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Research Paper

The effect of synthetic 4A and 5A zeolite-based nitrogen capture systems on diesel engine performance and emissions

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ABSTRACT

In the study, a filtration system was designed using pressure swing adsorption (PSA) technique and synthetic zeolites and its effects on exhaust emissions and performance attributes of a diesel engine were investigated by integrating this system into the intake line. Synthetic 4A and 5A zeolites were used as adsorbent materials in the PSA unit. Tests were conducted on a single cylinder diesel engine operated at constant speed under variable load conditions. SEM and EDX analyses were performed to characterize the surface properties of the zeolites. According to the oxygen measurements obtained at the outlet of the filtration system, the 4A and 5A zeolites provided an air outlet containing oxygen at the rate of 25.8% and 27.36%, respectively. The most remarkable improvements in exhaust emissions and performance parameters were obtained with the 5A zeolite. The use of 5A resulted in reductions in carbon monoxide, hydrocarbon, smoke density, and brake-specific fuel consumption by 17.31%, 13.83%, 17.42%, and 4.18%, respectively. Conversely, nitrogen oxides, brake thermal efficiency, exhaust gas temperature, torque, engine noise and vibration increased by 15.37%, 4.61%, 7.04%, 4.42%, 1.4%, and 3.1%, respectively. In-cylinder peak pressure also increased by 5.33% with PSA. This study provides the first experimental integration of a PSA-based continuous oxygen-enrichment system using synthetic 4A and 5A zeolites into a diesel engine, demonstrating how zeolite type and microstructure influence oxygen concentration and combustion behaviour. The findings show that continuous on-board oxygen enrichment can enhance diesel engine performance while reducing most exhaust emissions.

1. Introduction

Today, the use of electric vehicles is growing rapidly. Electric vehicles have an important potential to reduce transportation costs and environmental pollution when compared to internal combustion engines (ICEs). However, challenges such as the limited driving range, long charging times, and limited access to charging infrastructure increase the complexity of charging [1,2]. These limitations reduce user willingness to adopt electric vehicles and maintain increases the reliance on vehicles with ICEs. In addition, the fact that electric vehicles are not yet widely used (in agriculture, shipping, etc.) suggests that ICEs will continue to be used for some time.

In addition to studies aimed at improving the performance and efficiency of ICEs, numerous studies have been conducted to reduce harmful exhaust emissions that contribute to global warming and the greenhouse effect [3]. In particular, various studies have focused on reducing emissions and enhancing the performance of compression ignition engines, which inherently have higher efficiency than spark ignition engines. In the literature, methods such as using alternative fuels [4,5], modifying combustion chamber (CC) shapes [6,7], applying engine coatings [8,9], adding gas phase fuel additives [10,11], altering injection strategies [12,13], applying dual fuel and dual injection strategies [14,15] and using solid/liquid form fuel additives [16,17] have been explored. Among these approaches, studies in which oxygen (O_2) is supplied to the CC of diesel engines in the gas phase build up hopes in reducing harmful exhaust emissions and improving engine performance.

There have been numerous studies on the supply of extra oxygen to the CC in diesel engines. Baskar and Kumar [18] investigated the effect of using emulsified diesel fuel and O_2 enrichment on nitrogen oxide (NO) emissions and various engine parameters. The findings revealed that water-emulsified diesel fuel improved particulate matter and NO_X emission; however, it resulted in loss of power and torque. They also reported that increasing the O_2 rate in the intake line up to 27% increased engine performance and NO_X emissions while reducing HC emissions. Li et al. [19] increased the O_2 content in the intake air from

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Nomenclature

ICE	Internal combustion engine	Al	Aluminum
NO	Nitrogen oxide	AlO_4	Aluminate
HRR	Heat release rate	BSFC	Brake specific fuel consumption
Rpm	Revolutions Per Minute	EGT	Exhaust gas temperature
Nm	Newton-meter	SiO_4	Silicate
Na	Sodium	BTE	Brake thermal efficiency
SEM	Scanning electron microscope	RMS	root mean square
EDX	Energy Dispersive X-ray Spectroscopy	Ppm	Parts per million
PSA	Pressure swing adsorption	Fe	İron
O_2	Oxygen	Mg	Magnesium
N_2	Nitrogen	CO_2	Carbon dioxide
CC	Combustion chamber	CO	Carbon monoxide
Si	Silicon	HC	Hydrocarbon
		NO_X	Nitrogen oxides
		A/F	Air/Fuel

21% to 24% in a diesel engine using canola seed oil and evaluated exhaust emissions and combustion characteristics. They found that the additional O_2 reduced ignition delay and combustion duration, while in-cylinder temperature and pressure increased. In their study, CO, HC, and particulate emissions decreased due to O_2 enrichment, whereas NO_X values increased. Zhang et al. [20] examined the impacts of O_2 enrichment using emulsified diesel fuel, focusing particularly on NO emissions. To reduce NO emissions and smoke opacity without significantly compromising brake-specific fuel consumption (BSFC), they integrated oxygen-enriched intake air with emulsified diesel fuel 0–20% water and 21%–21.5% intake O_2. Their results showed that NO–smoke emissions were lower than the engine's baseline values when both methods were applied simultaneously. Ghany et al. [21] fed oxygen to a diesel engine at 30.6%, 37.8%, 45% and 54% by mass. They used diesel and biodiesel fuels in their study. According to their results, the heat release rate (HRR) and combustion rate increased for both fuels, along with NO_X emissions. Abdelaal et al. [22] analysed the influence of adding O_2 to the intake air in a pilot ignition natural gas-diesel engine on performance and exhaust emissions. In their study, the rate of O_2 fed to the CC varied between 21% and 27%. The findings indicated that O_2 enrichment led to a decrease in the ignition delay period and an increase in the in-cylinder peak pressure. Moreover, extra O_2 added to the combustion reduced the knocking tendency of the diesel engine running on natural gas under high load conditions. When the emission results were evaluated, they reported that the presence of oxygen decreased HC and CO emissions and resulted in a remarkable increase in NO_X emissions in particular. Jeevahan et al. [23] analysed the impact of oxygen-enriched intake air of a diesel engine on engine performance and emission properties. In the study, the oxygen content fed to the engine and measured in the intake line varied between 21% and 27%. As a result of the experimental study, they stated that O_2 enrichment contributed to the achievement of minimum fuel ignition by reducing the ignition delay time. In addition, they reported that an increase in the rate of O_2 fed to the CC led to a decrease in CO (~ 65%), HC (~ 23%), smoke emissions and BSFC (~ 7%) and an increase in NO_X (~ 57%).

In almost all oxygen enrichment studies on diesel engines, oxygen is fed into the intake line through a ready-made tube. In these applications, O_2 gas with >99.9% purity is fed into the intake line from such tubes. However, the limited storage capacity of these tubes restricts the practicality of oxygen enrichment in vehicles and real-time field applications. Therefore, there is a need for an oxygen purification system that can operate continuously. To address this limitation, selective permeable membranes have been used in some studies in the literature to purify O_2 from air [24,25]. In the present study, oxygen enriched air was supplied to the intake line of a diesel engine through a unique filtration system. In this filtration system, oxygen enrichment was achieved through the application of the pressure swing adsorption (PSA) technique. This technique was based on the separation of oxygen and nitrogen molecules in the air in accordance with the principle of pressurisation. A porous filtering material called zeolite was used for the separation process.

Beyond bottled oxygen supply, several intake-air oxygen enrichment strategies have been examined in the literature, including membrane-based separation systems and cryogenic oxygen sources [26]. Bottled high-purity oxygen allows accurate adjustment of intake O_2 concentration; however, its limited storage capacity, safety concerns related to high-pressure cylinders, and discontinuous operation make it unsuitable for real-time or on-board engine applications [18]. Membrane separation systems, although compact, suffer from low oxygen selectivity, sensitivity to temperature and humidity variations, and performance deterioration due to membrane fouling [25]. These limitations demonstrate that the currently available enrichment approaches face practical obstacles related to continuity, scalability, and operational stability. PSA using synthetic zeolites offers a promising alternative to overcome these drawbacks. Zeolites possess uniform pore structures and strong nitrogen adsorption affinity, enabling continuous generation of oxygen-enriched air without the need for storage tanks [27,28]. PSA systems can operate cyclically, are relatively simple and low-cost, and can maintain stable enrichment levels under varying engine loads [29]. Therefore, PSA-based enrichment provides a more practical and sustainable solution for continuous O_2 supply compared to conventional methods.

Zeolites belong to the group of soft aluminosilicate minerals with more than 50 natural types and about 1500 synthetic types [30]. They exhibit a three-dimensional structure consisting of interconnected tetrahedra of aluminum, silicon, and oxygen atoms. In zeolite crystal structures, the $[AlO_4]^{5-}$ and $[SiO_4]^{4-}$ units are bonded in such a way that the four oxygen atoms at the corner of each tetrahedron are shared with neighbouring tetrahedra [31]. The natural microporous structure (0.3–1 nm) of most zeolites provides size and shape selectivity, making them suitable to function as "molecular sieves". This feature makes zeolites prominent for adsorption applications [32]. Zeolites are used in petrochemical, wastewater distillation, construction, agriculture, and animal husbandry sectors with their properties such as chemical resistance, high porous structure, and ion exchange ability [33,34]. Zeolites, which can vary in terms of atom arrangement and Si/Al ratios, gain different capabilities according to these changing structures. Increasing Si/Al values of zeolites improves thermal stability. On the other hand, this change negatively affects the adsorption capability of zeolites [35]. Zeolites can contain water molecules in their structures. By applying dehydration process, these water molecules are separated from the structure and porous voids are formed. The resulting void structures only allow the passage of molecules smaller in size than themselves [36]. Numerous studies [29,37,38] have been conducted in the literature for the separation of different gases and the separation of gases such as CH_4,

N_2, CO_2 and O_2 has been investigated. Three different types of zeolites have been used for gas separation processes; i. natural zeolites, ii. modified zeolites, and iii. Synthetic zeolites. Synthetic zeolites have a more homogeneous pore structure compared to natural zeolites, and their pore size can be controlled during production and can be produced in the desired pore size. The fact that pore structures can be produced with desired properties allows synthetic zeolites to be used more efficiently compared to natural zeolites. In the present study, synthetic 4A and 5A type zeolites were used for the separation of nitrogen and oxygen molecules. The terms "4A" and "5A" used in synthetic zeolites indicate the pore size and molecular sieve properties of the zeolite. This classification refers to the measure of the pore size of the zeolite in angstroms (Å) and defines the types of zeolites that can be used for the separation of specific molecules.

In the study, the separated air to be fed to the diesel engine was formed using the PSA technique. The PSA method is based on the principle that gases are drawn into absorbent materials under high pressure and then the adsorbed gas is released by reducing the pressure value [39]. The low cost of the PSA method compared to other gas separation methods, its ability to provide high gas purity and its simple structure allow this system to be widely used [40]. In the PSA method, compressed air is directed through a column filled with a zeolite adsorbent, facilitating the separation of nitrogen, for which the adsorbent has a higher affinity compared to oxygen, is retained in the column. As a result of this process, an oxygen-enriched gas escapes from the column. When the adsorbent material reaches its nitrogen absorption capacity, the retained nitrogen is desorbed upon the reduction of pressure. This process allows continuous oxygen enrichment in a system with one or more columns [41,42]. O_2 purification studies with PSA method are available in literature. These studies [43–45], reported while clinoptilolite and chabazite type zeolites from natural zeolites were used, O_2 purification was achieved with the help of 13× type synthetic zeolites.

In the current study, a filtration system using PSA technique and synthetic zeolites was designed and its effects on exhaust emissions and performance values of a diesel engine were analysed as a result of the integration of this system into a diesel engine. Oxygen enrichment studies in literature have been carried out with oxygen gas in ready-made tubes with limited capacity. ICEs operate at different loads, speeds and durations under actual operating conditions, and feeding oxygen from a tube containing a limited amount of oxygen has been found to be a temporary solution method. This creates negativity in case the oxygen in the tube runs out. In the study, an alternative method was used to lower exhaust emissions and increase the performance of the diesel engine. The filtration system used in the study has the ability to continuously produce oxygen. In this filtration system, two synthetic 4A and 5A zeolites were used as filtering materials. The use of these synthetic zeolites in the oxygen enrichment approach for a diesel engine has been realised for the first time in literature. The use of these two different synthetic zeolites in the filtration system resulted in different O_2/N_2 ratios fed into the CC of the engine. The effects of these two zeolites, providing enrichment at different rates, on the exhaust emission and performance values of a diesel engine were investigated in detail. The primary aim of this research is to improve exhaust emissions and performance parameters by supplying air with reduced nitrogen content (increased oxygen content) to a diesel engine through the use of synthetic zeolites in a filtration system operating with the PSA technique.

Although numerous studies have explored oxygen-enriched combustion in diesel engines, the existing literature suffers from important limitations. Nearly all previously published works have relied on externally supplied high-purity oxygen cylinders or membrane-based concentrators, which cannot provide continuous, load-responsive oxygen enrichment suitable for practical engine applications. Furthermore, no prior study has experimentally integrated a PSA-based system using synthetic zeolites directly into the intake line of a diesel engine. The comparative behaviour of different zeolite types (particularly 4A and 5A) under real engine operating conditions also remains largely unexplored. Thus, there is a clear research gap concerning how zeolite microstructure, pore size, and adsorption selectivity influence achievable oxygen concentration and, consequently, combustion, performance, and emission characteristics of diesel engines. The present study addresses this gap by providing the first systematic experimental evaluation of a PSA system employing synthetic 4A and 5A zeolites for continuous on-engine oxygen enrichment. This work establishes a new pathway for practical, sustainable oxygen-enrichment strategies and offers novel insight into zeolite-dependent combustion behaviour that has not been previously reported.

2. Materials and methods

2.1. Development and operating principle of the filtration device

A filtration device operating based on the PSA technique was developed utilizing zeolites. This filtration device consists of an air compressor capable of pressurisation, two tubes containing zeolites, solenoid valves for directing pressurised air into the tubes and directing waste gases, a tank in which the enriched air is collected, an air flow adjusting valve at the outlet of the system, a solenoid valve and a control card that controls the opening and closing status. Since the system operates under pressure, especially the tubes were sealed. Fig. 1 presents a schematic representation of the filtration system.

The filtration device basically filters the nitrogen molecules in the tubes and ensures that the air with high oxygen content accumulates in the collection tank. The filtration system includes a 5 L collection tank, used to stabilise pressure and reduce flow pulsations. The device operates based on the PSA principle. The air sent to the system with the help of a compressor is directed by a solenoid valve and filled into a tube. The tubes contain synthetic 4A and 5A zeolites. The zeolite tubes operated within a pressure range of 6–7 bar, and the compressor used in the PSA system had a compression ratio of 8:1, providing the required pressurisation for the adsorption–desorption cycle. When the pressure in the tube reaches the specified value, nitrogen molecules are adsorbed in the zeolite pores (the pressurisation time in the tubes is set as 5 s). Then, the solenoid valve is activated and the air with increased oxygen concentration is sent to the collection tank. After this process, the solenoid valves are activated to release the nitrogen molecules accumulated in the tube with decreasing oxygen concentration to the atmosphere. At the same time, pressurisation starts in a second tube. This system is completely realised with solenoid valves and a control card controlling the valves. In this way, while one tube provides the pressurisation (purification) process, the other tube performs the pressure drop (discharge of waste nitrogen molecules) and these processes continue as a cycle. The high concentration of oxygen gas from the collection tank is connected to the intake line of the diesel engine by opening an air port. Fig. 2 shows the air port integrated into the intake manifold.

2.2. Zeolites used for oxygen enrichment

To achieve oxygen enrichment in the filtration device, 4A and 5A synthetic zeolite beads with a particle size range of 1.6–2.6 mm were employed as adsorbents. Fig. 3 shows the 4A and 5A zeolite types used in the experiments. The 4A and 5A zeolites used in the filtration system were commercially produced synthetic zeolite beads and were not synthesised by the authors. The materials were supplied in bead form by an industrial manufacturer and used without further modification. The molecular sizes of 4A and 5A zeolites with molecular sieve properties were 4 Angstrom (0.38 nm) and 5 Angstrom (0.48 nm), respectively. Fig. 3 shows the synthetic zeolites (4A and 5A) used in the tests. Since the 4A and 5A having the same particle sizes were purchased, they were physically almost identical in shape and size. Only the pore diameters of both zeolite types were different from each other. In addition, 4A and 5A zeolites used in the tests had the form of bead.

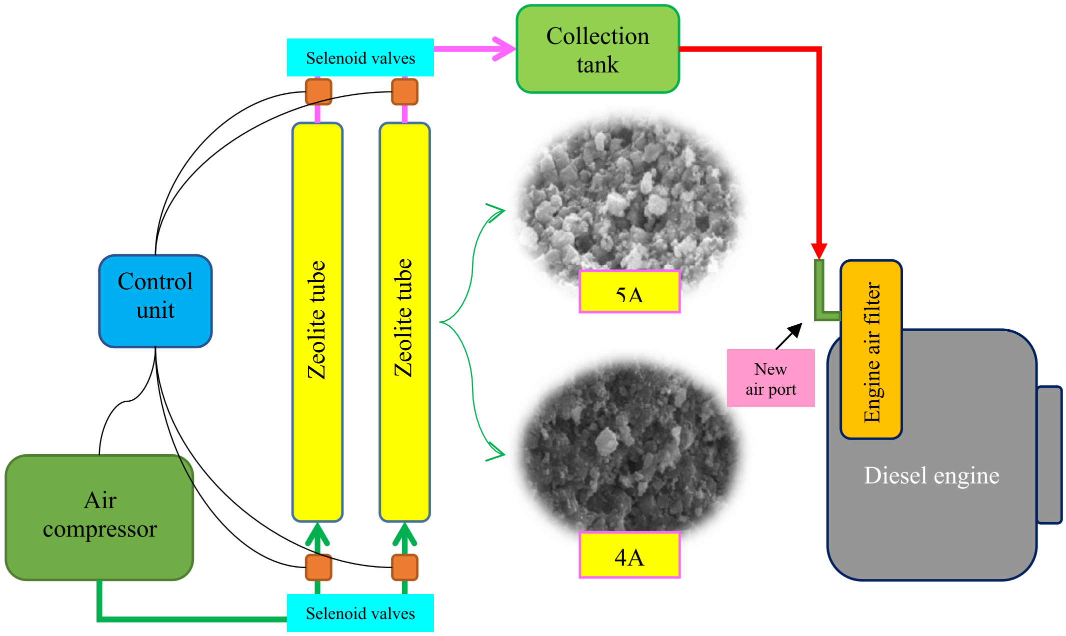


Fig. 1. Schematic representation of the filtration system.

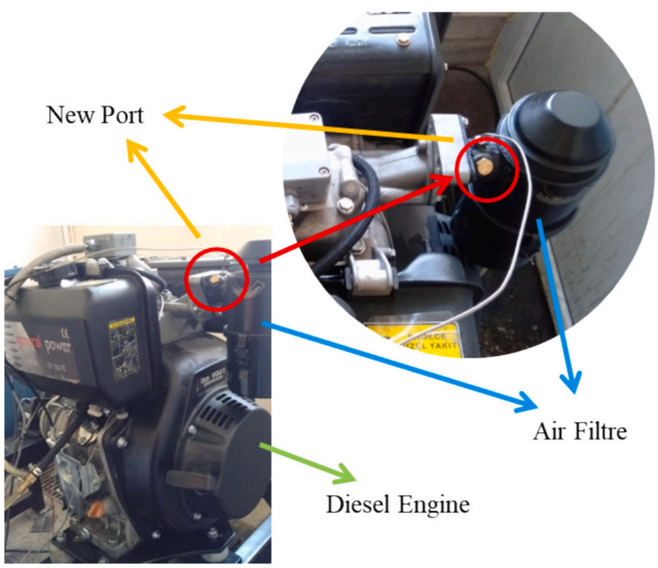


Fig. 2. Air port integrated into the intake manifold.

Fig. 3. Commercial synthetic 4A and 5A zeolite beads used in the tests.

2.3. Test equipment and procedure

In this study, air was passed through a filtration system containing zeolite to obtain an air with high oxygen and low nitrogen content, and the changes in exhaust emissions and engine performance were investigated by feeding this air to a diesel engine. For this purpose, the air hose from the filtration system was connected to the intake manifold of the engine. During the experiments, the volumetric flow rate of the oxygen-enriched air supplied from the filtration system to the engine intake manifold was kept constant at 5 L/min. This controlled flow rate, together with the regulated PSA outlet pressure, ensured a stable and repeatable intake charge throughout all test runs. Engine tests were carried out with a computer-controlled test cell. Computer control made it possible to both make torque/speed settings of the engine and measure speed (rpm), torque (Nm), load ratio (%), temperature (°C), in-cylinder pressure (kPa), exhaust gas temperature (°C), vibration (m/s^2) values of the engine. Fig. 4 shows the engine test set-up. In addition, the exhaust emissions of the engine were measured with a BOSCH brand exhaust gas analyser. CO, smoke density, HC, and NO_X values of the diesel engine were measured through this analyser. Table 1 shows the emission measurement accuracy of the gas analyser used in the tests.

During the experiments, a single-cylinder, four-stroke, air-cooled diesel engine with direct injection was utilized. Table 2 presents the mechanical specifications of the test engine. A Testo 816 audiometer was used to measure the noise levels of the engine. Noise levels were recorded from a predetermined measurement point and at a distance of 1 m from the engine.

Engine vibration values were obtained with a vibration sensor fixed on the engine block. The vibration sensor is capable of measuring engine vibration in three dimensions (X-Y-Z axes). Vibration measurements

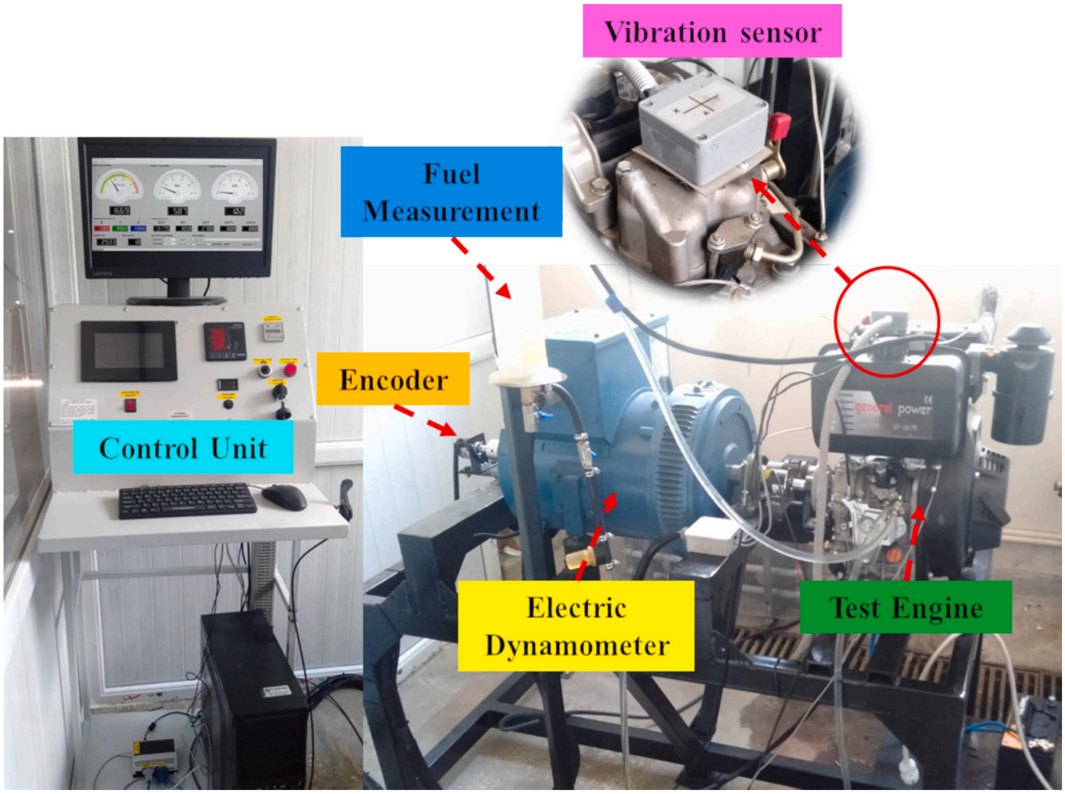


Fig. 4. Engine test set-up.

Table 1
Emission measurement accuracy of the gas analyser.

Data	Measurement extent	Measurement Accuracy
HC	0–9.999 ppm	1 ppm
CO	0–10%	0.001%
NO_X	0–5000 ppm	$\leq$ 1 ppm
CO_2	0–18%	0.01%
O_2	0–21.7%	0.01%

Table 2
Mechanical specifications of the test engine.

Number of Strokes	4
Number of Cylinders	1
Diameter/Stroke (mm)	86/70
Stroke Volume (cc)	406
Engine Speed (rpm)	3600
Maximum Power (hp)	10
Fuel Type	Diesel
Cooling Type	Air Cooled
Weight (kg)	43

were calculated using the RMS (root mean square) measure. Eq. 1 gives the equation for the time-dependent axial acceleration. Here, δ_w (m/s^2) is the weighted acceleration and T is the measurement time.

$$\delta w = \sqrt{\frac{1}{T}\int_0^T \delta^2(t)dt} \tag{1}$$

Eq. 2 shows the equation for the calculation of RMS values in three axes. Where δ_t is the composite value of the horizontal (δ_x), vertical (δ_y) and longitudinal (δ_z) vibration values (m/s^2) of the engine in RMS unit.

$$\delta t = \sqrt{\delta x^2 + \delta y^2 + \delta z^2} \tag{2}$$

Brake-specific fuel consumption values were measured in engine tests. BSFC (g/kWh) values were obtained by measuring the fuel consumption in a volumetric fuel chamber on the test set-up. Eq. 3 shows the formula used to calculate BSFC. In the study, the brake thermal efficiency (BTE) of the diesel engine was calculated based on the equation given in Eq. 4.

$$\mathrm{BSFC}(\mathrm{g/kWh}) = \frac{Fuel\ Consumption\left(\frac{g}{h}\right)}{Break\ Power\ (kW)} \tag{3}$$

$$BTE(\%) = \frac{Break\ Power\ (kW)*3600}{Fuel\ Consumption\left(\frac{kg}{h}\right)*C.V\left(\frac{kj}{kg}\right)}*100 \tag{4}$$

The testing process commenced with the evaluation of engine pollutants and operational efficiency of the diesel engine prior to the integration of the filtration system. The experiments were carried out under constant speed conditions (2000 rpm) and variable load conditions (1–3 kW). After assessing the engine emission levels and operational parameters under the specified test conditions, the filtration system was integrated into the engine. By placing 4A and 5A zeolites in the filtration system respectively, the air with increased oxygen content was fed to the engine through the filtration system and the tests were repeated under the same conditions. BSFC, EGT, power, torque, vibration, noise, in-cylinder pressure, smoke density, HC, CO and NO_X values were recorded during the tests. The test measurements were repeated five times for each condition and the final value was obtained by taking the arithmetic mean of the five measurements. The accuracy specifications of the measurement instruments used in the experimental setup are summarized in Table 3. In addition, SEM (Scanning Electron Microscopy) and EDX (Energy Dispersive X-Ray Spectrometry) analyses were performed to determine the pore structures and elemental analysis of synthetic 4A and 5A zeolites. Fig. 5 shows the Zeiss EVO MA10 device by which SEM and EDX analyses were performed.

Table 3
Accuracy specifications of the measurement instruments used in the experiments.

Measurement Device	Measured Parameter	Measurement Range	Accuracy
Computer-controlled test unit	Engine speed	0–4000 rpm	±1 rpm
Computer-controlled test unit	Torque	0–50 Nm	±0.2 Nm
K-type thermocouple	Exhaust gas temperature	0–1200 °C	±1 °C
Piezoelectric pressure sensor	In-cylinder pressure	0–200 bar	±0.5% F. S.
Testo 816 audiometer	Noise level	30–130 dB	±0.7 dB
Triaxial accelerometer	Engine vibration (X–Y–Z)	0–50 m/s^2	±0.5%
Volumetric fuel chamber	Fuel consumption		±1 ml

2.4. Uncertainty and error analysis

A comprehensive uncertainty analysis was conducted to assess the reliability of the measurements obtained throughout the experimental campaign. Since the study involved simultaneous monitoring of combustion, performance and emission parameters, the sources of uncertainty originated from both the measurement devices and the inherent variability in repeated engine operation. The accuracy specifications of the instruments used in the experiments are provided in Tables 1 and 3 and were taken as the baseline components of the uncertainty assessment. To minimise random fluctuations, each test point was repeated three consecutive times under identical operating conditions. The measured data were then averaged to represent the final reported value. The repeatability-based uncertainty was quantified using:

$$u_r = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{5}$$

where x_i denotes the individual measurements and x represents their arithmetic mean. The overall uncertainty for each parameter was then obtained by combining the device accuracy (u_a) and the repeatability component through:

$$u_c = \sqrt{u_a^2 + u_r^2} \tag{6}$$

This approach allowed the contribution of the measurement system and the engine's cycle-to-cycle variability to be evaluated simultaneously. The resulting combined uncertainties for the principal experimental outputs fell within ranges commonly reported in single-cylinder diesel engine studies. The uncertainties were calculated as approximately ±1.4% for torque, ± 1.3% for BSFC, ± 1.2% for BTE, ± 1.5% for exhaust gas temperature, and ± 1.0% for in-cylinder pressure. For emission measurements (CO, HC, NO_X and smoke opacity), the combined uncertainty was slightly higher due to sensor sensitivity and environmental influences, ranging between ±2–3%.

3. Results and discussions

3.1. Examination of zeolite microstructure and composition via SEM and EDX

Fig. 6 shows the SEM image and EDX spectrum analysis results of 4A synthetic zeolite. When EDX data were examined, it was observed that 4A synthetic zeolite contained 54.35% O, 15.37% Si, 12.4% Al, 10.61% Na, 1.05% Fe, 0.94% Mg, 0.6% Ca and K atoms. The Si/Al ratio of 4A synthetic zeolite was 1.23. Fig. 7 shows SEM images of 4A synthetic zeolite grown at different rates.

Fig. 8 shows the SEM image and EDX spectrum analysis results of 5A synthetic zeolite. EDX data showed that 5A synthetic zeolite contained 59.76 wt% O, 16 wt% Si, 12.64 wt% Al, 5.99 wt% Ca, 3.06 wt% Na, 1.83 wt% Mg, and 0.71 wt% Fe atoms. The Si/Al ratio of 5A synthetic zeolite was 1.26. Fig. 9 shows the SEM images of 5A synthetic zeolite grown at different rates.

The microstructural and compositional differences identified through SEM and EDX have a direct influence on the oxygen-enrichment behaviour of both zeolites within the PSA system. Although 4A and 5A share the same LTA aluminosilicate framework, their cation distribution differs significantly. The 4A zeolite exhibits a sodium-rich composition, whereas 5A contains a markedly higher Ca content due to partial ion exchange of Na^+ with Ca^{2+}. This exchange enlarges the effective pore opening from approximately 4.1 Å to 5.0 Å, increasing the accessibility of the α-cages and enhancing nitrogen adsorption capacity [46,47]. Since nitrogen molecules possess a higher quadrupole moment and stronger electrostatic interaction with Ca^{2+} than with Na^+, the 5A structure provides superior nitrogen uptake during the pressurisation stage of the PSA cycle. SEM images also show that 5A has a more uniform crystal morphology and well-defined cubic particles, supporting improved diffusivity. As a result, 5A removes nitrogen more efficiently, yielding a higher oxygen concentration at the outlet compared to 4A. Thus, the observed enrichment differences arise from the combined effects of cation type, pore aperture size, adsorption affinity, and microstructural uniformity.

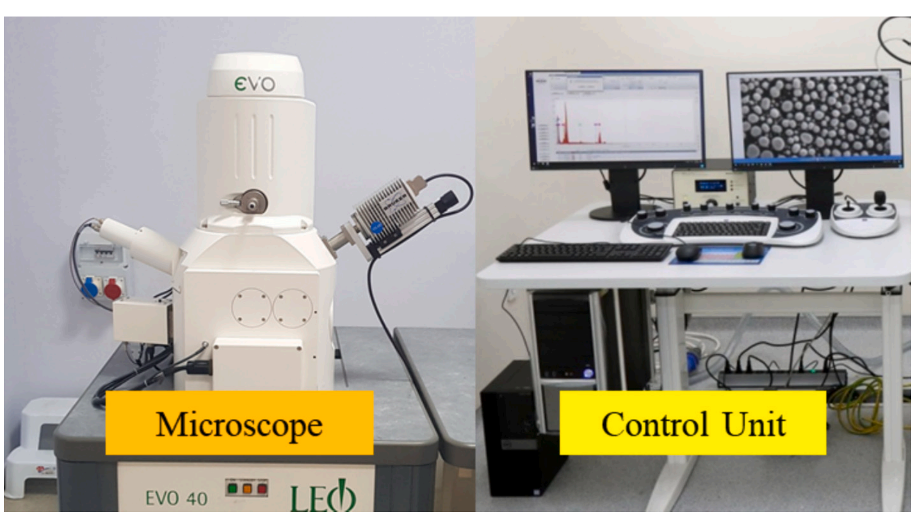
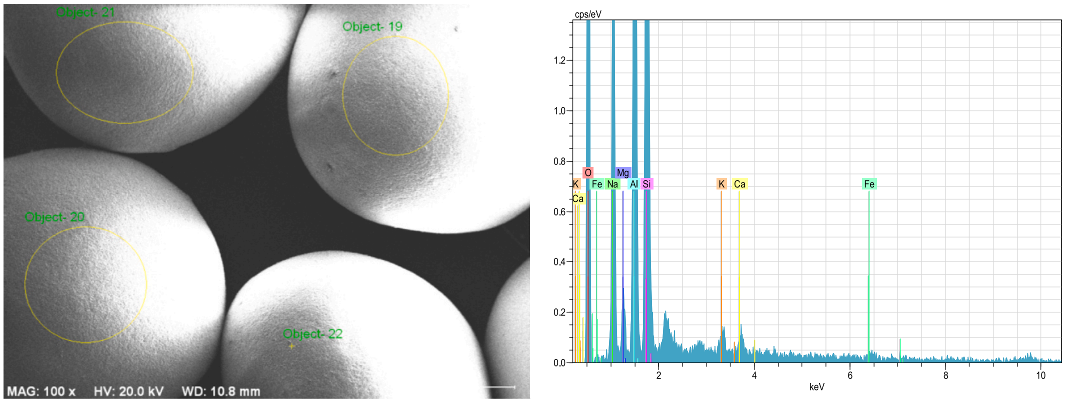
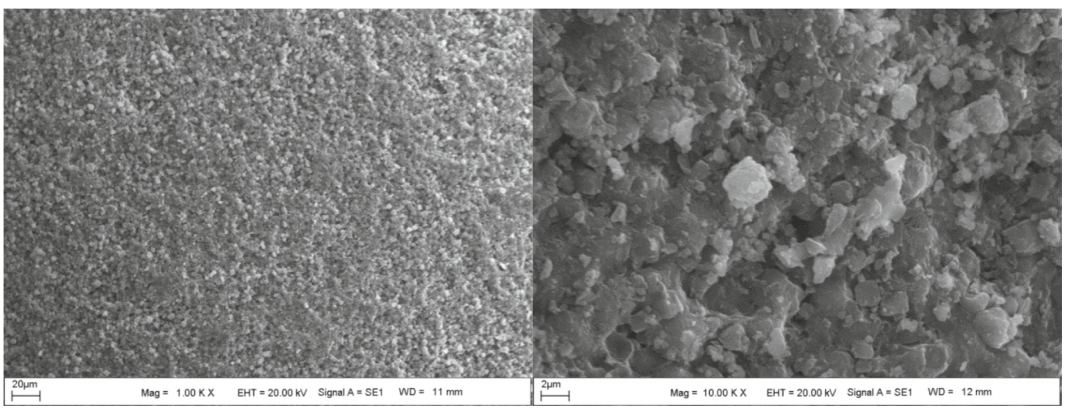


Fig. 5. The device used to perform SEM and EDX analyses.



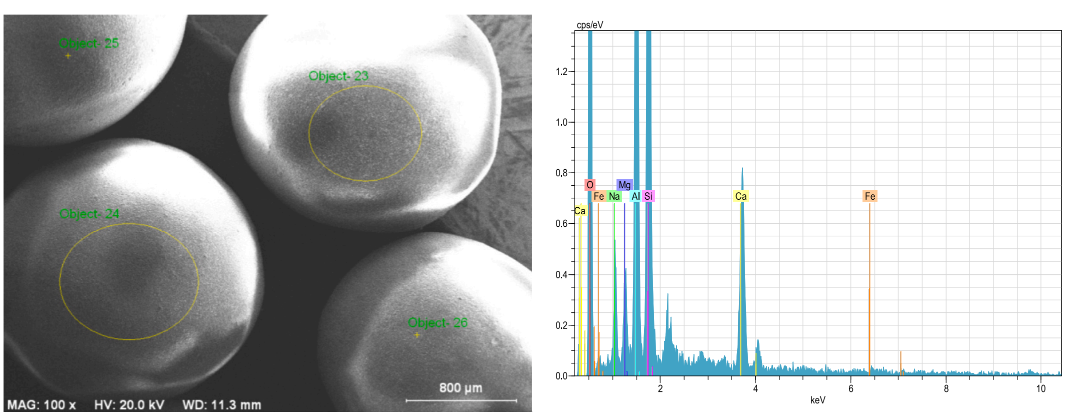
(a) (b)

Fig. 6. (a) SEM micrograph and (b) EDX spectrum of synthetic 4A zeolite at 100× magnification.



(a) (b)

Fig. 7. SEM micrograph of synthetic 4A zeolite at (a) 1000×, (b) 10,000× magnification.



(a) (b)

Fig. 8. (a) SEM micrograph and (b) EDX spectrum of synthetic 5A zeolite at 100× magnification.

3.2. Oxygen adsorption efficiency of synthetic zeolites

Fig. 10 illustrates the O_2 enrichment efficiency of the synthetic zeolites. The O_2 ratio in the test environment was 20.9%. At the outlet of the filtration system, O_2 rates due to the use of 4A and 5A synthetic zeolites were measured as 25.8% and 27.36%, respectively.

Synthetic zeolites were found to significantly increase the oxygen content. The high porosity rate and regular pore structure of synthetic zeolites were thought to be the main reasons for their high O_2 enrichment capacity. Compared to standard ambient air, 4A and 5A synthetic zeolites increased the O_2 ratio by 23.45% and 30.91%, respectively.

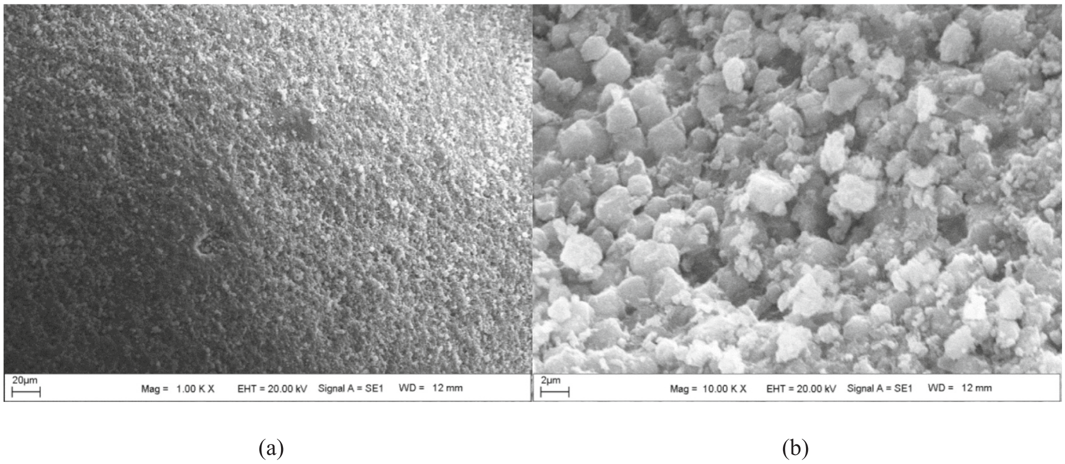


Fig. 9. SEM micrograph of synthetic 5A zeolite at (a) 1000×, (b) 10,000× magnification.

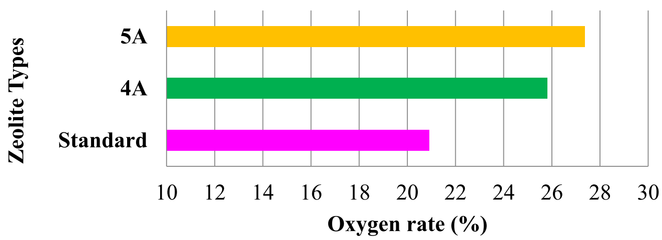


Fig. 10. Oxygen rates of air measured at the outlet of the filtration system depending on zeolite types.

3.3. Analysis results of performance parameters

- Assessment of Power and Torque Results

In ICEs, torque refers to the rotational force or torque produced by the engine. This force is the result of combustion in the engine's cylinders and is measured in Newton meters (Nm). Torque is an important criterion in determining the performance of the engine. Fig. 11 shows the characteristics of engine torque according to the type of zeolite.

As depicted in Fig. 11, an increase in load ratios resulted in a corresponding rise in engine torque. This trend is attributed to the enhancement of the combustion process, likely due to the elevated temperature at the end of combustion. A study [48], reported that the increase in engine load caused more fuel injection per cycle and this increased the in-cylinder temperature. As combustion efficiency improved, the in-cylinder pressure rose, consequently enhancing the torque generated by the engine. Experimental findings showed that the filtration system had a positive effect on engine torque. Two different zeolite types used in the filtration system had different effects on the torque values at each load level. It was thought that the filtration system increased the amount of oxygen in the CC, shortening the ignition delay, allowing the combustion process to start earlier and thus providing a more efficient combustion. Moreover, the rise in end-of-combustion pressure contributed to an increase in the torque output of the engine. Similar results were reached in the study [49] in the literature. It was determined that the use of 4A and 5A zeolites in the filtration system increased the torque values by 3.92% and 4.42%, respectively, compared to the standard case. This increase was attributed to the higher oxygen adsorption capacity of 5A synthetic zeolite in comparison to 4A. The graphs show that the effect of the filtration system became more pronounced as the engine load increased. Although it is known that the increase in engine load improves the combustion process up to a certain level, it was evaluated that at higher loads, the engine needed more fuel injections to produce the same power and therefore combustion may not be fully realised. However, it was thought that the filtration system contributed to more efficient combustion under rich mixture conditions through the additional oxygen it provided to the CC. In addition, the filtration system increased the end-of-combustion pressure, allowing more energy to be obtained from the same amount of fuel, which resulted in an increase in torque values.

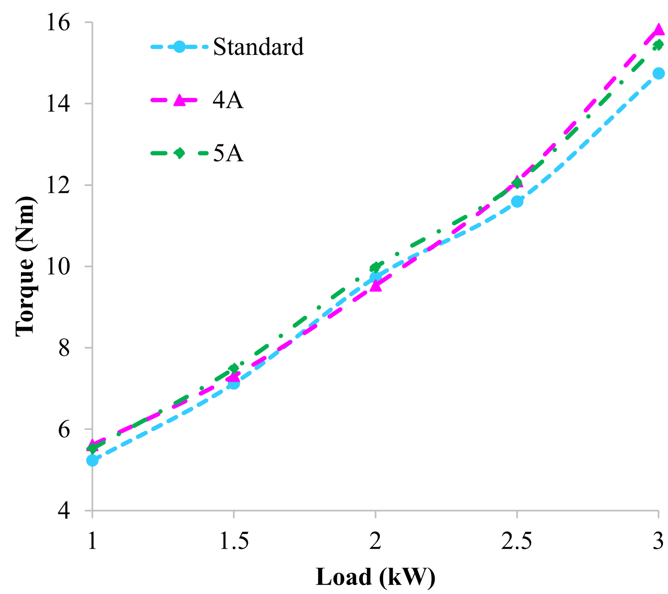


Fig. 11. Impact of zeolite type and engine load on torque.

The torque enhancements obtained with 4A and 5A zeolites are consistent with previously reported oxygen-enrichment studies. Li et al. [19] documented a 3–5% increase in torque when intake oxygen concentration was raised from 21% to 24%, while Jeevahan et al. [23] observed torque gains of approximately 4–6% for 23–27% O_2 ratios. Similar improvements were reported by Abdelaal et al. [22] for oxygen-enriched natural gas–diesel operation. The torque increases measured in the present study therefore fall squarely within the typical enhancement range produced by 2–7% absolute oxygen enrichment in the intake charge.

- Assessment of BSFC Results

BSFC is a measure of the engine's capacity to efficiently convert the potential energy of fuel into power generation. To improve engine performance, it is critical to minimise brake-specific fuel consumption while achieving the target power level. BSFC is strongly influenced by the distribution of fuel particles within the engine cylinder and the uniformity of the load inside the CC. [50]. Fig. 12 shows the effects of the filtration system filled with 4A and 5A synthetic zeolites on the BSFC values under various load conditions.

According to the data in the graph, the BSFC values decreased at load values between 1 kW and 3 kW due to the increase in the load. The increase in engine load led to a better interaction between fuel and oxygen molecules, resulting in higher in-cylinder temperatures, which improved the CC conditions and created a more stable combustion process. Furthermore, the rise in engine load was considered to enhance combustion efficiency by reducing the ignition delay period.

According to the data in Fig. 12, it was determined that the filtration system had a positive effect on the BSFC parameters across the entire load range. However, the influence of oxygen enrichment on BSFC exhibited a distinct load-dependent behaviour. At low load, the 5A zeolite achieved the lowest BSFC value, corresponding to a 4.9% reduction compared to the standard condition. In the intermediate load range of 1.5–2.0 kW, the 4A zeolite resulted in lower BSFC values than both the standard case and the 5A zeolite, with reductions of 3.1% at 1.5 kW and 3.0% at 2.0 kW. This trend aligns with the corresponding thermal efficiency behaviour presented in Fig. 14.

At higher loads, particularly at 2.5 and 3.0 kW, the 5A zeolite provided the most pronounced improvement due to its higher oxygen enrichment capacity. At 2.5 kW, the BSFC decreased from 339 g/kWh (standard) to 310 g/kWh with 5A, corresponding to an 8.6% reduction, which represents the largest improvement among all load levels. At 3.0 kW, the BSFC values for the 4A and 5A zeolites were nearly identical, both representing approximately a 4.8% reduction relative to the standard condition.

The observed reductions in BSFC were attributed to enhanced combustion efficiency under oxygen-enriched conditions. Increasing the oxygen concentration in the CC is known to shorten the ignition delay, elevate the end-of-combustion temperature, and accelerate fuel oxidation rates, thereby reducing BSFC. Similar observations regarding the acceleration of combustion and improved fuel conversion efficiency under oxygen-enriched operation have been reported in previous studies [51,52]. It is also hypothesized that the greater availability of oxygen molecules enables a higher proportion of hydrocarbons to participate in the combustion reaction, further improving combustion completeness. Accordingly, the differences observed in the BSFC values for the 4A and 5A zeolites were attributed to their varying oxygen adsorption capacities and the resulting load-specific effects on combustion behaviour.

The BSFC reductions observed in this work are comparable to findings from published oxygen-enrichment studies. Jeevahan et al. [23] reported a 7% reduction in BSFC at 27% O_2 intake concentration, while Li et al. [19] observed 3–6% improvements for modest oxygen enrichment (21–24%). Baskar and Kumar [18] similarly noted 4–7% BSFC reductions when O_2-enriched combustion improved premixed burn quality. The present results fall within, and in high-load conditions slightly exceed, the upper range of BSFC improvements reported in the literature, validating the effectiveness of PSA–zeolite–based enrichment.

- Assessment of Cylinder Pressure and HRR Results

In ICEs, the maximum in-cylinder pressure is achieved after the expansion phase. This pressure is influenced by the effectiveness of fuel-air mixing, particularly during the premixing phase, as well as the fuel-to-air ratio [53]. Fig. 13 shows the effects of the filtration system filled with 4A and 5A synthetic zeolites on the in-cylinder pressure.

As can be seen in Fig. 13, it was observed that the use of the filtration system and synthetic zeolite increased in-cylinder pressure values compared to the standard case. The data in the graph shows that the oxygen enriched air supplied to the CC by the filtration system has a significant effect on the combustion events in the cylinder. It was believed that with air with increased oxygen concentration, combustion started earlier, ignition delay reduced, fuel-rich local zones were minimised, and the fuel burns completely in the cylinder, increasing the in-cylinder temperature and pressure. Moreover, more oxygen was taken into the cylinder, caused more unburned HC to react, increased the in-cylinder pressure, and helped complete the reaction of some of the CO emissions, which are incomplete combustion or incomplete combustion products.

It was calculated that the use of 4A and 5A synthetic zeolites in the filtration system increased the in-cylinder peak pressure by 4.14% and 5.33%, respectively, compared to the standard case. The variations observed in in-cylinder pressure parameters were attributed to differences in the oxygen concentration levels of the zeolite types utilized in the filtration system. In this context, it was noted that the greater oxygen enrichment capacity of 5A zeolite, compared to 4A, resulted in higher in-cylinder pressure values when 5A was employed.

In addition to the increase in peak pressure, the oxygen-enriched cases exhibited notable changes in combustion phasing and duration. Examination of the crank-angle–resolved pressure data revealed that the

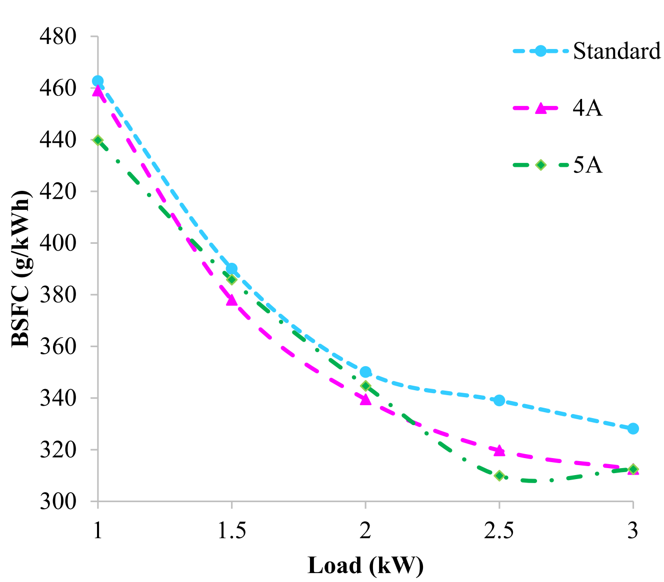


Fig. 12. Impact of zeolite type and engine load on BSFC.

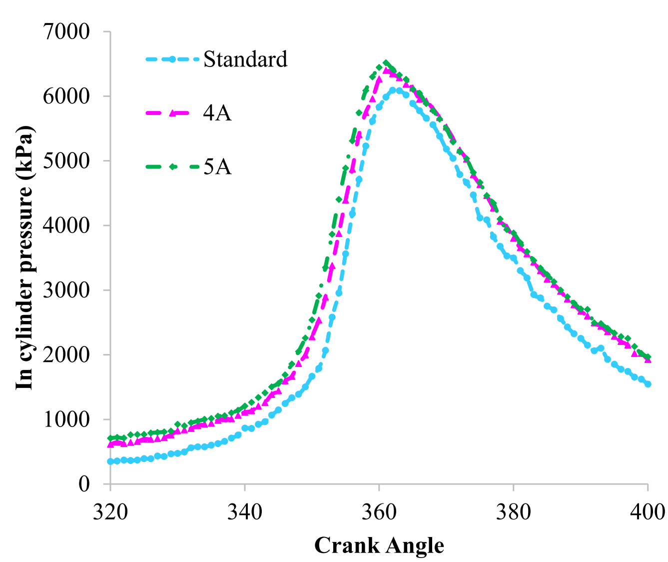


Fig. 13. Variations of in-cylinder pressure values depending on zeolite types and crank angle.

maximum in-cylinder pressure of the standard engine occurred at 362 ^{o}CA, whereas the 4A and 5A zeolite cases reached their respective peak pressures approximately 1 ^{o}CA earlier (361 ^{o}CA). This advance in peak-pressure location indicates a shorter ignition delay and a more rapid premixed combustion phase, driven by the enhanced reactivity associated with the higher oxygen molar fraction in the intake charge. Moreover, the sharper pressure decay following the peak in the 4A and especially the 5A case suggests that the diffusion burn phase is completed over a narrower crank-angle interval, confirming a reduction in overall combustion duration.

The increase in oxygen concentration from 21% in standard air to 27.36% with the 5A zeolite modifies the global fuel–air equivalence ratio (φ), as the injected fuel mass remains constant while the oxygen content per unit mass of air rises. Consequently, the equivalence ratio decreases, producing a slightly leaner overall mixture. This shift toward a lower φ enhances oxidation efficiency, strengthens the premixed heat-release stage, and contributes to the higher peak cylinder pressures and shorter combustion duration observed under oxygen-enriched operation.

Fig. 14 presents the apparent heat release rate (AHRR) variations of the diesel engine under standard operation and during the use of 4A and 5A synthetic zeolites at a representative engine load of 3 kW. The AHRR curves were derived from the measured in-cylinder pressure traces using a single-zone first-law formulation, assuming ideal gas behaviour and neglecting heat transfer and blow-by losses. Therefore, the results represent the apparent heat release characteristics of the combustion process. The oxygen-enriched operation with 4A and 5A zeolites leads to a noticeable advancement in the start of combustion compared to the standard condition. The earlier rise in the AHRR curves indicates a shorter ignition delay, which is consistent with the increased oxygen molar fraction supplied to the combustion chamber. This behaviour aligns with the peak pressure positions shown in Fig. 13, where the maximum pressure occurs at 361 ^{o}CA for both zeolites, compared to 362 ^{o}CA in the standard case.

Although the peak AHRR magnitude of the standard case is slightly higher, the 4A and 5A zeolite cases exhibit a more concentrated and earlier heat-release profile around top dead centre (TDC). This shift reflects a more rapid oxidation of fuel during the premixed phase and a more compact combustion event. The earlier phasing and improved combustion completeness under oxygen-enriched conditions explain the higher in-cylinder peak pressures and improved thermal efficiency observed in the 4A and 5A zeolite experiments. These findings are consistent with theoretical expectations: increasing the oxygen concentration in the intake charge enhances the availability of oxidiser molecules, reduces the ignition delay, and accelerates the premixed heat-release stage. As a result, the combustion process becomes more efficient, even if the peak AHRR magnitude does not exceed that of the standard case. The compact and advanced heat-release behaviour under oxygen-enriched operation ultimately contributes to the higher peak pressures and improved performance outcomes measured in the study.

The observed advancement in combustion phasing and increase in peak pressure are consistent with documented effects of oxygen-enriched combustion. Li et al. [19] reported similar earlier heat-release phasing and Pmax rises of 3–6% when intake oxygen was increased to 24%. Abdelaal et al. [22] likewise demonstrated reduced ignition delay and elevated peak pressure at 25–27% O_2 levels. The magnitude and direction of combustion phasing shifts in this study therefore align closely with established oxygen-enrichment behaviour in the literature.

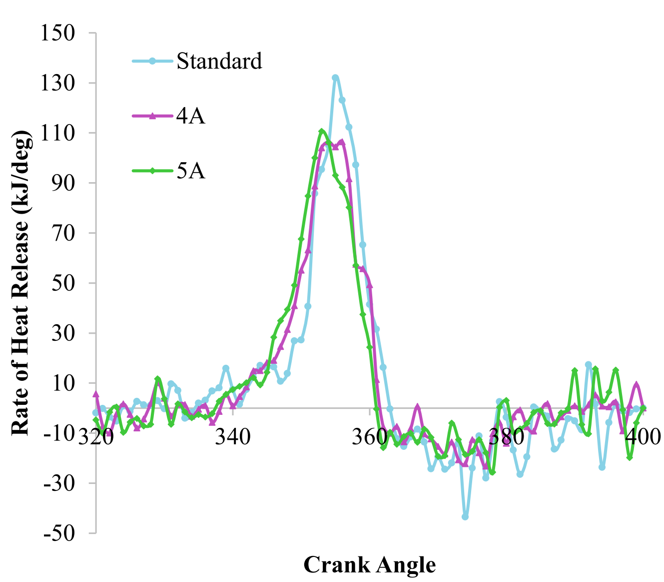


Fig. 14. Apparent heat release rate variations for different zeolite types as a function of crank angle.

- Assessment of BTE Results

BTE in ICEs serves as a performance metric that quantifies the proportion of fuel energy converted into mechanical work by the engine. This parameter is a key indicator to analyse the energy conversion capacity of the engine. Fig. 15 represents the variations of BTE values according to engine load and zeolite types used.

Fig. 15 shows that the increase in engine load led to an increase in BTE values. In all cases where the standard and filtration system were applied, the increase in load led to an increase in BTE values. At a constant operating speed, supplying additional fuel to the combustion chamber to enhance engine load resulted in a rise in the end-of-combustion temperature and an improvement in combustion efficiency. This increase in combustion efficiency allowed the fuel burned in the cylinder to produce a higher power and led to an increase in BTE values. Studies in the literature have reported such changes, as well [52].

The use of the filtration system was found to produce an increasing trend in the BTE values. While this change was not noticeable under low engine load conditions, it became more pronounced under high load conditions. Especially at 2.5 kW load conditions, a significant increase was recorded in BTE values. Under these conditions, BTE values increased by 6.04% and 9.39%, respectively due to the use of 4A and 5A synthetic zeolites. When all load conditions were evaluated, the average BTE increase rates for 4A and 5A synthetic zeolites were 3.62% and 4.61%, respectively. This increase was attributed to the rise in in-cylinder pressure and temperature, as the higher oxygen concentration facilitated a greater number of fuel molecules participating in the combustion process. The elevated in-cylinder pressure at a constant engine speed contributed to an increase in both torque and power

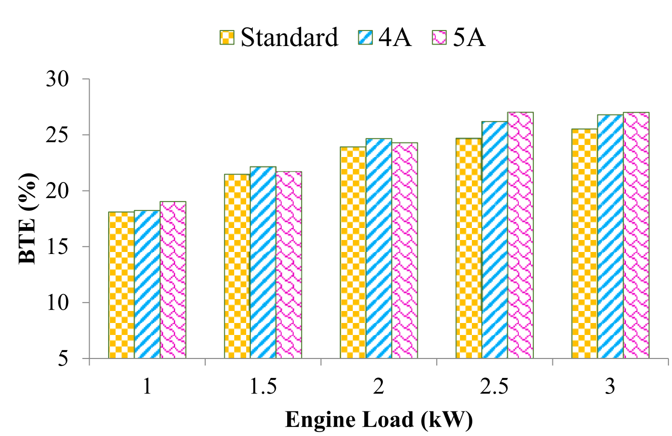


Fig. 15. Impact of zeolite type and engine load on BTE.

output. Additionally, the implementation of the filtration system resulted in a slight reduction in fuel consumption. These two factors were identified as the primary contributors to the enhancement of BTE values.

The average BTE improvements obtained in this study agree well with the efficiency gains documented in prior oxygen-enrichment investigations. Li et al. [19] reported 3–5% increases in thermal efficiency at 24% O_2, while Jeevahan et al. [23] observed 4–7% increases at 23–27% O_2. Abdelaal et al. [22] similarly found approximately 4% improvement with oxygen-enriched combustion. The maximum BTE enhancement obtained with 5A zeolite in the present study slightly exceeds the upper boundary of these reported ranges, reflecting the higher and more stable oxygenating capability of the PSA–zeolite system.

- Assessment of Exhaust Gas Temperature Results

EGT serves as an indicator of how effectively the heat energy stored in the fuel is utilized. Elevated EGT values signify lower thermal efficiency, often resulting from incomplete combustion or inefficient conversion of released energy into useful work. This inefficiency leads to excess heat being retained in the exhaust gases, thereby increasing exhaust temperature. In order to improve engine performance, EGT should be kept as low as possible [50]. Fig. 16 shows the effects of the filtration system filled with different zeolite types on the EGT values.

An analysis of Fig. 16 revealed that EGT values exhibited an upward trend as the load ratio increased. It is stated in the literature [48] that at low engine loads, in-cylinder temperatures remain at low levels due to less fuel combustion. With the increase in engine load, a greater amount of fuel was injected to maintain the same power output, resulting in a rise in in-cylinder peak pressure and end-of-combustion temperatures. The data in the graph shows that the filtration system caused an increase in EGT values at all load levels. It was found that the filtration system increased the amount of oxygen in the CC, which shortened the ignition delay and increased in flame temperature. As the combustion process was more efficient, it was thought that more heat energy was released. Oxygen concentration studies in the literature also support similar results [48,51].

The incorporation of 4A and 5A synthetic zeolites into the filtration system led to an increase in EGT values by 5.61% and 7.04%, respectively, in comparison to the standard condition. The reason for the different values obtained in the EGT results was thought to be the different degrees of oxygen concentration of 4A and 5A synthetic zeolites used in the filtration system. The rise in EGT values was found to be consistent with the oxygen enrichment capacity of the zeolites. A previous study [54], reported that flame velocity and HRR increased with the increase in oxygen concentration in the CC. This variation in EGT values was attributed to the higher specific surface area of 5A compared to 4A, along with its more favorable pore size distribution for nitrogen adsorption.

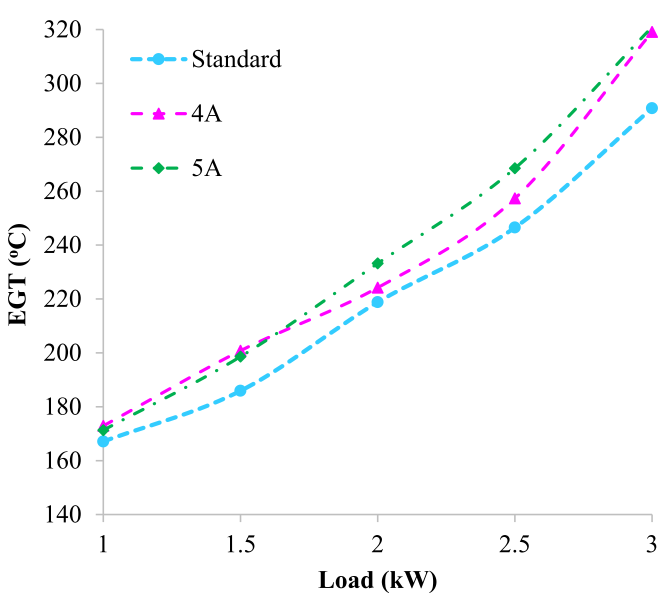


Fig. 16. Impact of zeolite type and engine load on EGT.

- Assessment of Engine Vibration Results

Vibrations in ICEs are caused by the reciprocating motion of engine components, rotational moments and the combustion process in the CC. Vibration and engine noise takes place by fluctuations in cylinder pressure, especially during the combustion process. Fluctuations in cylinder pressure are the primary source of vibrations in engine components, including the connecting rod, piston, and cylinder head [55]. Although the vibrations caused by combustion are controlled to some extent by other parts of the engine, the combustion process in the CC is considered to be the most important source of engine vibrations [56]. Fig. 17 shows the effects of using the filtration system filled with different types of zeolites on the vibration values of the engine.

As seen in Fig. 17, a similar increase was observed in vibration values as the engine load increased. It was determined that the rise in engine load resulted in a greater fuel supply to the combustion chamber, which elevated in-cylinder temperature. Consequently, the higher combustion pressures generated increased vibration energy. The test results revealed that the filtration system increased the engine vibration values. This system affected the combustion characteristics due to the oxygen-rich air provided to the engine. Combustion with oxygen-enriched air was considered to reduce the ignition delay, elevate the flame temperature, and consequently lead to higher peak temperature and pressure values within the cylinder. Increased in-cylinder pressure was predicted to increase the forces acting on the moving components of the engine and thus elevate the vibration level in the engine block. Similar studies in the literature have also reported that vibration values increase in this way [57]. The use of 4A and 5A synthetic zeolite in the filtration system increased the vibration values by 2.3% and 3.1% respectively compared to the standard case. There was a parallelism between the oxygen concentrating capacity of zeolites and the increase in vibration values (Fig. 17). It was determined that the zeolite that provided the most significant change in vibration values also offered the highest oxygen concentration.

- Assessment of Noise Results

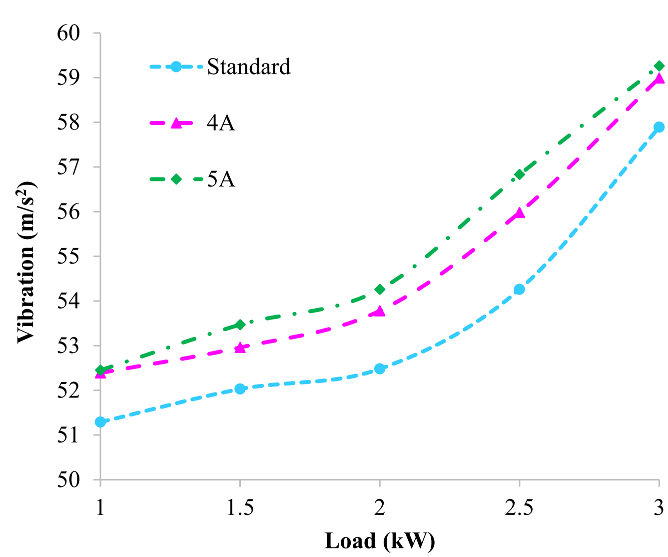


Fig. 17. Impact of zeolite type and engine load on engine vibration.

The noise level in ICEs is directly related to the mechanical forces resulting from combustion characteristics such as in-cylinder pressure, rate of pressure rise and HRR. The increase in in-cylinder pressure acts on the CC walls, causing vibrations in the engine block, which are felt as noise in the surrounding environment [58]. The variation in cylinder pressure and heat release dynamics significantly contribute to the generation of engine noise. The noise sources of ICEs are broadly divided into three groups: combustion noise, mechanical noise, and exhaust noise. Increasing the heat release rate leads to a more severe occurrence of combustion noise [59]. Fig. 18 shows the effects of the filtration system filled with different types of zeolites on the noise levels in detail. An analysis of the results revealed that the noise level increased as the engine load rose. At low engine loads, in-cylinder pressure remained relatively low; however, as the engine load increased, the amount of fuel injected into the cylinder also rose. This led to a richer mixture in the CC and an increase in in-cylinder pressure. A previous study [59] reported that with the increase in the load applied to the engine, a higher heat release rate was obtained and thus, combustion noise increased. It was also believed that increased engine load increased the frictional forces between the moving components of the engine, thereby increasing the overall engine noise.

The use of 4A and 5A synthetic zeolites in the filtration system elevated noise levels by 1.1% and 1.4%, respectively compared to the standard case. This elevation was thought to be attributed to the shortening of the ignition delay stemming from the increased oxygen concentration in the CC as well as the increase in the combustion pressure, the increase in the heat releasing as a result of the improvement in combustion efficiency, and the resulting increase in combustion noise. The change in noise values progressed in parallel with oxygen concentrations, and higher oxygen concentrations made the increase in noise levels more pronounced.

- Assessment of Thermal İmages

Thermal imaging analyses of ICEs offer significant benefits for improving engine performance and reducing exhaust emissions. Through precise detection of temperature distributions on the engine surface, issues such as combustion irregularities, temperature variations between cylinders, and cooling system-related problems can be effectively identified. This contributes directly to improved fuel efficiency and enhanced operational stability of the engine. Furthermore, optimized combustion prevents incomplete or excessive combustion, significantly reducing harmful exhaust emissions such as CO, NO_X, and HC. Fig. 19 presents thermal images illustrating the effects of the filter system, utilizing standard and zeolite-based filters, on engine block temperatures.

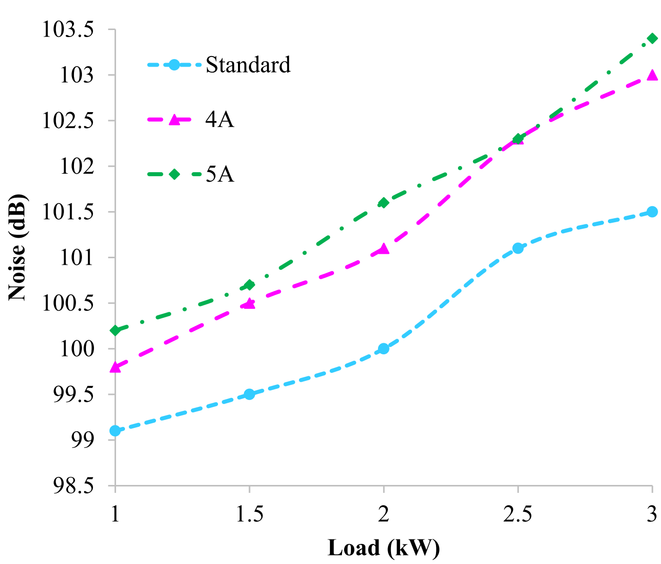


Fig. 18. Impact of zeolite type and engine load on engine noise.

The temperature distribution images were captured under conditions where the engine load was set to 3 kW. Under standard engine conditions, the peak engine block temperature was recorded as 70.8 °C. However, when the filter system incorporated 4A and 5A zeolite types, the temperature increased to 73.5 °C and 74.6 °C, respectively. Compared to the standard condition, the use of synthetic 4A and 5A zeolites in the filter device increased the peak engine block temperature by 3.81% and 5.37%, respectively. The observed increase in temperature is attributed to the enhancement of combustion efficiency and the rise in post-combustion temperatures due to the higher oxygen concentration during the combustion process. A higher oxygen content improves combustion efficiency by promoting more complete and rapid fuel oxidation. Consequently, this leads to elevated combustion temperatures, exposing engine components, particularly the engine block, to greater thermal loads. Furthermore, the increasing trend in engine block temperature has been found to be consistent with the variations in BTE and EGT values.

3.4. Analysis results of exhaust emissions

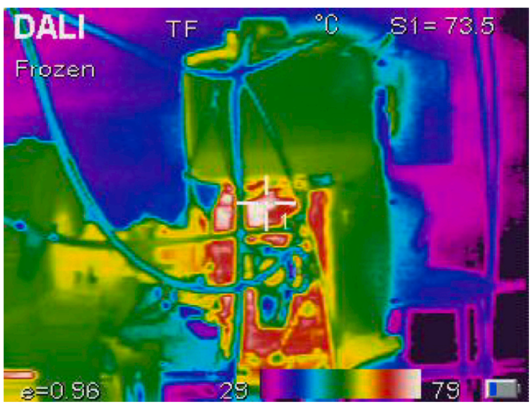
- Evaluation of Carbon Monoxide Emissions

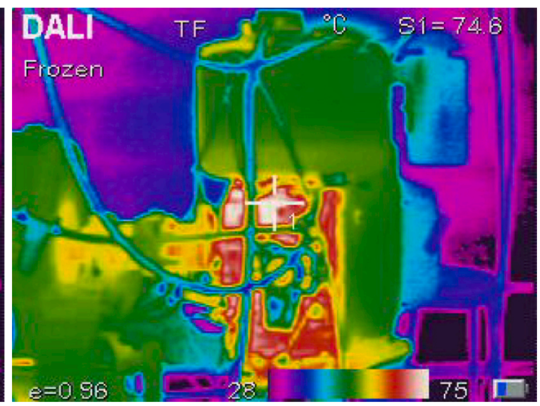
The formation of CO emissions is associated with the destabilisation of combustion reactions when the engine is running at low load. This is usually caused by low local temperatures inside the cylinder and areas where the air-fuel mixture is inadequate. At high engine loads, the enrichment of the fuel mixture and the lack of oxygen required for the complete conversion of carbon to carbon dioxide is another cause of CO formation [60]. Higher oxygen levels in the CC improve the oxygen-fuel balance in fuel-rich regions, resulting in more efficient premixed combustion. This allows carbon molecules to burn more and CO_2 is produced instead of CO, making the combustion process more efficient [61]. Fig. 20 shows the effects of the filtration system filled with different types of zeolites on CO emission.

As seen in Fig. 20, it was determined that as the engine load increased, CO emissions initially remained constant but then started to increase. Inadequate in-cylinder temperatures at low engine loads reduced combustion efficiency, limited CO_2 formation and increased CO emissions. An increase in engine load generally improves combustion efficiency by increasing the in-cylinder temperature and as a result, CO emissions are expected to decrease. However, as the engine load increases, a greater amount of fuel is supplied to the CC, resulting in the formation of locally rich fuel-air mixtures. Due to the lack of oxygen in these regions, CO could not be fully converted to CO_2, resulting in an increase in CO emissions. There are studies with similar findings in the literature supporting this situation [12].

According to the test results, it was determined that the filtration system had a significant effect in reducing CO emissions. As the engine load increased, a significant decrease was observed in CO emissions, and the largest decrease occurred at the highest engine load level. It was observed that the fuel delivery to the CC increased as the engine load rose [62]. It was considered that the higher fuel quantity led to rich combustion conditions, extending the ignition delay period and causing incomplete combustion. This process resulted in a reduction in the end-of-combustion temperature, consequently leading to an increase in CO emissions. The filtration system was found to enhance combustion efficiency and shorten the ignition delay by supplying oxygen-enriched air to the CC, thereby elevating the end-of-combustion temperature. It was also thought that CO_2 oxidation reactions took place more efficiently with the provision of sufficient oxygen, resulting in a decrease in CO emissions. There are similar results supporting this situation in the literature and various studies have obtained results parallel to these findings [49,62]. The use of synthetic 4A and 5A zeolites in the filtration

(a)





(b) (c)

Fig. 19. Impact of zeolite type on engine block temperature (a) standard, (b) 4A zeolite, (c) 5A zeolite.

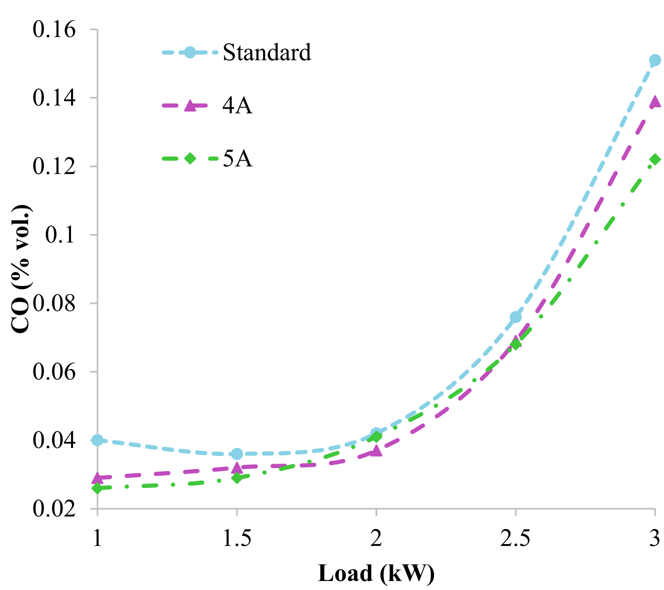


Fig. 20. Impact of zeolite type and engine load on CO emission.

system reduced CO emissions by 13.53% and 17.31%, respectively, compared to the standard case. The results indicated that 5A synthetic zeolite with higher oxygen enrichment capacity reduced CO emissions more. More O_2 concentration in the CC reduced CO emissions, which is an incomplete combustion product. Increased O_2 content was also thought to improve combustion efficiency and thermal efficiency, leading to reduced CO emissions. Benchmarking with previous studies shows that the CO reductions obtained in this work are comparable with the moderate-range improvements reported for similar oxygen-enrichment levels. For instance, Baskar & Kumar [18] reported reductions of 20–30% for 24–27% O_2, while Li et al. [19] reported 15% reduction at 24% O_2. Considering that our enrichment levels were achieved without bottled O_2 but solely through PSA–zeolite adsorption, the observed reductions align well with published results.

- Evaluation of Hydrocarbon Emissions

HC emissions are caused by incomplete combustion of fuel and vaporisation processes in the fuel system. The main factors in the formation of HC emissions are liquid fuel remaining in the cylinder, leakage of oil into the CC, leaks in the valve seats, and cold operating conditions. In addition, when flames in the CC hit the cold cylinder walls, this causes the flame to extinguish, which reduces the efficiency of fuel oxidation reactions and increases HC emissions [29]. Fig. 21 shows the effects of the filtration system filled with different types of zeolites on HC emissions.

The test results indicated that as the engine load increased, HC emissions initially remained at a constant level but started to increase after a certain point. It is indicated that as engine load increases, the fuel delivery to the cylinder rises, leading to an elevation in in-cylinder temperatures [63]. These modifications were anticipated to enhance combustion reactions, promoting more efficient fuel combustion within the cylinder and stabilizing HC emissions. However, the increased fuel injection limited the availability of oxygen necessary for ignition, and

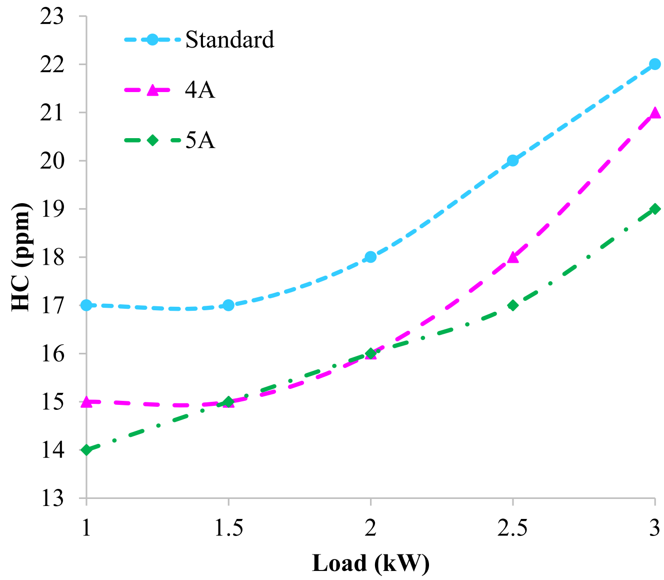


Fig. 21. Impact of zeolite type and engine load on HC emission.

the failure to achieve a homogeneous air-fuel mixture resulted in incomplete combustion, ultimately leading to elevated HC emissions. Studies with results similar to such findings are available in the literature [12,48].

The reducing effect of the filtration system on HC emissions was clearly observed in the graphs. It is well established that an increase in engine load corresponds to a greater fuel injection into the cylinder. This increase leads to an increase in the combustion time, so that combustion reactions need to continue for a longer period of time [62]. It was thought that with the use of the filtration system, the combustion process started earlier, and the ignition delay reduced due to the higher O_2 concentration. It was suggested that this system improved HC emissions by helping the complete combustion of the fuel in the CC. In addition, it was thought that a homogeneous air-fuel mixture was obtained by elevating the oxygen level in the CC, which increased the combustion efficiency, elevated temperature of the CC and caused a decrease in HC emissions. Results similar to these findings have been also observed in [64] studies in the literature. The use of synthetic 4A and 5A zeolites in the filtration system reduced HC emissions by 9.84% and 13.83%, respectively, compared to standard conditions. The fact that 5A has a higher oxygen concentrating capacity than 4A led to a larger reduction in these emissions. This was thought to be associated with the fact that the molecular structure of 5A was more complex and the pore diameters were more suitable for the oxygen concentration process. The HC reductions observed in this study fall within the range reported by earlier oxygen-enrichment studies. Li et al. [19] reported 10–18% HC reduction at 24% O_2, while Jeevahan et al. [23] observed 23% reduction at 27% O_2. Therefore, the improvements achieved with PSA-generated oxygen enrichment are consistent with published findings.

- Evaluation of Smoke Density

Smoke emissions, a common type of emission in diesel engines, usually occur as a consequence of incomplete combustion. These emissions are concentrated in the middle stages of the fuel injection process, in the rich regions of the high temperature A/F mixture [65]. Smoke generation is influenced by engine operating conditions, CC design, and the characteristics of the fuel utilized. [66]. Furthermore, inhomogeneous mixtures are one of the main sources of smoke emissions [48]. Fig. 22 shows the effects of the filtration system filled with synthetic 4A and 5A zeolites on the smoke density.

An evaluation of the test data revealed a substantial increase in smoke emissions as the engine load increased. Especially after 2.5 kW engine load, a sharp increase was observed in emissions. This increase was thought to be the result of the increase in the amount of fuel injected into the cylinder due to the increase in engine load, the formation of richer fuel zones and incomplete combustion. As the engine load increased, more fuel was injected for the same amount of air, leading to lower oxidation reactions and triggering an increase in smoke emissions. These results are compatible with similar findings reported in the literature [12].

As a result of the emission measurement tests, it was determined that the use of the filtration system resulted in a reduction in smoke emissions at all load levels. The most significant reduction was observed when the engine was operating at the highest load. It was considered that as engine load increased, the volume of fuel injected into the cylinder also rose, leading to a reduction in the air-to-fuel ratio and a delay in the combustion process. The filtration system provided a higher oxygen concentration in the cylinder, allowing the combustion process to start earlier and reducing the ignition delay. This indicated that oxygen enriched air promoted complete combustion and contributed to the reduction of smoke emissions. The use of synthetic 4A and 5A zeolites in the filtration system reduced smoke density by 14.48% and 17.42%, respectively, compared to the standard case. It was observed that the rise in oxygen enrichment rate was directly associated with a reduction in smoke density levels. The increased oxygen supply to the CC was thought to minimise locally rich fuel-air mixing zones, facilitating more complete hydrocarbon combustion and elevating the combustion reaction temperature. This, in turn, enhanced combustion efficiency, leading to a decrease in smoke density. Furthermore, 5A zeolite exhibited a more uniform molecular structure than 4A and possessed pore sizes better suited for nitrogen adsorption. Compared to published research, the smoke reductions obtained in this study are similar or slightly higher than the values reported in earlier works. Abdelaal et al. [22] reported 10–15% reduction for 21–27% O_2. The somewhat larger improvement in the present study may be attributed to the continuous and stable enrichment level characteristic of PSA-based systems.

- Evaluation of Nitrogen Oxide Emissions

NOX emissions in combustion processes primarily originate from three sources: thermal NO_X, fuel NO_X, and prompt NO_X. Thermal NO_X formation is considered the predominant source of NO_X emissions in the cylinder, primarily due to the elevated temperature conditions during

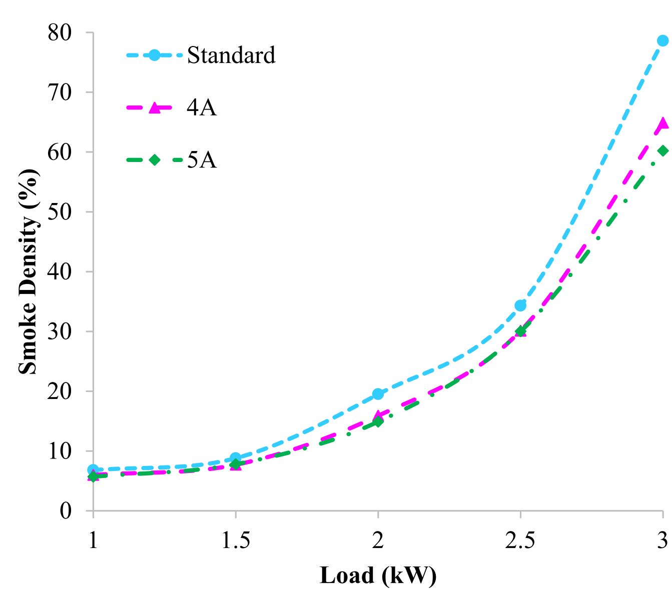


Fig. 22. Impact of zeolite type and engine load on smoke density.

combustion. The formation rate of NO_X is primarily influenced by the combustion flame temperature, the duration nitrogen molecules remain at this temperature, and the oxygen concentration within the CC. [67]. NO_X emissions vary depending on factors such as combustion temperature, local oxygen concentration, and residence time [63]. During combustion in the cylinder, oxygen atoms dissociate at high temperatures, initiating chain reactions to oxidize nitrogen molecules to NO and NO_2. Consequently, NO_X formation is significantly affected by local temperature, the concentration of oxygen and nitrogen atoms, and the duration available for oxygen-nitrogen reactions [68]. Fig. 23 shows the effect of the filtration system filled with different synthetic zeolites on NO_X emissions.

Analysis of the test data indicated that NO_X emissions initially remained stable with increasing engine load but subsequently decreased in proportion to the load. At low engine loads, in-cylinder temperatures remained relatively low, which was believed to restrict NO_X formation. As engine load increased, a greater amount of fuel was introduced into the cylinder, resulting in a rise in the end-of-combustion temperature [63]. Furthermore, the increase in engine load improves combustion efficiency. It is well established that the temperature at the end of combustion plays a crucial role in NO_X emission formation. Based on this premise, NO_X emissions were anticipated to rise with increasing engine load; however, experimental results indicated a decline in NO_X emissions as the load increased. This phenomenon can be attributed to the reduction in the air-fuel ratio entering the cylinder as engine load rises [69]. It was also suggested that with increasing engine load, the oxygen concentration in the CC decreased, resulting in increased CO emissions. This was supported by the fact that in the tests, the peak of CO emissions coincided with the period when the engine load was the highest.

As a result of the tests with the filtration system, it was determined that NO_X emissions increased at all engine loads. The filtration system containing zeolite increased the amount of oxygen in the CC of the engine, shortened ignition delay, and increased the flame temperature. It has been previously reported that higher flame temperature increased NO_X emissions [54]. The introduction of oxygen-enriched air into the cylinder via the filtration system enhanced the combustion process, elevating the end-of-combustion temperature and creating the conditions required for nitrogen and oxygen molecules to react and form NO_X compounds. Consequently, this resulted in an increase in NO_X emissions. The use of synthetic 4A and 5A zeolites in the filtration system increased NO_X emissions by 10.46% and 15.37%, respectively, compared to the standard case. Both 4A and 5A zeolites were found to contribute to an increase in NO_X emissions. The oxygen concentration within the combustion chamber was considered a key factor influencing NO_X formation. Since 5A zeolite exhibited a greater oxygen enrichment capacity, it resulted in a more pronounced rise in NO_X emissions. It was suggested that the differences in NO_X emissions were caused by factors such as channel structure, pore diameter, Si/Al ratio, and molecular structure of the zeolites. The 5A zeolite was thought to have a more regular channel structure and a higher porosity rate compared to 4A and therefore have a higher oxygen concentrating capacity. Increases in NO_X of 10–60% under oxygen-enriched operation are well documented in the literature [18,22,23]. The present study reported NO_X increases of 10.46% (4A) and 15.37% (5A), which fall at the lower bound of previously published ranges. This is consistent with the moderate enrichment levels produced by the PSA-zeolite system and the relatively stable combustion phasing observed in the tests. The increase in NO_X emissions observed under oxygen-enriched conditions indicates that, in practical engine applications, appropriate NO_X reduction technologies such as SCR or EGR systems may be required to ensure compliance with emission limits.

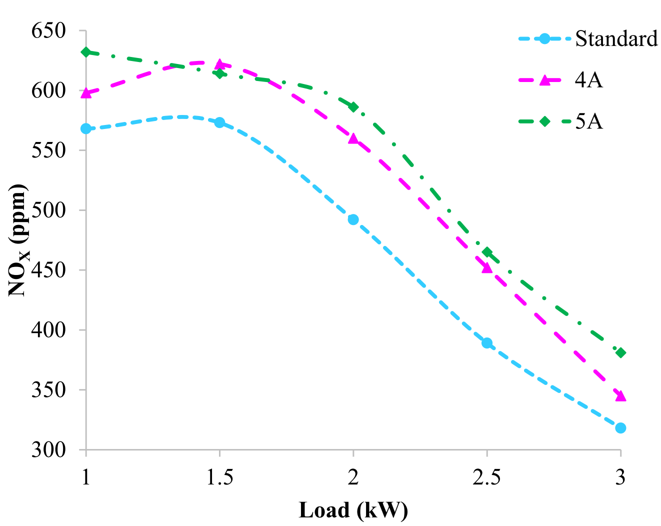


Fig. 23. Impact of zeolite type and engine load on NO_X emission.

4. Conclusions

In this research, a filtration mechanism utilizing the PSA technique and synthetic zeolites was developed, and its impact on the exhaust emissions and performance parameters of a diesel engine was evaluated following its integration into the system. Unlike previous oxygen-enrichment studies that rely on bottled oxygen or membrane systems, the present work demonstrates (for the first time) a continuously operating PSA-based enrichment unit using synthetic 4A and 5A zeolites directly coupled to an engine intake. The use of these two different synthetic zeolites in the filtration system resulted in different O_2/N_2 ratios fed to the CC of the engine. The results obtained as a result of the tests can be summarized as follows:

1. By using synthetic 4A and 5A zeolites in the filtration system operating with the PSA method, the nitrogen molecule in the air was reduced and the oxygen ratio was increased.
2. According to the O_2 measurements obtained from the outlet of the filtration system, synthetic 4A and 5A zeolites provided air outlet containing 25.8% and 27.36% O_2, respectively.
3. When compared to the standard condition, the integration of 4A and 5A zeolites into the filtration system led to the following changes in engine performance and emissions. Averaged over all load conditions, torque increased by 3.92% (4A) and 4.42% (5A), BSFC decreased by 3.46% and 4.18%, and BTE increased by 3.62% and 4.61%, respectively. Substantial emission reductions were also observed: CO decreased by 13.53% and 17.31%, HC by 9.84% and 13.83%, and smoke density by 14.48% and 17.42% with 4A and 5A, respectively. In-cylinder peak pressure increased by 4.14% (4A) and 5.33% (5A), consistent with enhanced combustion phasing. The only adverse effect was the increase in NO_X emissions (10.46% and 15.37%), attributable to higher flame temperature and oxygen availability. These quantified improvements demonstrate that the PSA–zeolite system produced performance gains of practical and measurable significance rather than merely reproducing general expectations of oxygen-enriched combustion.

Overall, the PSA-based filtration system demonstrated a continuous oxygen enrichment capability, and both synthetic zeolites improved combustion behaviour, engine performance, and most emission parameters compared with the standard condition. Although the 5A zeolite provided the highest oxygen concentration and therefore produced the largest overall improvements when results were averaged across all loads, the experimental findings also revealed a clear load-dependent behaviour. In particular, the 4A zeolite outperformed the 5A zeolite in some intermediate load conditions, especially in terms of BSFC and BTE. This finding suggests that the optimal zeolite choice is not universal but depends on the operating load of the engine. Future work should therefore focus on tailoring zeolite selection, pore structure, and adsorption characteristics to match specific engine operating regimes, as well as exploring modified or hybrid zeolite formulations to further enhance system performance.

CRediT authorship contribution statement

Hanbey Hazar: Writing – original draft, Validation, Project administration, Methodology, Conceptualization. **Selahattin Ozgur Firat:** Writing – original draft, Visualization, Investigation, Formal analysis. **Huseyin Sevinc:** Writing – original draft, Visualization, Methodology, Conceptualization.

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.

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Data availability

Data will be made available on request.

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