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Research Article

Influence of Exhaust Gas Recirculation, and Injection Timing on the Combustion, Performance and Emission Characteristics of a Cylinder Head Porous Medium Engine

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Homogeneous combustion has the potential of achieving both near-zero emissions and low specific fuel consumption. However, the accomplishment of homogeneous combustion depends on the air flow structure inside the combustion chamber, fuel injection conditions, and turbulence as well as ignition conditions. Various methods and procedures are being adopted to establish the homogeneous combustion inside the engine cylinder. In this research work, a highly porous ceramic structure was introduced into the combustion chamber (underside of the cylinder head). The influence of operating parameters such as exhaust gas recirculation (EGR) and injection timing on the combustion, performance, and emission characteristics of such developed engine was investigated in this research work.

1. Introduction

Reduction in diesel engine emissions, in particular nitrogen oxide and particulate emission, is becoming serious problem to be tackled, as emission norms are getting more and more stringent nowadays. Numerous research works have been performed on the influence of in-cylinder mixture formation and combustion process on the outcome of exhaust emissions from an internal combustion engine [1–3]. It is well proven that homogeneous mixture results in lower particulate emission from diesel engines [4–6]. Researchers are trying various technologies to accomplish homogeneous mixture formation, combustion, and subsequently lower particulate emission. One such technique to realize lower particulate emission from diesel engines is porous medium combustion [4, 5]. Low nitrogen oxide emission will be the supplementary benefit of porous medium combustion technique [7, 8].

The most critical process in this technique is the fuel vapourization. Imperfections within this process directly influence the quality of the combustible fuel-air mixture, resulting in higher exhaust gas emissions of carbon monoxide, nitrogen oxide, and unburned hydrocarbons [9]. With enhanced evaporation of liquid fuels by the presence of porous medium and in the presence of oxygen, rapid and complete combustion can always be achievable, which leads to much lower emissions from the porous medium (PM) engine.

2. Literature Review

Shahangian et al. [10] investigated the role of porous medium in the homogenization of high pressure diesel fuel spray in a constant volume chamber. In this work, the author explored the influence of porous medium on the air-fuel mixture formation through image processing techniques and heat release and heat transfer models. The system pressure and temperature on the mixture formation were also investigated.

Shahangian and Ghojel [11] performed an investigation about the interaction between diesel sprays and porous medium in a constant volume chamber. The author found that increasing the injection pressure increased the number of secondary sprays emerging from porous medium and their penetration. It was also concluded that the fuel distribution inside the chamber volume was strongly affected by the characteristics of porous medium.

Weclas et al. [12] simulated the thermodynamic conditions of the heat release process of a diesel engine in a special combustion chamber. The analysis was further extended to a free volume combustion chamber with no porous medium. A common rail diesel injection system was used for simulation of fuel injection process and mixture formation conditions as such in a real engine. The results showed that thermodynamic condition of heat release process depends on porous medium heat capacity, pore density, specific surface area, and pore structure.

Weclas et al. [12] investigated low and high temperature oxidation processes including thermal autoignition under diesel engine-like conditions (nonpremixed mixtures). A special combustion chamber, characterized by constant volume and adiabatic conditions, was used as an engine simulator. In this study, five characteristic regions of the processes were considered: region 1 corresponds to processes occurring at low initial pressure over a wide range of initial temperatures; region 2 corresponds to low initial temperatures over a wide variation of initial pressure; region 3 corresponds to middle pressure and higher temperatures; region 4 corresponds to middle temperatures and higher pressure; and region 5 corresponds to high initial pressure and high temperatures. This research work ended with a conclusion note that the ignition delay reduces with increasing chamber temperature and pressure.

Mohammadi et al. [13] performed the simulation of internal combustion engine equipped with a chemically inert porous medium to homogenize and stabilize the combustion of engine. A three-dimensional numerical model for porous medium engine was developed based on a modified version of the KIVA-3V code. In this simulated study, methane gas injected directly inside the hot porous medium (mounted on cylinder head) was considered as fuel. Mixture formation and pressure and temperature distribution in porous medium and in-cylinder fluid with the production of pollutants such as CO and NO were also studied. The numerical results of porous medium engine were validated with experimental data of lean methane-air mixture under filtration in packed bed.

Zhou et al. [14] developed an axisymmetric model with detailed chemistry and two-temperature treatment into a variant of KIVA-3V code to simulate the working process of a porous medium engine. The comparisons were made with the same engine without porous medium implementation. The key factors affecting heat transfer, combustion and emissions of the porous medium engine such as porosity, the initial temperature of porous medium, and equivalence ratio were analyzed. The results showed that the characteristics of heat transfer, emissions, and combustion of the porous medium engine are superior to the engine without porous medium. Moreover it was found that porous medium engine is able to sustain ultra lean combustion.

At the end of literature review, it is evident that properly implemented porous medium will produce positive influence on emissions and performance characteristics of an internal combustion engine. Majority of previous works that reported on porous medium are confined to either numerical simulation or experimentation in a constant volume chamber. Limited research works have reported on the practical implementation of porous medium in an engine whose operation is limited to lean mixture strength. In this research work, an attempt was made to achieve the porous medium combustion in direct injection (DI) diesel engine with the inclusion of highly porous ceramic material into the space of combustion chamber (underside of the cylinder head). In addition, the porous medium engine was being operated from no load to peak load conditions; that is, the engine operation was not limited to lean mixture strength. The influence of operating parameters such as EGR and injection timing on the combustion, performance, and emission characteristics of such developed porous medium engine was analyzed and compared with the conventional engine.

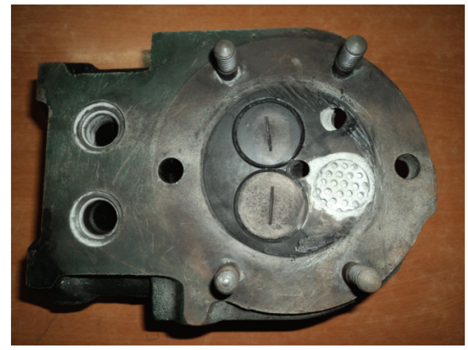
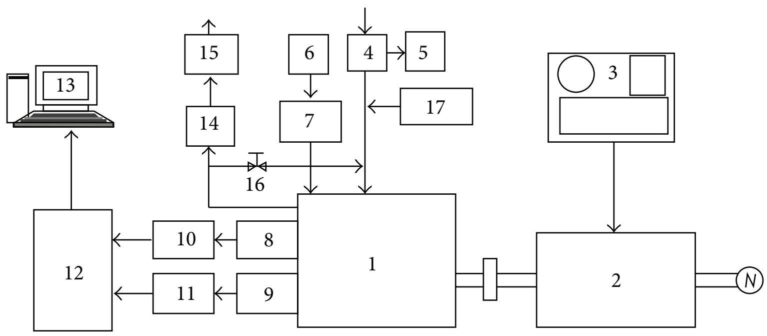


Figure 1: Photographic view of cylinder head with ceramic coated wire mesh PM implementation.

3. Development of Cylinder Head Porous Medium Engine

After detailed literature survey, a suitable porous medium with high porosity was selected for developing a porous medium engine. High porosity made the medium transparent for gas flow, spray, and flame. In a porous medium engine, the porous medium can be placed in one of the following locations: cylinder, cylinder head, or piston. In this investigation, porous medium was placed on the underside of the cylinder head. In order to accommodate the porous medium on this location, a certain volume of material was removed from the underside of cylinder head and porous medium was placed in that recess and detained in its position by an appropriate locking mechanism. Due to the removal of material from the underside of cylinder head, the compression ratio of porous medium engine reduced to 16 : 1 as against 17.5 : 1 in the conventional engine. The photographic view of such cylinder head with porous medium implementation is shown in Figure 1. The dimensions and important properties of porous ceramic medium used in this experiment are given in Table 1.



(1) Engine (2) Dynamometer (3) Dynamometer controls
(4) Air box (5) U tube manometer (6) Fuel tank
(7) Fuel measurement (8) Pressure transducer (9) TDC position sensor
(10) Charge amplifier (11) TDC amplifier circuit (12) Analog to digital card
(13) Computer (14) Exhaust gas analyzer (15) AVL smoke meter
(16) EGR control valve (17) Electrical heater

Figure 2: Experimental setup.

Table 1: Dimensions and properties of porous ceramic medium.

Diameter of porous medium	30 mm
Height of porous medium	20 mm
Porosity	75%
Melting point	2700°C
Density	5.89 g/cm^3
Thermal heat conductivity	2 W/mK
Specific heat capacity	400 J/kg K
Thermal expansion coefficient	11×10^{-6}/°C

Table 2: Specifications of test engine.

Make	Kirloskar
Model	TAF 1
Type	Direct injection, air cooled
Bore × stroke	87.5 mm × 110 mm
Compression ratio	17.5 : 1
Swept volume	0.661 L
Rated power	4.4 kW
Rated speed	1500 rpm
Start of injection	23.4 before TDC
Injector operating pressure	200–205 bar

4. Experimental Setup and Testing Procedure

The engine setup used for the experimental investigation is shown in Figure 2. The tests were conducted on a single cylinder four-stroke, naturally aspirated, air cooled direct injection diesel engine which was operated from no load to peak load through an eddy current dynamometer coupled to that engine. The main specifications of the test engine are given in Table 2.

In order to determine the engine torque, the shaft of the test engine was coupled to an electric dynamometer, which was loaded by an electric resistance. A strain load sensor was employed to determine the load on the dynamometer. The engine speed was measured by an electromagnetic speed sensor installed on the dynamometer. The fuel consumption rate of the engine was determined with a weighing scale having a sensitivity of 0.1 g and an electronic chronometer having a sensitivity of 0.1 s. The engine was equipped with an orifice meter connected to an inclined manometer to measure mass flow rate of the intake air. An air damping tank was used for damping out the pulsations produced by the engine, thus obtaining a steady air flow.

AVL GH12D miniature pressure transducer with AVL 3066A02 piezocharge amplifier and angle encoder was used to obtain the variation of pressure in the combustion chamber. The mean pressure history in the combustion chamber was obtained by averaging 100 cycles in sequence. The AVL 615 indimeter software was used to compute the heat release rates from the measured values of pressure and crank angle (CA). An exhaust gas analyzer was used to measure carbon monoxide (CO), unburned hydrocarbons (UBHC) by infrared sensors, and NO_x by electrochemical sensors.

Tests were first conducted with conventional engine to obtain the base data. Each test was repeated for three times. From the experimental measurements, it was found out that around 90% of the measurements were within 2 standard deviations from the average. Under the same operating conditions, the testing was repeated to the porous medium engine, which was under investigation. The influence of operating parameters such as EGR and injection timing on the combustion, performance, and emission characteristics of porous medium engine were carried out and compared with those of conventional engine characteristics.

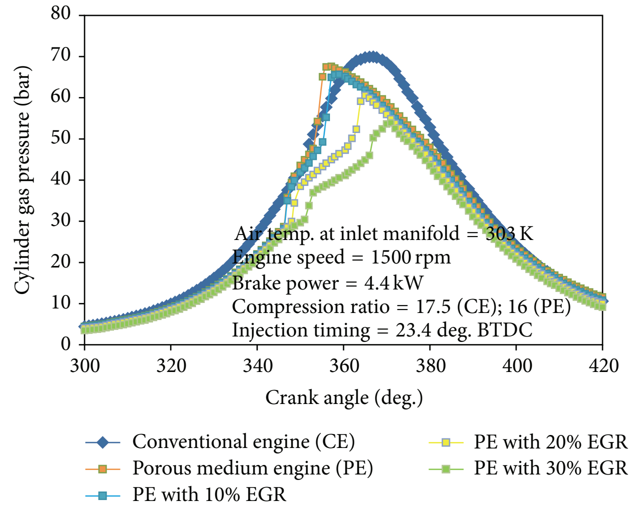


Figure 3: Influence of EGR on cylinder gas pressure of cylinder head porous medium engine.

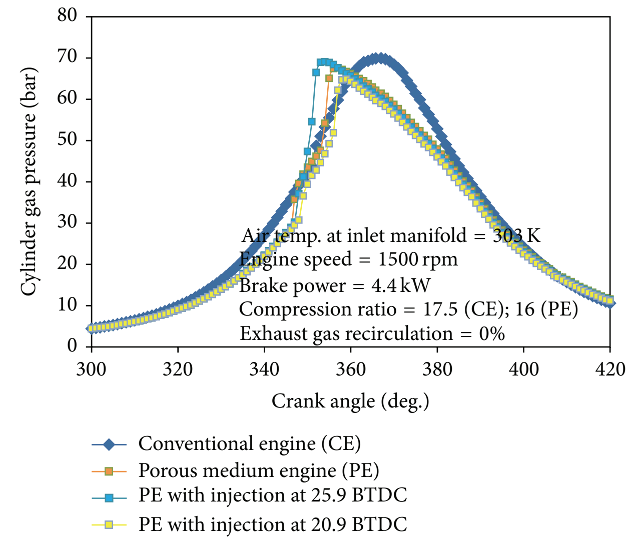


Figure 4: Influence of injection timing on cylinder gas pressure of cylinder head porous medium engine.

5. Error Analysis

Errors and uncertainties in the experiments can arise from instrument selection, condition, calibration, environment, observation, reading, and test planning. Uncertainty analysis is needed to prove the accuracy of the experiments. The percentage uncertainties of various parameters like brake power and brake thermal efficiency were calculated using the percentage uncertainties of corresponding measuring instruments. An uncertainty analysis was performed using this method and the total error was found to be = square root of {(uncertainty of total fuel consumption)^2 + (uncertainty of brake power)^2 + (uncertainty of brake thermal efficiency)^2 + (uncertainty of CO)^2 + (uncertainty of UBHC)^2 + (uncertainty of NO_x)^2 + (uncertainty of smoke number)^2 + (uncertainty of pressure pickup)^2} = square root of $\{(1)^2 + (0.2)^2 + (1)^2 + (0.2)^2 + (0.2)^2 + (0.2)^2 + (1)^2 + (1)^2\} = 2.04\%$.

6. Influence of EGR and Injection Timing on the Combustion, Performance, and Emission Characteristics of Porous Medium Engine

6.1. Combustion Characteristics

6.1.1. Cylinder Pressure. The combustion in porous medium led to two-stage ignition reaction, which was inferred from the cylinder gas pressure versus crank angle diagram shown in Figure 3. The first stage was associated with low temperature reactions (LTR) and released relatively small amount of energy. The first stage might have happened in the porous medium, which was placed on the underside of the cylinder head. The second stage was associated with high temperature oxidation reactions and released most of the energy, which was considered as main combustion stage (MCS). This might have happened in the free volume of cylinder outside the porous medium.

Even with an increase in % EGR, a significant change in the occurrence of first stage of combustion was not observed in the porous medium engine. The presence of hot porous ceramic medium placed on the underside of cylinder head could be the possible reason for this observation. But it was found that the second stage of combustion got retarded due to the impact of inert gases present in recirculated gases on the heat release rate, which in turn delayed the second stage of autoignition. The peak pressure was found to be occurring at crank angles of 367, 357, 359, 365, and 371 for conventional, porous medium engine with 0%, 10%, 20%, and 30% EGR. This is shown in Figure 3.

On advancing the injection, the cylinder pressure reached a higher value as compared to retarded injection scheme. This was mainly due to the fact that, on advancing the injection, larger amount of fuel was injected (injection starting earlier and stopping later). Higher pressure was also found before top dead centre (TDC) with advancement due to early start of combustion. With retarded injection timing, the occurrence of peak pressure shifted towards TDC. Cylinder gas attained a peak value of 67.60 bar, 69.10 bar, and 64.89 bar for porous medium engine with standard, advanced, and retarded injection timings. This is shown in Figure 4.

6.1.2. Heat Release Rate. The heat release from the porous medium engine was showing a distinct two-stage heat release pattern as such in homogeneous charge compression ignition (HCCI) engine [15]. Figure 5 showed the heat release pattern for a porous medium engine. In that, low temperature reactions (LTR) were found to be followed by high temperature reactions (HTR). The conversion region of LTR to HTR with negative temperature-coefficient was called NTCR. With an increase in % EGR, NTCR was found to be increased in proportion. In addition to this, the amount of heat released in both LTR and HTR region was getting reduced with increasing % EGR.

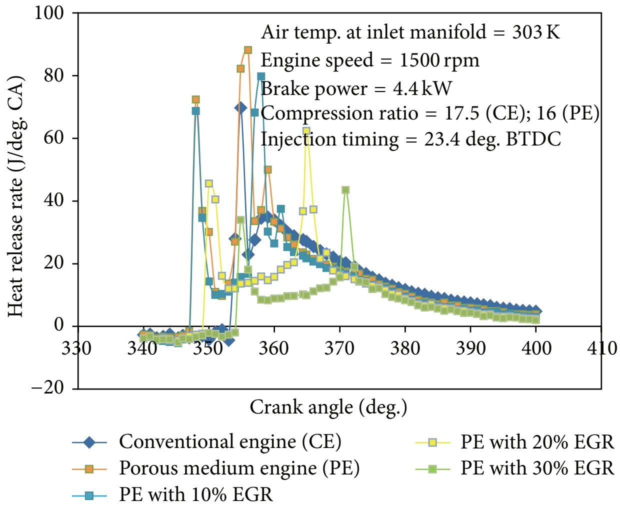


FIGURE 5: Influence of EGR on heat release rate of cylinder head porous medium engine.

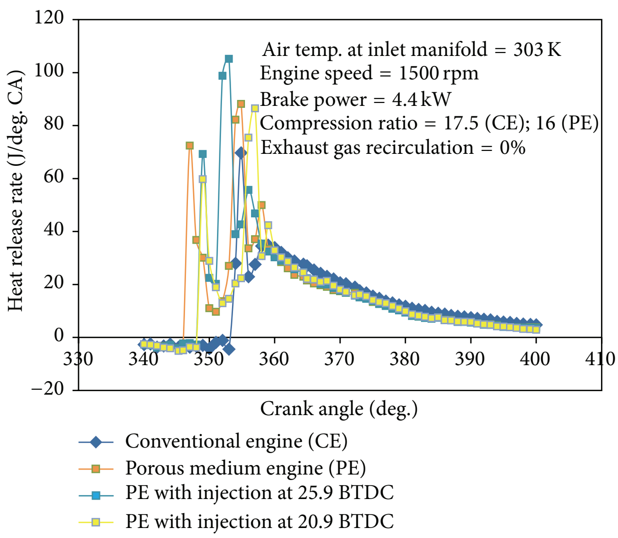


FIGURE 6: Influence of injection timing on heat release rate of cylinder head porous medium engine.

More amount of heat was released well before TDC with advanced injection timing. At rated power, the HTR region was found to be occurring at crank angles of 355, 353, and 357 for porous medium engine with standard, advanced, and retarded injection timings. This is shown in Figure 6.

6.2. Performance Characteristics

6.2.1. Brake Specific Fuel Consumption. In porous medium engine, the brake specific fuel consumption was found to be increasing with an increase in % EGR like conventional diesel engine. The excess air declined with EGR causing the loss in fuel economy as compared to porous medium engine operation without EGR. It was found that excessive charge dilution led to unstable combustion and misfiring, which in turn resulted in power loss and higher specific fuel consumption. This was the reason why porous medium engine was producing poor performance characteristics in excess of 20% EGR. The brake specific fuel consumption was 5%, 17%, and 34% higher for porous medium engine with 10%, 20%, and 30% EGR than for that with 0% EGR which is shown in Figure 7.

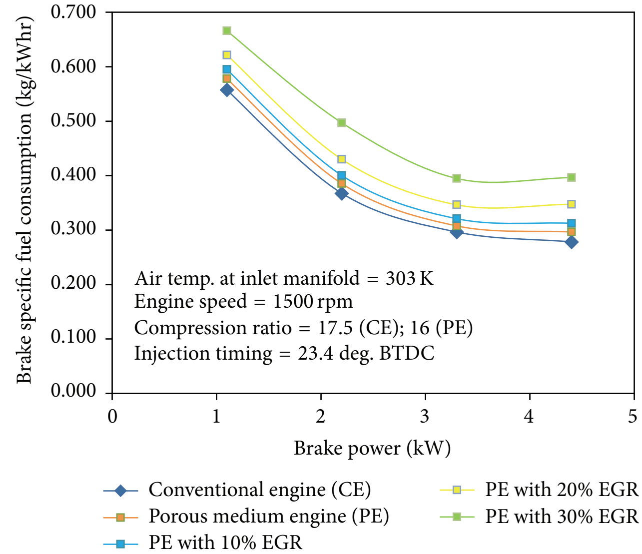


FIGURE 7: Influence of EGR on brake specific fuel consumption of cylinder head porous medium engine.

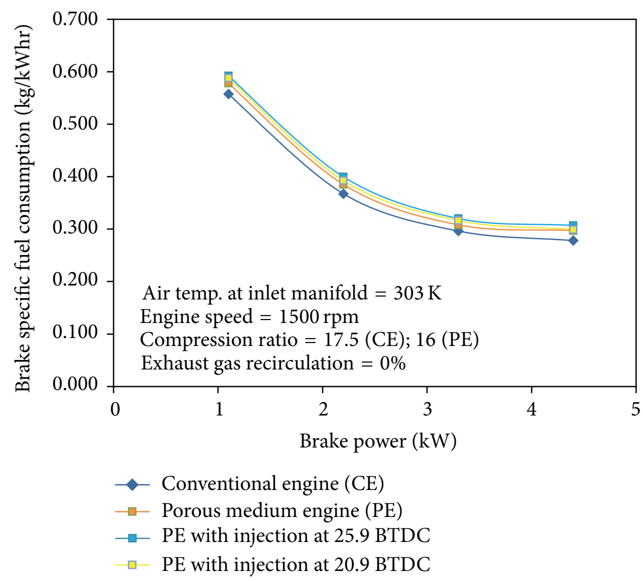


FIGURE 8: Influence of injection timing on brake specific fuel consumption of cylinder head porous medium engine.

The influence of injection timing on brake specific fuel consumption for conventional and PM engine configuration is shown in Figure 8. The brake specific fuel consumption for porous medium engine was found to be slightly higher for advanced and retarded injection timing than with standard injection timing. At advanced injection timing, more of the fuel was injected and injection started earlier in the cycle leading to earlier pressure rise before the piston reaches TDC position. Greater pressure rise in the compression stroke

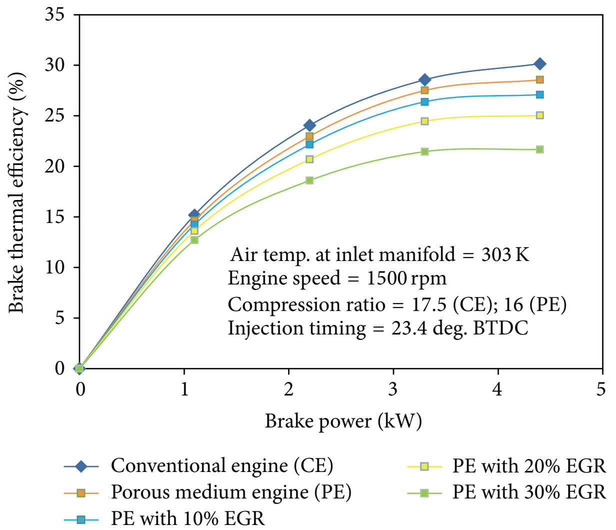


Figure 9: Influence of EGR on thermal efficiency of cylinder head porous medium engine.

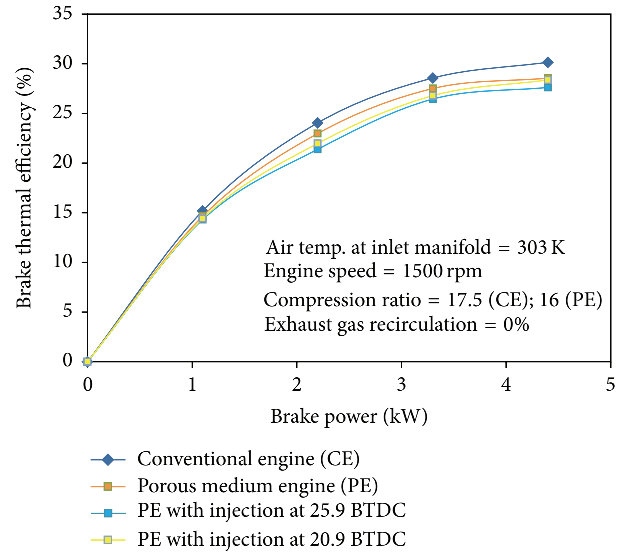


Figure 10: Influence of injection timing on thermal efficiency of cylinder head porous medium engine.

increased the negative work and consumed the most of the flywheel momentum. At retarded injection timing too, the brake specific fuel consumption was higher than porous medium engine with standard injection timing. This may be due to the operation of porous medium engine at reduced compression ratio. At rated power, the brake specific fuel consumption for porous medium engine was 3.1% and 1% higher with advanced and retarded injection timing than with standard timing.

6.2.2. Brake Thermal Efficiency. The brake thermal efficiency of porous medium engine was found to be reasonably good up to 20% EGR. When EGR was further increased beyond this limit, a substantial reduction in brake thermal efficiency was observed. At rated power, a reduction of about 24% was observed with 30% EGR than porous medium engine operation with 0% EGR, which is shown in Figure 10. This may be due to unstable combustion and misfiring that might have occurred inside the engine cylinder due to excessive charge dilution. The brake thermal efficiency was found to be lower for porous medium engine with advanced and retarded injection timing than that of standard injection timing. At rated power, the brake thermal efficiency was found to be 30.45%, 28.56%, 27.62%, and 28.37% for conventional, porous medium engine with standard, advanced, and retarded injection timings. This is shown in Figure 9.

6.3. Emission Characteristics

6.3.1. Unburned Hydrocarbons. In porous medium engine, HC emission was observed to be increasing with an increase in % EGR. Reduced burned gas temperatures due to strong heat absorption characteristics of porous medium and little probability for the later stage oxidation of unburned hydrocarbons that were formed during the initial stage combustion might be the reasons for excessive hydrocarbons in the engine exhaust. A sharp increase in HC emissions was

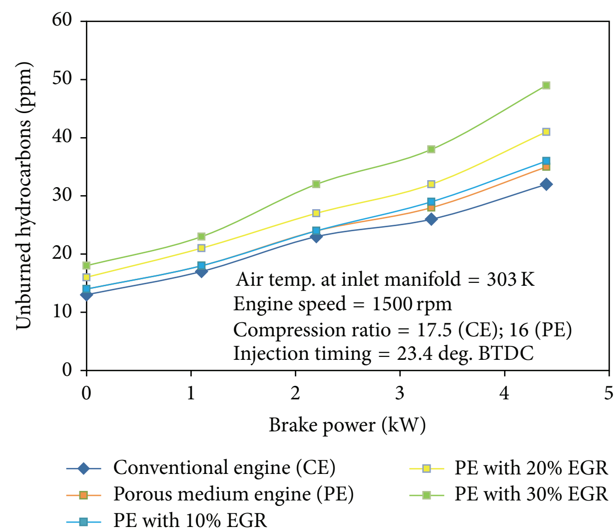


Figure 11: Influence of EGR on unburned hydrocarbon emissions of cylinder head porous medium engine.

observed for excess of 20% EGR for the given configuration of porous medium engine. Above 20% EGR, partial engine misfiring in addition to reduced postflame oxidation collectively contributed to higher HC emissions in the exhaust of porous medium engine than in the conventional engine. The unburned hydrocarbon emissions were 3%, 17%, and 40% higher for porous medium engine with 10%, 20%, and 30% EGR than with 0% EGR. This is shown in Figure 11.

From Figure 12, it was evident that advanced injection timing had the tendency of decreasing the hydrocarbon emissions at all loads. This may be due to availability of more time for the injected fuel quantity to get burned completely during expansion stroke. The reverse trend was observed with retarded injection timing. However, the penalty was not too much since the presence of the hot porous medium permitted

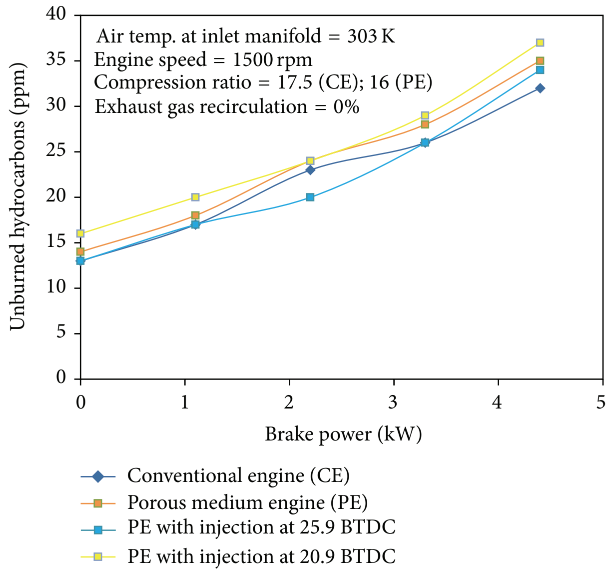


FIGURE 12: Influence of injection timing on unburned hydrocarbon emissions of cylinder head porous medium engine.

the fuel to burn at later stage in the expansion stroke. At rated power, the unburned hydrocarbons were found to be 9%, 6%, and 16% higher for porous medium engine with standard, advanced, and retarded injection timing than conventional engine.

6.3.2. Carbon Monoxide. It is well proven that the carbon monoxide is not capable of being completely converted into carbon dioxide at lower in-cylinder temperatures. Due to the heat absorption characteristics of porous medium that was placed on the underside of the cylinder head, the gas temperatures were lower in porous medium engine than in the conventional engine. Thus, the reduced in-cylinder gas temperatures led to comparatively higher CO emissions from that engine. With an increase in % EGR, the in-cylinder gas temperatures were further getting reduced, which eventually resulted in higher CO emissions. The carbon monoxide emissions were found to be 3%, 13%, and 39% higher for porous medium engine with 10%, 20%, and 30% EGR than with 0% EGR. This is shown in Figure 13.

The carbon monoxide emissions were found to be slightly higher for porous medium engine with standard and retarded injection timings than for conventional engine. This may be due to the reason that the heat absorption by porous medium from the reaction zone reduced the in-cylinder gas temperature, which further inhibited the oxidation of CO into CO_2 during the expansion stroke. The advanced injection timing produced the higher cylinder temperature and increased oxidation process between carbon and oxygen molecules which eventually resulted in lower CO emissions than the standard and retarded injection schemes. At rated power, CO emission was 13.8% lesser than conventional engine for porous medium engine with advanced injection timing. However, CO emissions were 3.4% and 13.8% higher than conventional engine for porous medium engine with

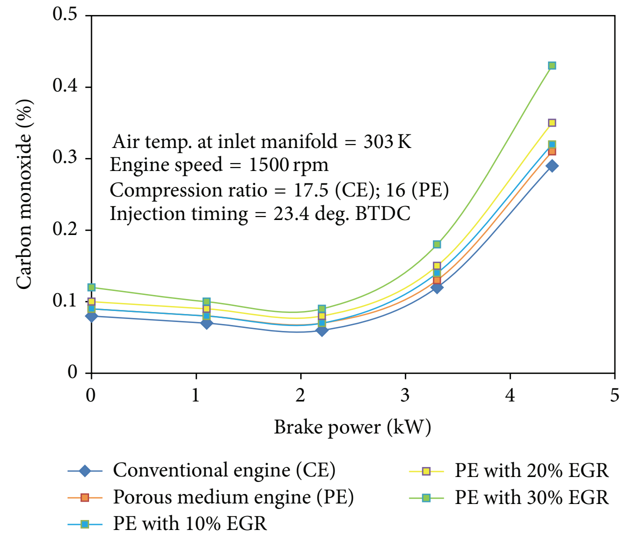


FIGURE 13: Influence of EGR on carbon monoxide emissions of cylinder head porous medium engine.

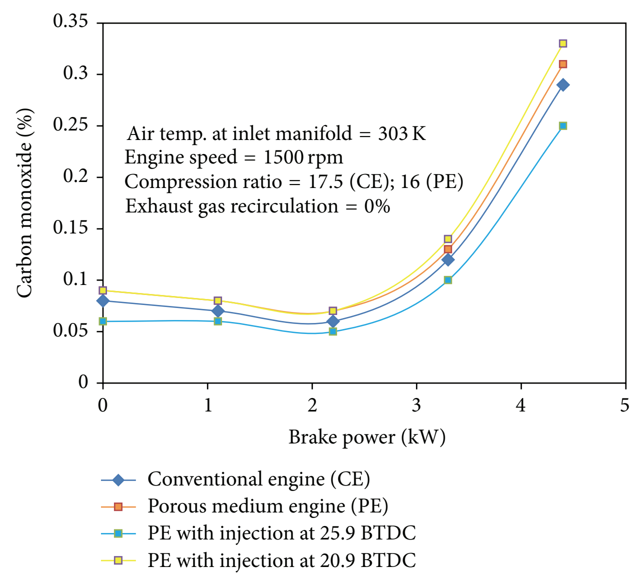


FIGURE 14: Influence of injection timing on carbon monoxide emissions of cylinder head porous medium engine.

standard and retarded injection timing. This is shown in Figure 14.

6.3.3. Oxides of Nitrogen. Burned residual gases left from the previous cycle or part of exhaust gas recirculated back to the engine acted as diluents, due to which the combustion temperatures started to decrease. The decrease will be proportional to heat capacity of the diluents. CO_2 and H_2O present in recirculated exhaust gas will result in larger NO_x reductions than for the same volume of N_2 due to their higher specific heat. The additional effects of charge dilution are reduction in oxygen concentration in the charge and slowing down the combustion rates. These will cause further reduction in the burned gas temperature. With the NO_x

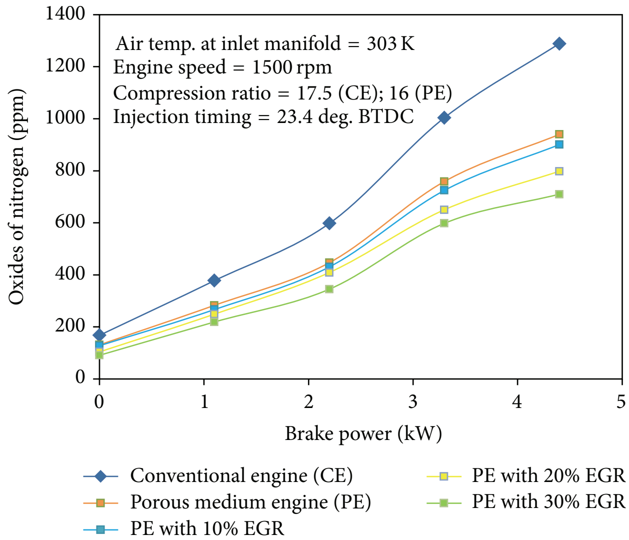


FIGURE 15: Influence of EGR on nitrogen oxide emissions of cylinder head porous medium engine.

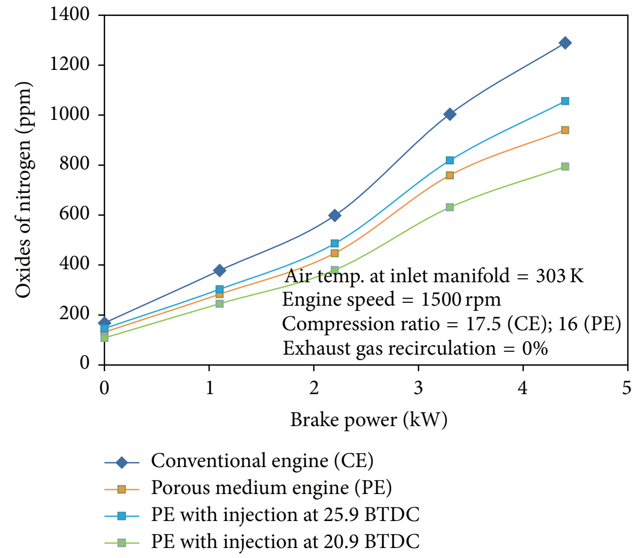


FIGURE 16: Influence of injection timing on nitrogen oxide emissions of porous medium engine.

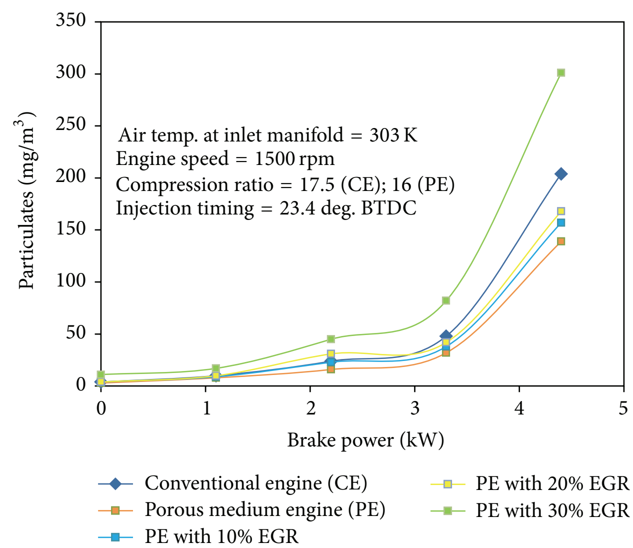


FIGURE 17: Influence of EGR on particulate emissions of cylinder head porous medium engine.

formation being the exponential function of temperature, even a small reduction in flame temperature has a large effect on NO_x kinetics. Increase in heat capacity of charge caused by EGR has generally been thought to result in reduction of NO_x emissions. Moreover, in this investigation, the porous medium absorbed heat from the reaction zone, which in succession reduced the in-cylinder temperature and NO_x emissions. NO_x emissions were found to be 27.1%, 30.1%, 38.1%, and 44.9% lower for 0%, 10%, 20%, and 30% EGR operation of porous medium engine than conventional engine operation. This is shown in Figure 15.

Injection timing has a strong effect on NO_x emissions for DI engines. Retarding the injection timing decreases the peak cylinder pressure because more of fuel burns after TDC. In general, lower peak cylinder pressure results in lower peak temperature. As a consequence, the NO_x concentrations start to decrease. However, with advanced injection timing, increasing NO_x emissions were observed. This may be due to compression of burning charge by the displacing piston. But, still, NO_x emissions were lower in porous medium engine than in conventional engine with all different injection timings. At rated power, the NO_x emissions were 27.1%, 18.08%, and 38.4% lower for porous medium engine with standard, advanced, and retarded injection timing than for conventional engine. This is shown in Figure 16.

6.3.4. Particulates. If oxygen availability increases during combustion, it will boost the flame temperature, which would further help in oxidation of soot during the postflame reactions. It is proven that increase in % EGR reduces the available oxygen content in the combustion chamber which may result in higher particulate emissions. However, in porous medium engine, this effect was found to be predominant, when EGR was increased further beyond 20%. It was also observed that particulate emissions in porous medium engine were still lower than conventional engine by 31.9%, 23%, and 17.6%, respectively, with 0%, 10%, and 20% EGR operation. This may be due to enhanced evaporation, thorough mixing of fuel vapour and air by the presence of porous medium in the engine cylinder and with sufficient availability of oxygen for combustion up to 20% of EGR. When EGR was increased further than 30%, a sharp rise in particulate emissions was observed which may be due to either poor combustion or partial engine misfiring or combination of two. This is shown in Figure 17.

Owing to lower temperature in the reaction zone, very fast vapourization, more homogeneous mixture composition, and relatively long residence time in the reaction zone (porous medium volume) with a homogeneous temperature distribution, the particulate emissions were found to be lower in porous medium engine than in conventional engine.

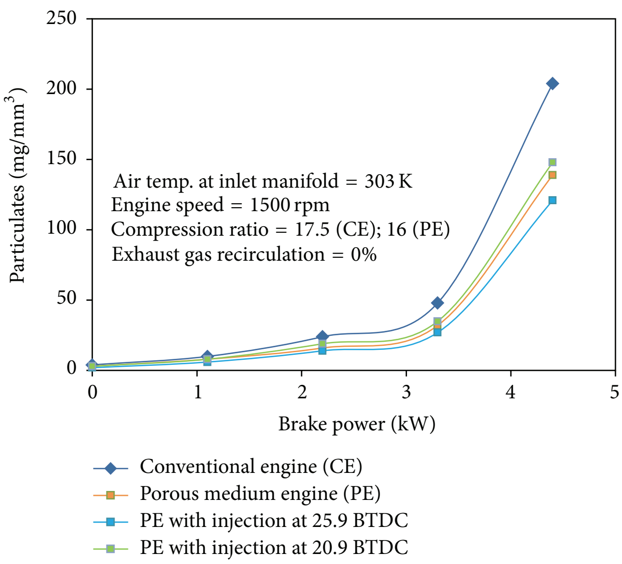


FIGURE 18: Influence of injection timing on particulate emissions of cylinder head porous medium engine.

The particulate emissions are 31.9%, 23%, and 27.5% lower for porous medium engine with standard, advanced, and retarded injection timing than for conventional engine. This is shown in Figure 18.

7. Conclusion

The influence of operating parameters such as EGR, injection timing on the combustion, performance, and emission characteristics of cylinder head porous medium engine has been performed and the findings are listed below:

(i) Two-stage combustion is found to be occurring in the cylinder head porous medium engine, believing that first stage of combustion is occurring in porous medium under favourable ignition conditions subsequently followed by second stage of combustion in the rest of the combustion chamber.

(ii) The operating parameter EGR is having major influence on the combustion, performance, and emission characteristics of porous medium engine than the other operating parameter injection timing, which is considered in this investigation.

(iii) The porous medium engine is found to operate without any problems up to 20% EGR. In excess of that, too much charge dilution is found to initiate unstable combustion due to partial engine misfiring and results in considerable power loss.

(iv) Even though the injection timing is not having considerable influence on the characteristics of porous medium engine, retarded injection scheme is preferable over the advanced injection scheme in the case of cylinder head porous medium engine. But both modified injection timings are found to produce inferior characteristics when compared to original injection timing. Hence, it is suggested to operate this porous medium engine with original injection timing.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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