stroke and some amount of burnt gases are trapped in the cylinder. So, to get the exhaust gases out during the exhaust stroke, the piston must work harder [5]. Therefore, during the exhaust stroke, the piston must exert more force to expel the exhaust gases. Thus, the crankshaft's total power output decreases. Therefore, the pumping losses during the exhaust stroke increases proportionally to the increase in back pressure. This will increase the total power output [6].

To counteract the reduced airflow due to higher back pressure, turbocharging or supercharging could be one option. These options force additional fresh air into the combustion chamber, helping maintain a high airflow rate, even with moderate back pressure [7]. But as a concern with spark ignition engine, it increases the fuel evaporation rate which further leads to increasing excessive knocking (detonation), thermal losses and poor fuel efficiency.

In a turbocharged engine, a rise in back pressure leads to a decrease in the pressure drop across the turbine, resulting in a reduction in the speed of the turbocharger shaft. Consequently, the intake boost pressure and the mass flow of intake air also decrease [8]. The back pressure had a detrimental effect on the naturally aspirated engine. Increasing the diameter of the exhaust system can alleviate back pressure, but the confined space in passenger vehicles prevents the installation of a bigger exhaust system. Optimal engine performance requires the presence of backpressure, and eliminating it might result in a decrease in power and torque [9].

Excessive back pressure has significant effects on the operation of internal combustion engines, including reduced power production, increased fuel consumption, and heightened smoke emissions from the exhaust [10]. Therefore, minimizing the flow constraints in exhaust system design is crucial for mitigating the adverse effects of exhaust gases-induced back pressure. However, adhering to stringent pollution control regulations makes it exceedingly challenging to keep the necessary level of back pressure [11]. To maximize engine efficiency, minimize total emissions and keep ambient sound energy within acceptable limits, back pressure must be optimized through careful design of the exhaust system, especially the muffler and exhaust manifold [12].

Methods to reduce back pressure:

Optimizing the exhaust system:

- Bigger pipes and smoother elbows: Reduce restrictions and improve flow.
- High-flow catalysts: Designed with less restrictive materials and structures.
- Performance exhaust systems: Larger diameter pipes and less restrictive mufflers are often used, but these can compromise noise levels.

Considering Engine Modifications:

- Camshaft modifications: Intake and exhaust opening overlap can be optimized for more efficient exhaust clearance.
- Light valves and springs: Reduce inertia and improve valve opening/closing speed to facilitate exhaust flow.
- Turbochargers and superchargers: Push more air into the engine, which may require reduced exhaust back pressure for optimal performance.

The review of literature indicates that the back pressure fluctuates with the injected air-flow rate, thus aiding in maintaining the engine›s performance at an optimal level during increased engine revolutions per minute (rpm). Conversely, in some cases, increased backpressure effectively reduces the emission of nitrogen oxides (NOx) in the exhaust gas due to higher temperatures [13]. Therefore, minimizing exhaust backpressure is crucial for improving the performance of any internal combustion engine, provided that the emission of nitrogen oxides (NOx) remains unaffected. This study involves introducing fresh jet air at various flow rates into the exhaust system to reduce the concentration of exhaust gas contaminants and provide the desired backpressure while accounting for changes in engine speed.

LITERATURE REVIEW

Effects of Exhaust Backpressure on Efficiency, Power, and Fuel Use in Internal Combustion Engines [13].

Since the back pressure prevents the exhaust gas moving from the cylinder to the outside of the cylinder, the pistons in a spark ignition (SI) or compression ignition (CI) engine must use more energy to remove the exhaust gas. This causes the engine to lose some power and durability. The EBP study aims to establish the correlation between power and the power output of spark ignition and compression ignition engines [2]. The engine loses power due to back pressure, which increases the power to remove gas from the cylinder. For every 1 kPa decrease in exhaust pressure, engine power increases from 0.22 kW to 0.45 kW. Every 10 kPa decrease in back pressure reduces fuel consumption by approximately 1.5% to 3%. When the piston moves in opposition to the exhaust gas, it can lead to exhaust blockage issues. When the catalyst back pressure decreases by 40%, then the torque increases by 5.5 Nm. The optimized exhaust silencer can recover 90% of the engine's lost torque by reducing the back pressure [13].

Effect of Exhaust Backpressure on Internal Combustion Engine Emission Determinants [14].

Exhaust backpressure typically results in a greater concentration of harmful pollutants, including carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxides (NO_x), hydrocarbons (HC), and particulate matter (PM) [15]. Nitrogen oxide production normally peaks in cold weather, and nitrogen oxide emissions from diesel engines are generally higher. Most motor vehicles install exhaust gas recirculation (EGR) in their CI engines to reduce nitrogen oxides (NO_x). This increases the temperature of the exhaust gas [16]. Further, studies have shown that EGR enhances energy recovery, leading to longer combustion times and an increase in HC emissions. Improving EGR can reduce NO_x production in the internal combustion engine but will also lead to long combustion times, increased PM and HC emissions, and other adverse effects [17].

It is known that the fuel remaining in the cylinder will slow down the flame and therefore change its combustion properties. The breakdown that occurs when fuel residue lowers the temperature of the cylinder leads to reduced NOx emissions. However, this process also increases carbon emissions, such as THC and CO, and increases engine power due to engine instability at high speeds (such as idle) [18]. The remaining gas in a cylinder slows the flame, which changes the combustion characteristics, as is well established. In addition, this process makes the car body vibrate more when the engine is not stable, which happens often during idling and other low-speed rotational situations [19].

This experimental study is focused on investigating the effect of lowering the back pressure change in response to fresh air addition in the exhaust pipe system on the performance of the petrol engine. It also focuses on optimizing the exhaust manifold design to reduce engine back pressure and enhance engine performance. Researchers have conducted numerous experiments on the parts of the exhaust pipe system, including the catalytic converter and silencer, to understand how backpressure impacts the performance and pollution levels of internal combustion engines.

Previous investigations have played a significant role in exploring further research through experimental analysis, engine simulations, and computational fluid dynamics (CFD) models [16]. Given its convergent geometry, carry out an experiment to ascertain the impact of a change in return force on the exhaust gas during the idling of both exhaust systems. The findings indicate that the shape of the junctions in the H-type exhaust pipe system maximizes the discharge pipe pressure. This impact leads to THC receiving the highest score in the emission results. However, because of the influence of the connection geometry, the X-type exhaust system demonstrates the worst performance. Murali R. et al. [13] concluded their study on the impact of high back pressure on the performance of internal combustion engines. In general, increasing backpressure was determined to reduce engine performance and reduce the return of 40% of the torque of approximately 5.5 Nm. When back pressure increases, RGF increases and combustion efficiency decreases. The increase in EBP significantly impacted the small valve overlap angle. Further increase in EBP has affected residual exhaust gas, as the decrease in the valve overlap angle leads to an increase in residual exhaust gas [20].

Gülmez Y. et al. [18] carried out studies to investigate the negative effects of exhaust gas, pollution, and emissions of diesel engines. The results showed that the rear pressure increase could delay the combustion stage up to a 4° crank angle, reduce the average pressure, and reduce the cylinder pressure of the maximum engine load from 78.36 to 70.7 bar. When the backpressure increases to 24.66 kPa, brake specific fuel consumption (BSFC) increases by 3.29%. Leman AM. et al. [9] conducted a review of research comparing the performance of a catalytic converter with back pressure and cold start in internal combustion engines. One of the key concerns regarding a vehicle's engine combustion operation is a cold start. To minimize the amount of polluting gas exposed to the atmosphere, particularly during the cold-start phase, catalytic converter modification is an essential factor that must be taken into consideration. Additionally, we must handle the emission gas fluxes in the catalytic converter more carefully to prevent fuel waste and engine power losses.

Lee J. et al. [8] conducted a thorough investigation of the use of a turbocharger system to expand the working limits of a hydrogen spark ignition engine under heavy loads. The results indicate that higher boosts from the turbocharger helped high-load situations last longer. However, the high exhaust pressure stopped high-load situations from getting better at high speeds. Bhure S. [21] investigated the impact of back pressure on the efficiency and emissions of diesel engines equipped with electronic fuel injection. During the investigation, he manually controlled back pressure control valves (BPCVs) at three different levels: 100%, 87.5%, and 75% BPCV lifts. According to the data, there is a 15% decrease in NOx and a notable decrease in HC and CO. However, exhaust smoke and BSFC levels have increased.

Sivaram A R. et al. [19] examined the impact of exhaust pipe length on a single-cylinder diesel engine's fuel economy and volumetric efficiency. The results of the study demonstrated that longer exhaust pipes, which raise backpressure, can result in higher fuel consumption and lower volumetric efficiency. Sapra H. et al. [22] studied a medium-speed diesel engine equipped at different speeds and loads compared to different values of static back pressure. The performance of a turbocharged engine, both pulsed and constant pressure, was evaluated in a validated model simulation under two distinct valve overlap levels and a one-meter water column (mWC) high back pressure.

Bhandari R. et al. [6] identified which factors were most important in changing back pressure and how they were related. He determined the diameter of the punched holes, the distance between the holes, and the total number of holes. He uses a typical damper model to test the setup and understand how the different boundary conditions of the Fluent CFD analysis affect the results. K. S. Umesh et al. [12] conducted tests on the exhaust manifold of a four-stroke, four-cylinder engine at 1500 rpm. Improving fuel consumption is the primary goal of this effort, which employs both experimental and computational methods to decrease backpressure in the exhaust manifold. From a business perspective, the engine's total performance can be improved by modifying its geometry to use lengthy bends, changing its exit position (from center exit to reducer), and so on.

From the review of the literature, it is inferred that the researchers have primarily studied the effect of back pressure on internal combustion engine performance and its emissions. In general, exhaust back pressure negatively affects the efficiency of either an SI or CI engine. However, exhaust back pressure is not completely avoidable due to the muffler's intake and transmission losses, which are necessary to reduce the amount of sound energy released into the surrounding air. In addition, all harmful emissions of exhaust gases, except NOx, increase under the influence of back pressure. There is a need to optimize the back pressure through careful design of the exhaust system, especially the muffler and exhaust manifold, to maximize engine efficiency, minimize exhaust emissions. Experiments were carried out to ascertain the impact of adding fresh air to the exhaust system on back pressure and its impact on automobile spark ignition engine performance. Furthermore, emission characteristics related to engine power performance to assess the impact of decreased back pressure were examined.

EXPERIMENTAL SETUP

A 4-cylinder SI engine (Make: Hyundai Motor) was used for the experimental studies. Table 1 presents the engine specifications. To develop an experimental setup to inject fresh air into the exhaust pipe of a car, an air injection system, which includes an air pump or blower, air hoses and fittings, airflow control valves, and an air filter, has been used. For the exhaust system modifications, a fitting at a chosen point downstream from the engine, ideally near the catalytic converter, was welded into the exhaust pipe to serve as the air injection port. The nozzle was fixed from one end of the hose inserted into the exhaust pipe. The connector is provided at the other end of the hose to the blower outlet end. The steady fresh air flow rate is ensured by using a digital rotating vane anemometer. The maximum error rate of the device for mass flow rate measurement was less than ±2% for air. For measuring the back pressure, the easiest method is to install the back pressure gauge (±1%) to the oxygen sensor port by unscrewing it and then install the adapter provided in the kit by screwing the adapter into the oxygen port. The K-type thermocouples measured the temperature at the desired point in the exhaust pipe. The uncertainty of a K-type thermocouple is usually a maximum of ±0.4°C. Launch C Reader VI engine scanner was used to measure engine rpm. The blower was connected to the variable speed controller to regulate the fresh air flow rate.

After that, pressure transducer, temperature measurement system and oxygen sensors were fixed at both upstream and downstream of the injection point to measure back pressure.

Table 1. Engine specifications

Item	Specification
Engine type	1.2 Kappa 4CYL Inline Naturally Aspirated MPSFIE
Total displacement	1197
Compression ratio	10.5:1
Number of cylinders	4
Number of valves per cylinder	4
Fuel supply system	MPFI
Maximum power at 6000 RPM	78.9 BHP
Maximum torque at 4000 RPM	111.7 N- m
Super Charge	Not Available
Bore & Stroke	71 x 75.6 mm
Firing order	1-3 - 4-2
Fuel	Gasoline

EXPERIMENTAL PROCEDURE

Experiment was carried out by varying the engine speed from 800 to 3000 rpm at some regular intervals. The measurements were noted firstly at the normally designed engine setup, and later on, the readings are taken with the injection of fresh air at the exhaust system. A blower is used to create the vacuum in exhaust pipes, hence facilitating the easier escape of exhaust gases from the cylinder. This exhaust fan creates a pressure difference by reducing the pressure outside the engine's cylinders. The forced intake of new air creates a zone of negative pressure within the engine's exhaust system. As a result, the combustion chamber directs its exhaust gases toward the area of lower pressure and swiftly releases them into the atmosphere.

Measurements such as air pressure, atmospheric air temperature, throttle valve opening percentages, intake air mass flow rate, volumetric efficiency, brake torque, and engine power, while running the engine without air injection were taken at first. Then, we replaced the setup and injected fresh air at the desired flow rates of 2 m^3/min, 3 m^3/min and 4 m^3/min. For one data point 4 set of readings are measured at different rpm. All the measurement values are very close to each other. The average value of each point is used to show the result. These specific airflow rates allow for an analysis of the system's efficiency at each

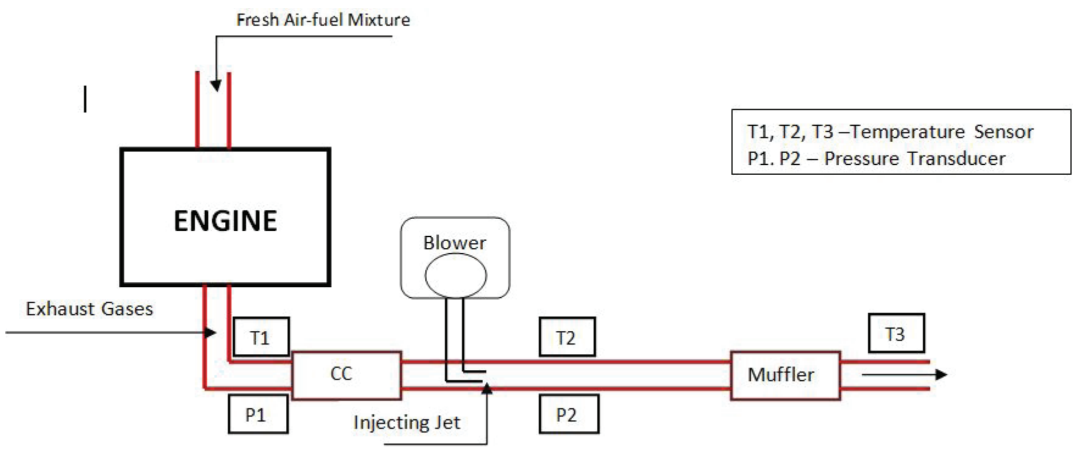

Figure 1. Schematic diagram illustrates the process of injecting fresh air into the exhaust system.

Figure 2. Pictorial view of exhaust system of experimental setup.

rate, thereby helping to identify optimal flow conditions for the desired performance outcomes. The back pressure was recorded while varying the engine speeds and airflow rates. The results of the back pressure measurements confirmed that there was a difference in back pressure that corresponded to the change in the flow rate of injecting fresh air into the exhaust pipe. This study examined the impact of changing the flow rate of injected fresh air on temperature and pressure by installing a pressure transducer and temperature sensors in an exhaust system. Figure 1 shows the schematic diagram of the setup of injecting fresh air into the exhaust system. Figure 2 represents the pictorial view of the exhaust system of the experimental setup with the arrangement of injecting fresh air.

RESULTS AND DISCUSSION

In conventional automobile engines, the exhaust valve opens prior to the completion of the power stroke and continues to remain open even after the commencement of the intake stroke. At the conclusion of the power stroke, the pressure within the cylinder exceeds the external pressure, facilitating the expulsion of exhaust gases from the cylinder. In this study, an exhaust fan to generate the necessary pressure differential and minimize the counteracting force has been employed so that the exhaust valve may remain closed for more time during the entire power stroke. This approach enabled us to harness the additional power that would otherwise be lost when the exhaust valve is opened prematurely to facilitate the expulsion of exhaust gases.

The variation of EBP with engine rpm for different flow rates of fresh air in the exhaust system is depicted in Figure 3. At lower engine speeds, the impact of pumping losses is insignificant. However, at higher speeds, the piston must exert a substantial amount of effort to expel the exhaust gases. Therefore, the increase in back pressure within the engine's exhaust system reduces the power output at the crankshaft.

Figure 4 illustrate the enhancement in volumetric efficiency resulting from a decrease in exhaust back pressure. In this situation, the enhancement in volumetric efficiency is a result of the gradual decrease in the amount of residual gases trapped in the combustion area. During the experiment we found that at flow of rates 2 m^3/min, at moderate speed of 2000 rpm, the system experiences reduced pressure losses and less frictional resistance, which tends to enhance volumetric efficiency. This enables the cylinders to draw in a greater amount of fresh air during the intake stroke, thereby enhancing the combustion process. An increase in the volumetric efficiency from 4.5 to 6.25% at 2000 rpm was observed during the study.

The impact of decreasing back pressure on the opening of the throttle valve is depicted in Figure 5. To evaluate the driver's desired acceleration relative to the complete depressed position of the accelerator pedal, the throttle valve opening is expressed as its percentage. The throttle position sensor on the accelerator control detects the driver's desired acceleration. In essence, reducing back pressure facilitates the expulsion of exhaust gases from the cylinder. This decreases the amount of force needed for the engine to pump, facilitating the downward movement of the piston during the exhaust stroke. As a result, the engine experiences less resistance, leading to a higher generation of power at the same throttle opening compared to situations

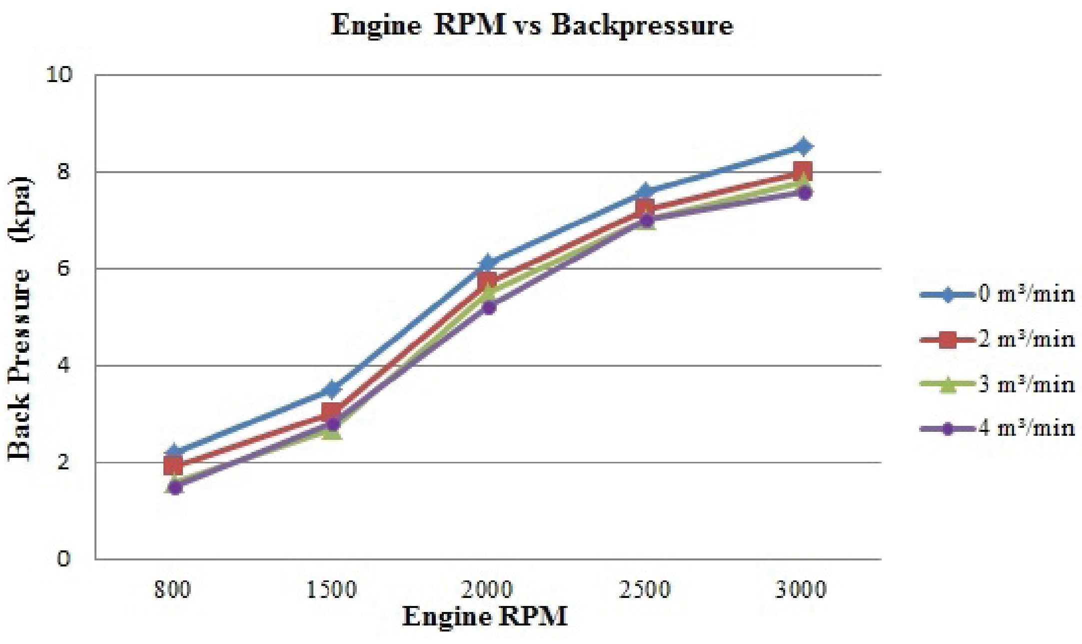

Figure 3. Variation of EBP with engine rpm for different flow rates of fresh air in the exhaust system.

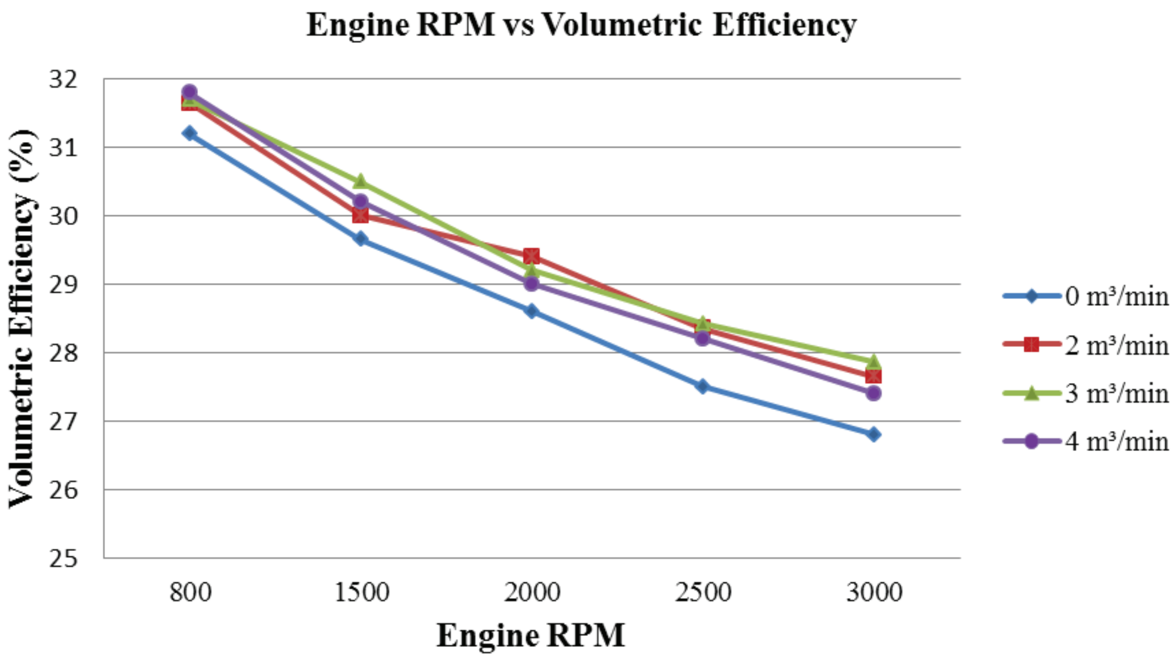

Figure 4. Variation of volumetric efficiency with engine rpm for different flow rates of fresh air in the exhaust system.

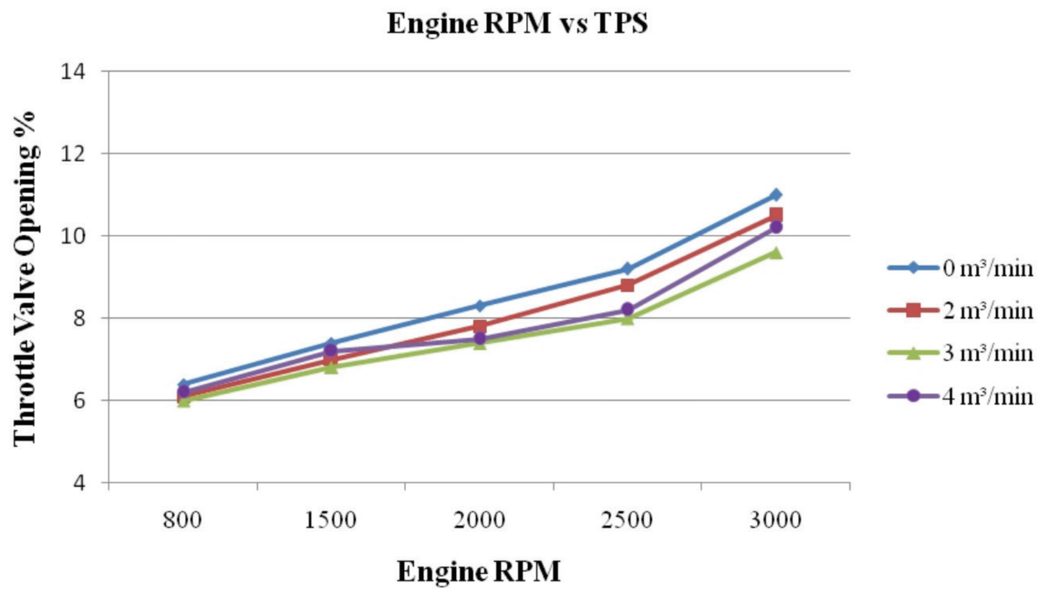

Figure 5. Variation of TPS % with engine rpm for different flow rates of fresh air in the exhaust system.

where the back pressure is greater. Therefore, if the target power output remains constant, the throttle may open to a slightly lesser extent in order to obtain that power as a result of the enhanced efficiency.

Figure 6 shows that reducing the back pressure in a SI engine generally leads to a decrease in the exhaust gas temperature. This is a result of an enhanced scavenging process. Reducing pressure in the lower back region enhances the process of "scavenging" the cylinder, creating space for the intake stroke to accommodate the fresh air-fuel mixture. This extra amount of fresh air fuel mixture lowers the amount of heat absorption from the cylinder walls, which lowers exhaust temperatures. The results indicate a decrease in exhaust gas temperature between 50°C and 90°C.

Figure 7 depicts the variation of engine power with engine rpm at various airflow rates. As a result, the

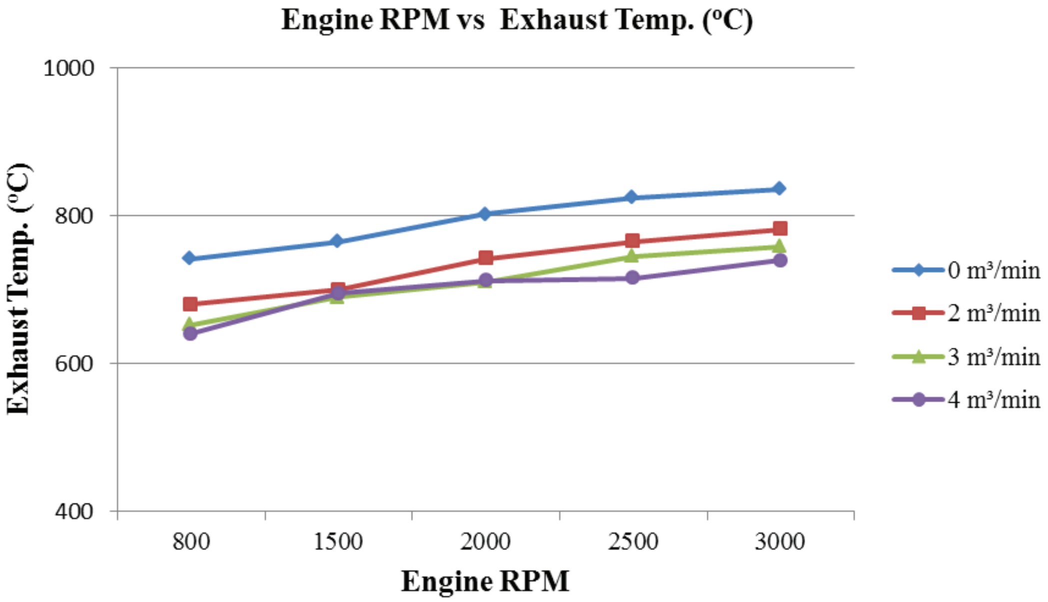

Figure 6. Variation of exhaust temperature with engine rpm for different flow rates of fresh air in the exhaust system.

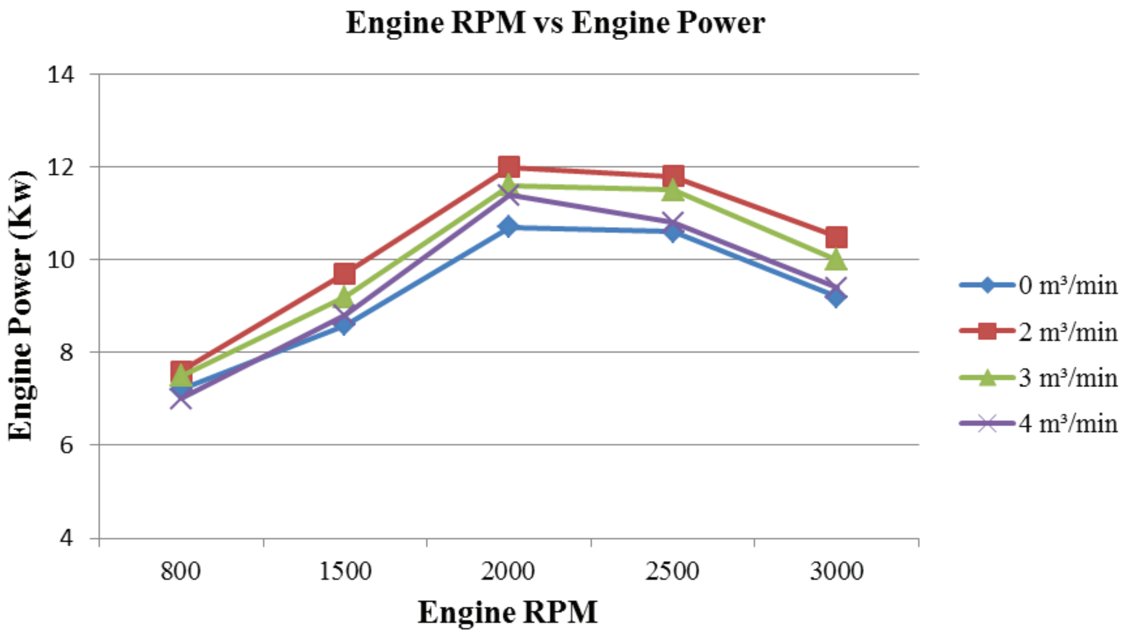

Figure 7. Variation of engine power with engine rpm for different flow rate of fresh air in exhaust system.

crankshaft's power output drops significantly at higher engine speeds. The engine scavenging efficiency could be enhanced by lowering the exhaust back pressure. As a result, the combustion chamber discharged exhaust gases more effectively during the exhaust stroke, making room for a greater quantity of fresh air-fuel mixture during the intake stroke. This enhanced breathing results in a boost in engine power. Lowering the back pressure indicates the engine power increases from 6 to 8.2%.

CONCLUSION

Experimental studies were carried out in the present work to ascertain the impact of reducing EBP on engine performance parameters in a naturally aspirated MPSFIE spark ignition engine. Excessive back pressure has several negative effects on internal combustion engine performance, including decreased power output, increased specific fuel consumption, and increased exhaust smoke. The effects of backpressure reduction on the engine's exhaust emissions, volumetric efficiency, throttle valve position, and in-cylinder pressure characteristics were analyzed. The uncertainties associated with the measuring devices used in this study are considered. The results obtained are within an acceptable margin of error, supporting the accuracy and reliability of the results. The following conclusions are drawn from the present work.

1. As the engine's backpressure decreased, its specific fuel consumption also diminished. The reduction in leftover gases in the combustion chamber facilitates the intake stroke's ability to take in additional fresh air, thereby improving the combustion process and resulting in marginally higher volumetric efficiency from 4.5 to 6.25% at an air injection flow rate 2 m^3/min.
2. Compared to the conditions of elevated back pressure, the engine experiences reduced resistance and can generate greater power at the same throttle position. Due to enhanced efficiency, the throttle may require a reduced opening to generate the same power output if the desired power level remains unchanged.
3. Reduced backpressure facilitates improved scavenging in the cylinder. Decreased back pressure enables a more complete expulsion of these heated gases, allowing room for the new air-fuel mixture to enter during the intake stroke. This reduces heat absorption from the cylinder walls, thus lowering exhaust temperatures.
4. Reducing exhaust back pressure improves the engine's scavenging efficiency. Consequently, the combustion chamber expels exhaust gases more efficiently during the exhaust stroke, hence accommodating a larger volume of fresh air-fuel combination during the intake stroke. This improvement leads to an increase in engine output from 6 to 8.2%.

The current study has some limitations; the power consumed by the air blower is not considered. However, in the study the power required to drive the blower can be taken from the battery. Further investigation can be conducted to optimize the engine operational parameters considering the power consumption of the blower.

AUTHORSHIP CONTRIBUTIONS

The authors have contributed equally to this work.

DATA AVAILABILITY STATEMENT

The authors have confirmed that the data supporting the findings of this study are available within the article. Raw data that support the findings of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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