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Research Article

Effect of diesel injection pressure for enhancing combustion and reducing mechanical vibration and noise emissions in a non-road diesel engine

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Abstract: In this study, the combustion, performance, emissions, noise, and vibration characteristics of a single-cylinder, four-stroke, air-cooled diesel engine used for non-road purposes were investigated by controlling different injection pressures with a common rail fuel injection system. The aim of this study is to enhance the combustion performance and improve the existing noise and vibration levels of this commonly used non-road diesel engine in fields such as agriculture, wetlands, and the construction sector by optimizing the injection pressure. The experiments were conducted under low and medium load conditions and at a constant engine speed. The single-cylinder, non-road engine's fuel injection system was controlled using a common rail fuel delivery system, and four different diesel injection pressures (250, 300, 350, and 400 bar) were utilized. The experimental results have shown that the combustion performance, emissions, noise, and vibration values of the non-road diesel engine improved with an increase in diesel injection pressure (DIP). At 0.43 MPa BMEP, increasing the DIP from 250 bar to 400 bar resulted in higher maximum combustion pressures due to the fuel being sent to the combustion chamber in a more atomized form. This led to reductions in HC, CO, and smoke emissions by up to 25%, 48%, and 59%, respectively. Moreover, vibration values also decreased by up to 25%.

Keywords: Combustion, emissions, engine performance, injection pressure, vibration and noise.

1. Introduction

Diesel engines have the capability to operate at high compression ratios, allowing them to generate higher torque compared to gasoline engines. Furthermore, the operation of diesel engines with air excess leads to higher efficiency, lower pumping losses, and fuel consumption as opposed to gasoline engines [1]. Due to these significant advantages, diesel engines are increasingly preferred not only in on-road vehicles but also in various non-road applications such as agriculture, power generation, construction, and irrigation sectors [2]. The growing demand for diesel engines in these non-road applications is driving their usage rate upward. However, the increased usage of diesel engines is accompanied by a series of issues, including the formation of high levels of NO_x and particulate matter (PM) emissions [3], noise, and vibration. Additionally, various studies indicate that PM emissions resulting from combustion in diesel engines not only degrade air quality but also negatively affect human health, especially the heart and lungs [4],[5]. Therefore, both on-road and non-road diesel engines used for various purposes need to reduce the exhaust emissions generated during combustion.

Various applications are carried out on diesel injection, including alternative fuel implementations, to enhance the engine performance of diesel engines and reduce combustion-related emissions. Diesel injection pressure is one of these applications. An increase in diesel injection pressure enables the fuel to be sent to the combustion chamber in a more atomized form. This allows the fuel to mix with air at multiple points and vaporize more rapidly. As a result, the fuel exhibits a quicker ignition characteristic, leading to a smoother combustion behavior. It is also a highly effective method for improving engine performance and reducing exhaust emissions [6]. Liu et al. [7] investigated the effects of methanol-diesel blend and fuel injection pressure on combustion and emissions in a six-cylinder, turbocharged, common-rail diesel engine. The results showed that the addition of methanol led to deteriorating combustion stability, which improved with an increase in injection pressure, resulting in a more stable combustion phase. In the methanol-diesel dual fuel operation, increasing the diesel injection pressure ensured that the cyclic variation remained below a rate of 2.1%. In the sole diesel operation, however, elevating the diesel injection pressure to 130 MPa resulted in main-

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taining cyclic variation below 1%. Additionally, with the increase in injection pressure, the combustion duration decreased, while the peak cylinder pressure and heat release rate increased. Moreover, as the diesel injection pressure increased, NO_x, HC, and CO emissions increased, while smoke emissions decreased. İçingür et al. [8] focused on the effect of octane number (46, 51, 54.5, and 61.5) and diesel injection pressure (ranging from 100 to 250 bar with increments of 50 bar) on engine performance under full load conditions. According to the study results, reducing the injection pressure to 100 bar significantly increased smoke emissions. Increasing the injection pressure led to a reduction in smoke emissions, while it resulted in an increase in NO_x emissions. Xu et al. [9] focused on the effect of diesel injection pressure on the fuel atomization's physical and chemical properties. The study was conducted on a heavy-duty diesel engine, under two different engine loads and three different diesel injection pressures (ranging from 600 bar to 1000 bar with increments of 200 bar). It was found that carbon, an element emitted in the emissions, showed a reduction of up to 64% with the increase in diesel injection pressure. Additionally, the particulate oxidation reactivity was reported to increase with the increase in diesel injection pressure. Can et al. [10] investigated the effects of adding 10% and 15% ethanol volumetrically to diesel fuel at different diesel injection pressures (150, 200, and 250 bar) on engine performance and emissions. The study was conducted at full load and various engine speeds. Additionally, 1% isopropanol was added to ensure the homogeneity of the diesel-ethanol blend and prevent phase separation. According to the study results, increasing the diesel injection pressure led to a reduction in CO and particulate emissions (up to 80%) of the ethanol-diesel blended fuel. Pickett et al. [11] found that reducing the injection pressure in the diesel fuel jet from 184 MPa to 43 MPa increased the smoke level. Kannan et al. [12] reported that increasing the injection pressure (280 bar) and advancing the injection timing resulted in improvements in thermal efficiency, gas pressure, and heat release rate. In the study, it indicated that with biodiesel fuel at an injection pressure of 280 bar, there was an observed increase of 1.44% in brake thermal efficiency (BTE) compared to diesel operation. Additionally, NO emissions showed a reduction of 38 ppm. Smoke emissions, on the other hand, experienced a decrease of 34.9% with biodiesel fuel and high injection pressure.

On the other hand, another significant issue with diesel engines used for non-road purposes is their low injection pressure and single-cylinder configuration, which leads to high noise and vibration during operation. The high vibration characteristic in these engines can reduce the lifespan of engine components and cause mechanical failures. Additionally, the vibration and noise factor have the potential to negatively impact human health [13]. Typically operating at low injection pressures, these engines may experience diesel knock due to delayed ignition timing, which can further increase the levels of vibration and noise. In the literature, various studies can be found concerning the effects of DIP on engine performance, noise, and vibration. Jaikumar et al. [14] conducted research to investigate vibration and noise in a diesel engine by varying the diesel injection pressure to 200, 220, and 240 bars. Additionally, they used diesel-biodiesel fuel blends as fuel. Upon analyzing the results, it was determined that an increase in DIP resulted in lower noise and vibration effects. The lowest noise and vibration values were obtained at 240 bars of DIP and with a blend of 20% biodiesel and 80% diesel. Compared to the sole diesel operation, the lowest noise level was measured at 39.71 dB with a 20% biodiesel + 80% diesel blend. Carlucci et al. [15] focused on the impact of injection parameters, such as main injection pressure and timing, on engine block vibration. In the study, injection timing showed minimal effect on engine block vibration, while injection timing and quantity were reported to significantly influence engine block vibration. Jaikumar et al. [16] focused on the effects of different injection pressures (180, 200, and 220 bar) and fuel blends (diesel, 10%, 20%, and 40% biodiesel additions) on combustion, noise, and vibration in a single-cylinder, water-cooled diesel engine using diesel and diesel-biodiesel blends. The study results indicated that increasing the injection pressure improved combustion performance. At a diesel injection pressure of 220 bar, the cylinder peak pressure increased by 4.98%, and the net heat release rate (HRR) showed a rise of 9.23%. Furthermore, it has been reported that the noise level decreased by 3.54% for the fuel mixture containing 20% biodiesel. Similarly, Carlucci et al. [17] determined that diesel injection pressure and injection duration are highly effective in influencing engine noise emissions.

As seen in the literature summaries, obtaining a comprehensive evaluation of diesel injection timing's impact on combustion, engine performance, and noise emissions in non-road engines is quite challenging, and there are limited studies in this area. Additionally, diesel injection pressures in mechanical injection non-road engines can only reach up to 240 bars, which poses a limitation. In the current study, the fuel system of the non-road engine is adapted to a common rail fuel system, allowing the diesel injection pressure to be increased up to 450 bars. Considering the limitations in diesel injection pressure for non-road engines and the restricted overall assessment of combustion, performance, noise, and vibration, this study can serve as a resource for future research and provide new insights for non-road engines. Moreover, having a comprehensive assessment of combustion, noise, and vibration will help to reduce the existing knowledge gap in the literature.

The most significant distinction of this study from other research lies in the control of a single-cylinder, air-cooled diesel engine with a common rail fuel system, and the elevation of existing diesel injection pressures beyond the limit of a non-road engine. The novelty of this study lies in investigating the vibration and noise characteristics of a single-cylinder, air-cooled non-road engine at high injection pressures. In this study, the aim is to improve combustion performance, emissions and reduce noise and vibration levels of diesel engines commonly used for non-road purposes. Therefore, a single-cylinder, air-cooled, non-road diesel engine is investigated for its combustion, noise, and vibration characteristics at different diesel injection pressures. The experiments are conducted at low and medium loads, where noise and vibration are more prominent.

2. Materials and methodology

2.1. Engine setup

The experiments are conducted on a single-cylinder, air-cooled diesel engine model AD320 from Antor, which is adapted with a common rail fuel system. Non-road diesel engine characteristics are presented in Table 1. The engine setup and test measurement system consist of a DC dynamometer, emission device, in-cylinder pressure measurement system, and noise and vibration system. The schematic representation of the engine setup and the measurement devices used in the tests are presented in Fig. 1.

To precisely control the engine torque and speed, an ABB brand DC dynamometer with a measurement capacity of 0-49.3 kW and an efficiency of 93.6% is used. Power transmission from the dynamometer to the engine is achieved through a coupling.

A common rail fuel injection system and an electronic control unit (ECU) are used in the single-cylinder, air-cooled, non-road diesel engine to control the diesel injection pressure. Due to its compatibility with the AD320 engine's displacement, the common rail fuel injection system of the 1.3 Multijet engine is chosen. For fuel system control, a Motec brand M142 model Electronic Control Unit (ECU) is employed. The ECU allowed the creation of single-cylinder operating conditions through

Table 1. Non-road diesel engine characteristics [18].

Parameter	Characteristics of Antor AD320	
Engine type	Single cylinder, four stroke, non-road diesel engine	
Cooling type	Air-cooled	
Swept volume	315 cm^3	
Compression ratio	17.3:1	
Cylinder diameter x stroke	78 mm x 66 mm	
Rated torque	11 Nm (@1850 rpm)	
Rated power	3 kW (@3050 rpm)	
Fuel system	Common rail direct injection (CRDI)	
Injection timing	13°CA bTDC	
Piston type	Shallow depth re-entrant geometry (Original)	
	Opening	Closing
Intake valve	10°CA BTDC	42°CA ABDC
Exhaust valve	58°CA BBDC	10°CA ATDC

the GPR-DI software. The common rail pump, enabling high injection pressures, was driven by a 2.2 kW electric motor and controlled by a speed driver.

2.2. Data acquisition

The AVL combustion analysis system is used for combustion pressure measurement under variable diesel injection pressures. Combustion pressure measurement, signal converter, and crank angle measurement are performed using AVL QC34D pressure sensor, Flexifem amplifier, and 365C model encoder, respectively. The technical specifications of the combustion analysis system are presented in Table 2.

For exhaust emission measurements, HC, CO, NO, and smoke emissions are analyzed by using Bosch brand

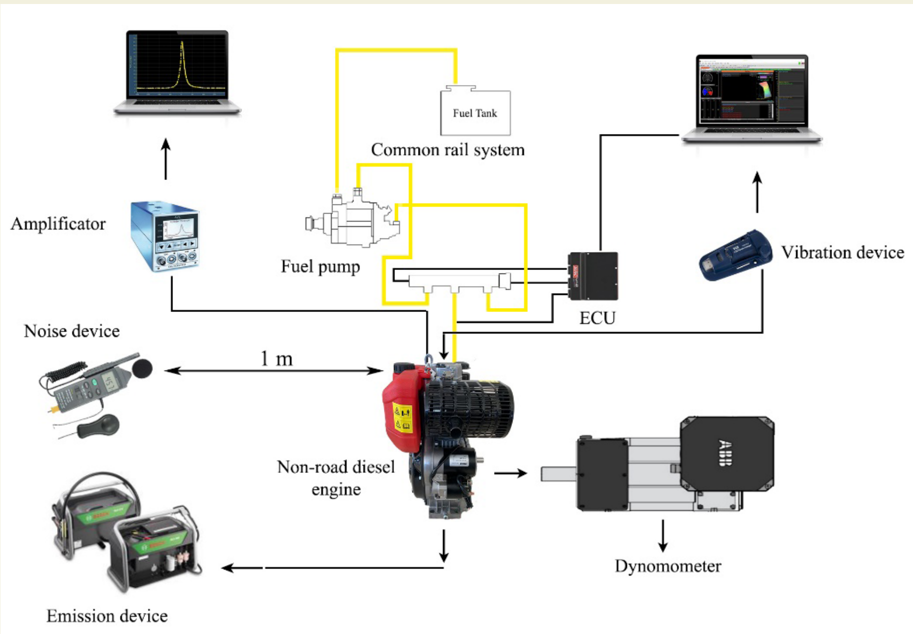

Figure 1. The schematic representation of the engine setup and the measurement devices used in the tests.

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Table 2. Technical specifications of the combustion analysis system

Combustion pressure sensor/AVL QC34D	
Sensor type	Piezoelectric
Max. measuring pressure	300 bar
Max. operating temperature	350 °C
Measuring range	0-250 bar
Precision	19 pC/bar
Amplifier/AVL Flexifem	
Output signal	-10/+10 volt
ADC resolution	16 bit
Max. operating temperature	50 °C
Digital output	4
Encoder/AVL 365C	
Encoder type	Optical
Measuring range	0/20000 rpm
Max. operating temperature	120 °C
Resolution strike	0.1°CA

BEA60 and BEA70 models. The technical specifications of the exhaust analysis system are presented in Table 3.

Table 3. The technical specifications of the exhaust analysis system [18].

Emissions type	Measuring range	Accuracy
CO (% volume)	0-10	0.001
HC (ppm)	0-9999	1
NO (ppm)	0-5000	1
Smoke Opacity (1/m)	0-9.99	0.01

Engine vibrations occurring at different injection pressures are measured with a PCE-VD3 model vibration device equipped with a three-axis accelerometer sensor. The accelerometer sensor has a measurement accuracy of ±18 for the X, Y, and Z axes. During the experiments, vibration measurements are carried out for 180 seconds, and these measurements are recorded in the database. The vibration device is mounted on the engine cylinder head to accurately measure all three coordinates. The non-road diesel engine noise emissions are measured at a distance of one meter from the engine block in dB(A) units. GERATECH DT 8820 model noise meter is used for the measurements.

2.3. Methodology

The diesel fuel used in the combustion, emission, noise, and vibration experiments was obtained as EURO diesel from the Karaman BP fuel station. The experiments were conducted at Karamanoğlu Mehmetbey University. Before starting the experiments, the engine is operated without load and at idle speed until it reached the operating temperature (approximately 75°C). During the tests, the engine oil temperature and surface temperature are frequently monitored. This is done to prevent the engine oil and surface from overheating and affecting the engine test data. The experiments are conducted at the engine's maximum torque speed of 1850 rpm. Additionally, the maximum engine torque speed is considered suitable for city driving conditions. The experiments are performed at two different engine loads (0.43 MPa and 0.55 MPa) and four different diesel injection pressures (250, 300, 350, and 400 bar). Combustion, emission, noise, and vibration parameters are investigated under these two different loads and four different injection pressures. The experimental matrix is presented in table 4.

Table 4. Experimental matrix

Study	BMEP (bar)	Engine speed (rpm)	Diesel injection pressure (bar)	Abbreviation
Case 1	0.43	1850	250	DIP 250
			300	DIP 300
			350	DIP 350
			400	DIP 400
Case 2	0.55	1850	250	DIP 250
			300	DIP 300
			350	DIP 350
			400	DIP 400

The measurements made in the study and the calculations of these measurements are presented below. Utilizing the first law of thermodynamics, one can determine alterations patterns of heat release rate (HRR) across the cycle based on crank angle (CA) 43. Eq. (1) finds application in the computation of HRR for different diesel injection pressure operations.

$$\frac{dQ_{net}}{d\theta} = \left(\frac{n}{n-1}\right) P \frac{dV}{d\theta} + \left(\frac{n}{n-1}\right) V \frac{dP}{d\theta} \tag{1}$$

Here $\frac{dQ_{net}}{d\theta}$ represents the net HRR values in units of (J/CA) based on the CA. Also, θ, P, V, and n 's in Eq. 5 are defined as crank angle, pressure, volume, and specific heat value, respectively [19].

BSFC and BTE are calculated by equation (2) and (3), respectively. Here, $\dot{m}_f$ denotes fuel consumption in kg/second, N_e denotes brake engine power. $\dot{E}_f$ represents the total fuel energy [20].

$$BSFC = \left(\frac{\dot{m}_f \times 3600}{N_e}\right) \tag{2}$$

$$BTE = \left(\frac{N_e}{\dot{E}_f}\right) \tag{3}$$

3. Results and Discussions

3.1. Combustion analysis

Cylinder pressure and HRR curves stand as crucial parameters in combustion analysis. Through these parameters, the combustion behaviour within the cylinder can be anticipated [20]. Observing combustion behaviour under different diesel injection pressures holds signifi-

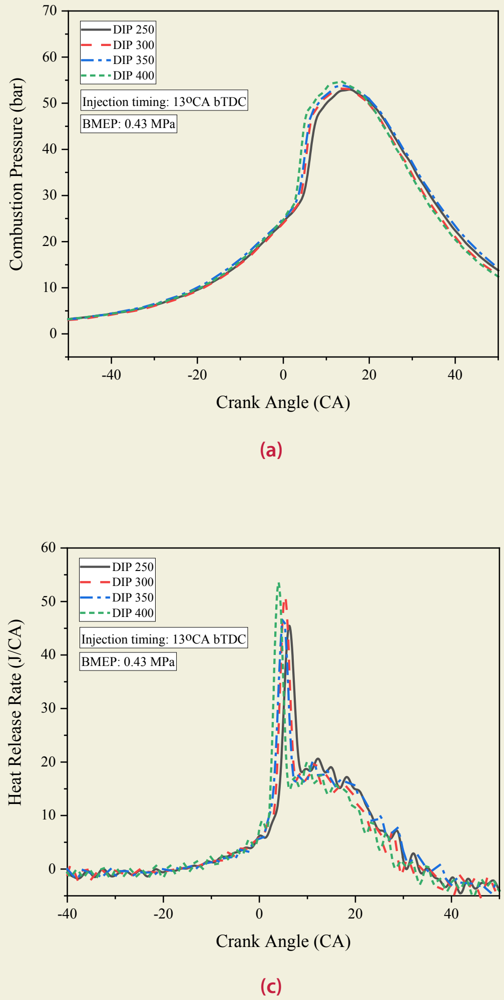

Figure 2. Variation of combustion pressure and HRR for non-road single-cylinder diesel engine at varying DIP.

cance. This is because the increased injection pressure leads to a more atomized fuel delivery into the combustion chamber, enabling the visualization of early or delayed ignition and the cylinder's internal peak pressure states. Fig. 2 presents the impact of DIP on the variation of combustion pressure and heat release rate (HRR) for non-road single-cylinder diesel engine. As seen in Figures 2a and 2b, an increase in DIP for both engine loads leads to an increase in the maximum combustion pressure. The higher DIP causes diesel fuel particles to penetrate the combustion chamber in a more atomized form. This allows the diesel fuel droplets to encounter air over a wider area and evaporate more rapidly. Consequently, the diesel fuel that vaporizes at multiple points exhibits faster ignition behavior, and the majority of the main fuel continues to burn under higher cylinder temperatures. This is one of the factors contributing to the increase in maximum combustion pressure. On the other hand, at low injection pressures, diesel fuel particles have a smaller surface area, resulting in slower evaporation and ignition of the fuel. As shown in Figures 2c and 2d, as the DIP increases, the HRR curves approach Top Dead Center

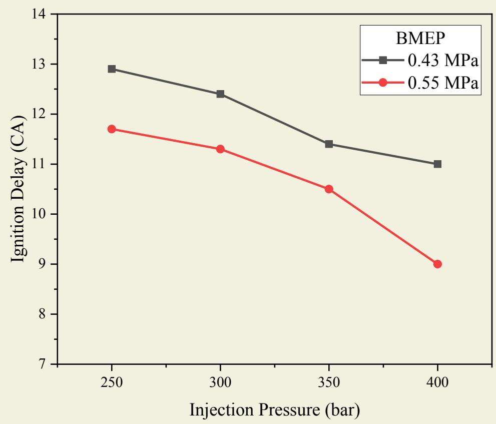

Figure 3. Variation of ID for non-road single-cylinder diesel engine at varying DIP.

(TDC). This indicates that combustion initiates earlier at higher injection pressures. Conversely, at low DIP, the HRR curves are farther away from TDC, indicating a delayed start of combustion. The slower evaporation of fuel at low DIP causes the fuel to accumulate mass, which in turn lowers the ambient temperature, contributing to the delayed ignition.

Fig. 3 presents the impact of DIP on the variation of ignition delay (ID) for non-road single-cylinder diesel engine. Diesel fuel particles become more atomized with an increase in injection pressure. This allows for an earlier ignition timing because the increased fuel droplets increase the surface area and come into contact with the available air more, leading to faster vaporization. As a result, ignition occurs more rapidly. For both BMEP values, the ID time shortens with an increase in DIP. Increasing DIP to 400 bar in the non-road diesel engine results in a reduction of 1.8°CA and 2.7°CA in the ID time for 0.43 MPa BMEP and 0.55 MPa BMEP, respectively.

3.2. Engine performance

A single-cylinder, air-cooled, non-road common rail diesel engine's Brake Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE) are investigated under various loads and diesel injection timings. Fig. 4 presents the impact of DIP on the variation of BSFC for non-road single-cylinder diesel engine. Under both load conditions, increasing the DIP from 250 bar to 400 bar shows a tendency of decreasing BSFC values. The lowest BSFC value is achieved at 400 bar DIP and 0.55 MPa BMEP. This is due to the increased engine load resulting in a more stable combustion phase. Higher BSFC values at lower DIPs are attributed to delayed vaporization and ignition phases of the diesel fuel. This condition leads to reduced engine performance and increased fuel consumption. At 0.55 MPa BMEP, the BSFC with 400 bar pressure improves by 4% compared to 250 bar DIP. Similarly, at 0.43 MPa BMEP, BSFC improves by 5%.

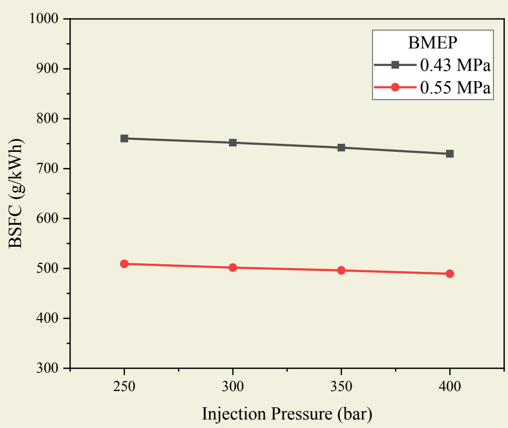

Figure 4. Variation of BSFC for non-road single-cylinder diesel engine at varying DIP.

Fig. 5 presents the impact of DIP on the variation of BTE for non-road single-cylinder diesel engine. For both engine load conditions, the gradual increase in DIP enhances BTE. Lower fuel consumption at higher DIP levels contributes to a higher BTE. Injecting diesel fuel at higher pressures and at a later stage aids in achieving ignition BTDC of the piston. This leads to a shorter ignition delay and a more stable combustion behavior, ultimately increasing thermal efficiency. The highest BTE value is achieved at 400 bar DIP and 0.55 MPa BMEP, reaching 17.3%. This represents a 4% improvement compared to 250 bar DIP under the same load conditions.

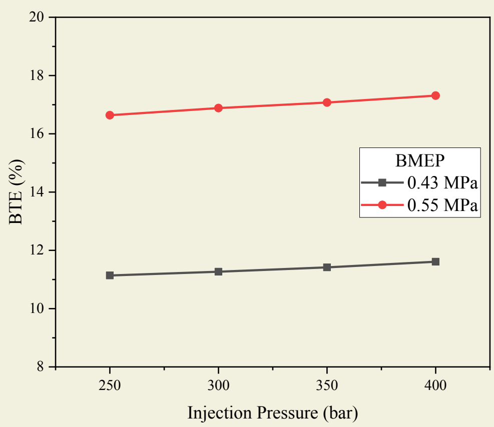

Figure 5. Variation of BTE for non-road single-cylinder diesel engine at varying DIP.

3.3. Exhaust emissions

The formation of HC emissions is influenced by various factors, such as combustion chamber design, injection timing, injection pressure, pockets unreachable by the flame front, incomplete combustion, fuel characteristics, and air-to-fuel ratio [6, 20]. Fig. 6a presents the impact of DIP on the variation of HC emissions for non-road single-cylinder diesel engine. Indeed, an increase in engine load and DIP significantly affects HC emissions. The rise in engine load leads to an increase in peak combustion pressure and, consequently, higher combustion temperatures, resulting in a more stable combustion phase. This condition plays a crucial role in reducing HC emissions. On the other hand, thanks to DIP, diesel fuel droplets are more atomized during injection, leading to a more stable combustion phase and achieving higher combustion temperatures. This situation contributes to the reduction of HC emissions effectively. The lowest HC emissions for both engine loads are achieved with a 400 bar diesel injection pressure. At 0.43 MPa BMEP, a 25% reduction in HC emissions is observed compared to a 250 bar DIP at 400 bar DIP. Similarly, at 0.55 MPa BMEP, a 14% reduction in HC emissions is obtained with a 400 bar DIP compared to a 250 bar DIP.

Sayin et al. [21] stated that under low load conditions, there is less fuel injection, which results in fuel droplets not adhering to the cylinder walls. Consequently, it was stated that due to excess air and low combustion temperatures, these fuel droplets are expelled without participating in the combustion reaction. Under low-load conditions, the increased HC emissions can be significantly reduced by increasing the DIP, as shown in Figure 4a.

Fig. 6b presents the impact of DIP on the variation of CO emissions for non-road single-cylinder diesel engine. The in-cylinder air/fuel ratio is a significant factor in the trend of CO emission increase/decrease [22, 23]. Diesel engines operating under lean mixture conditions result in lower CO emissions compared to gasoline engines. However, the presence of inhomogeneous mixtures, multiple rich mixture regions, and an unstable combustion phase leads to an increase in CO emissions. For all engines, an increase in BMEP value leads to more fuel injection into the cylinder, causing a decrease in the air/fuel ratio. Consequently, due to the formation of a rich mixture condition, CO emissions increase. The lowest CO emissions for both engine loads are achieved with a 400 bar diesel injection pressure. At 0.43 MPa BMEP, a 48% reduction in CO emissions is observed compared to a 250 bar DIP at 400 bar DIP. Similarly, at 0.55 MPa BMEP, a 38% reduction in CO emissions is obtained with a 400 bar DIP compared to a 250 bar DIP. Similar results were obtained in the study conducted by Gumus et al. [24]. The authors found that an increase in engine load leads to an increase in CO emissions, while an increase in injection pressure results in a decrease in CO emissions.

Fig. 6c presents the impact of DIP on the variation of NO emissions for non-road single-cylinder diesel engine. Indeed, NO emissions increase due to high combustion temperatures, high oxygen density, and an increase in the combustion reaction duration [24],[25]. Both the increase in BMEP value and the increase in DIP values have led to an increase in NO emissions. As indicated in the combustion analysis, sending diesel fuel droplets in a more atomized form into the combustion chamber has resulted in higher maximum combustion pressures. This, in turn, has led to an increase in combustion temperatures, resulting in elevated NO emissions. The highest NO emissions for both engine loads are achieved with a 400 bar diesel injection pressure. At 0.43 MPa BMEP, a 24% increase in NO emissions is observed compared

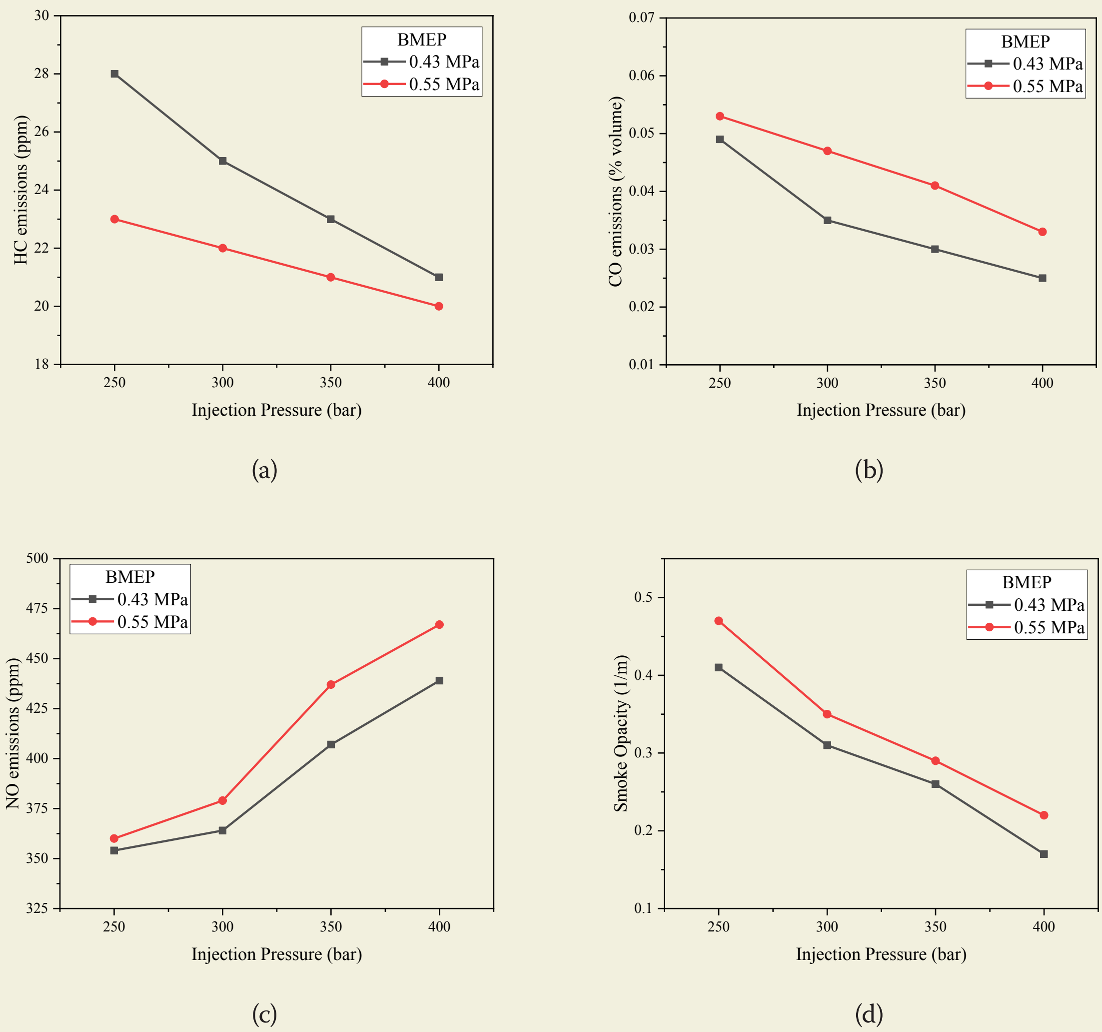

Figure 6. Variation of (a) HC, (b) CO, (c) NO, and (d) smoke emissions for non-road single-cylinder diesel engine at varying DIP.

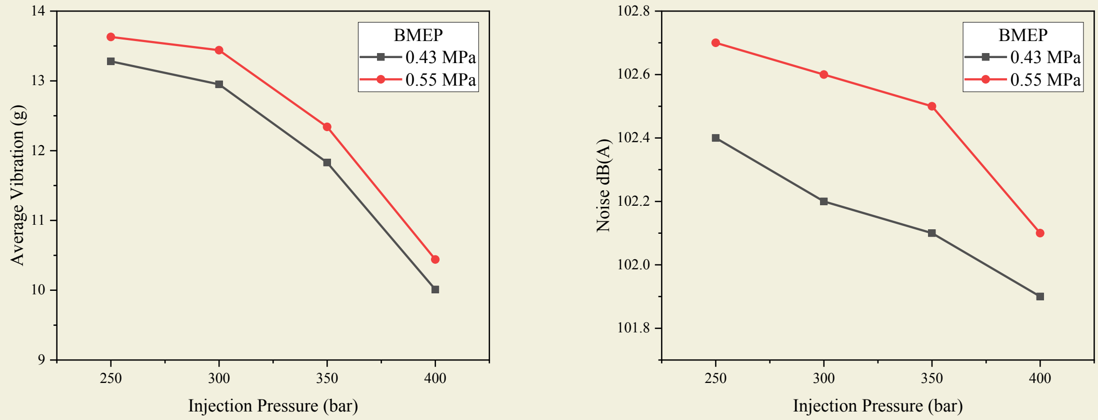

Figure 7. Variation of vibration and noise emissions for non-road single-cylinder diesel engine at varying DIP.

to a 250 bar DIP at 400 bar DIP. Similarly, at 0.55 MPa BMEP, a 29% increase in NO emissions is obtained with a 400 bar DIP compared to a 250 bar DIP. Agarwal et al. [26] determined in their study on injection timing and pressure that an increase in DIP resulted in an increase in NOx emissions.

Fig. 6d presents the impact of DIP on the variation of smoke emissions for non-road single-cylinder diesel engine. While smoke emissions are adversely affected by the increase in BMEP, they are positively influenced by the increase in DIP. The increase in BMEP requires more fuel injection into the combustion chamber, leading to the formation of richer mixture regions. The increase in richer mixture regions is one of the main reasons for smoke emission formation. On the other hand, the higher DIP allows fuel particles to be sent to the combustion chamber in a more atomized form, reducing the presence of richer mixture regions and enabling better fuel-air mixing. As a result, smoke emissions tend to decrease. The lowest smoke emissions for both engine loads are achieved with a 400 bar diesel injection pressure. At 0.43 MPa BMEP, a 59% reduction in smoke emissions is observed compared to a 250 bar DIP at 400 bar DIP. Similarly, at 0.55 MPa BMEP, a 53% reduction in smoke emissions is obtained with a 400 bar DIP compared to a 250 bar DIP. In their study, Li et al. [27] stated that an increase in DIP can lead to a reduction in smoke emissions. The authors mentioned that the increase in DIP results in the fuel being sent to the combustion chamber in a more atomized form, which improves the combustion process. Additionally, the fuel being sent in a more atomized manner increases the cylinder's internal temperature, leading to a faster combustion phase and thus reducing smoke emissions.

3.4. Vibration and noise characteristics

One of the significant issues with non-road diesel engines, apart from emissions, is vibration and noise emissions. These emissions can have serious adverse effects both on humans and the environment [28],[29]. Vibration is a major factor that affects the lifespan and efficiency of mechanical components in the engine. Therefore, non-road diesel engines, commonly used in urban and non-urban areas such as agricultural fields, wetlands, and construction sites, need to be improved in terms of vibration and noise to mitigate their negative impacts. Fig. 7 presents the impact of DIP on the variation of vibration and noise emissions for non-road single-cylinder diesel engine. With an increase in BMEP, there is a higher fuel delivery into the cylinder, resulting in more energy release. The increased energy leads to higher cylinder pressure, which in turn causes an increase in engine vibration. On the other hand, lower DIP values result in higher vibration levels, whereas increasing DIP contributes to reducing vibration levels. Although increasing DIP leads to higher combustion pressures, the absence of knocking combustion results in a softer combustion behaviour, which leads to a decrease in vibration levels. The lowest vibration values for BMEP values are obtained at 400 bar DIP. For BMEP values of 0.43 MPa and 0.55 MPa, there is a respective decrease of 25% and 23% in vibration levels compared to 250 bar DIP. Similarly, noise emission values increase with an increase in BMEP, while they tend to decrease with an increase in DIP. The soft combustion characteristics at higher DIP values have been effective in reducing noise emissions. The lowest noise values for BMEP values are obtained at 400 bar DIP. For BMEP values of 0.43 MPa and 0.55 MPa, there is a respective decrease of 0.5 dBA and 0.6 dBA in noise levels compared to 250 bar DIP.

4. Conclusions

To improve the combustion performance, reduce vibration and noise emissions of a single-cylinder, air-cooled diesel engine used for non-road purposes, it is adapted with a common rail fuel system. Experiments are conducted at various diesel injection pressures and loads. The results and recommendations derived from these experiments are as follows:

- In non-road diesel engines operating at low DIP values, increasing DIP contributes to the increase in maximum combustion pressures. The increasing injection pressure leads to a more atomized delivery of fuel into the combustion chamber. This results in an earlier ignition and facilitates the attainment of higher cylinder peak pressures.

- Increasing DIP from 250 bar to 400 bar results in the heat release rate (HRR) curves approaching TDC. This indicates that combustion starts earlier due to the fuel being sent to the combustion chamber in a more atomized form.

- Higher DIP contributes to the improvement of both BSFC and BTE. The enhanced stability of the combustion phase at higher DIP levels leads to an increase in BTE and a decrease in BSFC.

- Under low-load conditions, HC emissions are higher, but increasing DIP leads to a reduction in HC emissions by up to 25%. Fuel injected in a more atomized manner fosters the formation of a better mixture. Furthermore, the increased cylinder peak pressure plays a significant role in reducing HC emissions as it raises the in-cylinder combustion temperatures.

- CO and smoke emissions also showed a significant decrease at high DIP values. CO emissions decreased by up to 48%, while smoke emissions decreased by up to 59%.

- The injection pressure also has a significant effect on vibration and noise emissions. Vibration emissions showed a 25% reduction at high DIP, while noise emissions showed a decrease of up to 0.6 dBA. The reduction in ignition delay with an increase in DIP aids in the engine exhibiting a soft combustion behaviour, leading to decreased engine vibration.

As seen, the adaptation of the non-road diesel engine's fuel delivery system from mechanical to common rail and increasing the injection pressure to 400 bar has significant effects on both performance and emissions. For non-road applications, to have better control over NO and smoke emissions, Exhaust Gas Recirculation (EGR) or dual fuel (gas-diesel) applications can be implemented.

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