

Research Article

Investigation of bioethanol low-carbon fuel for diesel engines under idling conditions: Combustion, engine performance and emissions

Jun Cong Ge^{a,*}, Lifeng Wang^c, Hongliang Luo^b, Nag Jung Choi^a^a Division of Mechanical Design Engineering, Jeonbuk National University, Jeollabuk-do 54896, Republic of Korea^b College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China^c Weifang Litro Electronic Technology Co., Ltd., Weifang, 261000, China

ARTICLE INFO

Keywords:

Diesel engine
Low-carbon fuel
Combustion
Engine performance
Idling emissions

ABSTRACT

In this study, the low idle operation is defined as the engine running at the lowest engine speed with a few slight loads. Idling is necessary for most vehicles, especially for buses and trucks that frequently travel long distances, as drivers often rest inside the vehicle. However, under idling conditions, weak air flow and low air-fuel ratio result in poor air to fuel mixture, ultimately causing incomplete combustion and the production of more harmful exhaust emissions. Bioethanol, as a low-carbon fuel, has great potential for application in diesel engines due to its unique properties. In this research, the influences of different diesel-bioethanol blends (BE0, BE5, BE10, BE15) on combustion and emissions of a diesel engine were investigated under idle conditions. The main results show that there was no phase separation phenomenon even up to 15% bioethanol was directly blended with diesel by volume. And adding bioethanol to diesel had no significant impact on combustion pressure peak, but it postponed the start of combustion (SOC). Surprisingly, the nitrogen oxide (NO_x) and smoke were simultaneously decreased by over 52% and 78% with the intervention of bioethanol, respectively.

1. Introduction

In recent decades, internal combustion engines (ICE), especially diesel engines, have been playing an important role in the fields of on-road and off-road machinery. Although electric vehicles (EVs) can solve on-road transportation pollution problems. However, if the electricity used by EVs comes from traditional thermal power generation, EVs are not purely zero-emission vehicles. Even studies have shown that EVs that rely on coal-fired power generation emit higher CO₂ emissions than ICE in terms of life cycle assessment (LCA) (Petrauskienė et al., 2020). In addition, the current global ownership of EVs in the world is far from being compared with ICE, so the ICE is still the main transportation machinery at present. Especially the diesel engine, which has the advantages of large power, fuel economy and good durability, is widely used in on-road and off-road operations (e.g., heavy trucks, ships, agricultural machinery, etc.) (Othman et al., 2017). However, compared with gasoline engines, diesel engines emit more nitrogen oxide (NO_x) and smoke emissions (Lu, 2011). Compared with conventional mechanical and system optimization methods, developing emerging suitable alternative fuels to reduce diesel emissions has become a hot topic. Some alternative fuels have attracted the attention from the world, such as

biodiesel, methanol, ethanol, dimethyl ether (DME) and others (Campos-Fernández et al., 2012; E et al., 2017; Wang et al., 2022; Ying et al., 2008).

As a typical alternative fuel, biodiesel is rich in sources and can be obtained from animals, vegetable oils, seaweeds and others by transesterification (E et al., 2017). Biodiesel is a low-carbon, renewable, clean, high oxygen fuel that can be mixed with diesel in any blending ratio (Roy et al., 2014). Many studies have shown that using a certain amount of biodiesel can effectively control the emissions of CO and PM, but it may slightly increase NO_x and fuel consumption (Basha et al., 2009; Devarajan, 2019). Besides, the high viscosity of biodiesel directly affects the atomization quality, which deteriorates the atomization effect, leading to poor fuel flow in the cylinder and increasing the mixing time with air (Erdoğan et al., 2019). Similar to biodiesel (oxygen content: 11 wt%), ethanol is also a high-oxygen and low-carbon alternative fuel (oxygen content: 35 wt%). Unlike biodiesel, ethanol is commonly used as an anti-knock additive in gasoline engines due to its high octane number (Abdellatif et al., 2021). The low cetane number of ethanol makes it unsuitable as a standalone fuel for diesel engines. Furthermore, another advantage is that the cost of ethanol is much lower than that of biodiesel due to its inexpensive raw materials for preparation. There are research results showing that the

* Corresponding author.

E-mail address: jcge@jbnu.ac.kr (J.C. Ge).

production cost of ethanol is as low as 0.09–0.12 USD/L (Khounani et al., 2019), while for biodiesel is as high as 0.42–0.75 USD/L (Mizik and Gyarmati, 2021). Ethanol can be prepared from various sugar- and starch-containing raw materials as well as lignocellulosic biomass through fermentation and saccharification processes (Busić et al., 2018). Moreover, cheaper ethanol can be produced from coal through coal gasification under the action of non-precious metal catalysts (Kang et al., 2021).

The application of ethanol low-carbon fuel in diesel engines has attracted widespread global attention. Many researchers have reported that the ethanol can be directly blended with diesel or diesel-biodiesel mixture to prepare binary or ternary blended fuels. These prepared blended fuels can be directly burned on diesel engines without any changes. Ethanol has the advantages of high oxygen content, high latent heat of evaporation, high volatility, and low carbon content, which directly improve combustion and emissions. However, its disadvantages are lower cetane number and low calorific value, which will increase ignition delay and ignition energy. In addition, its lower viscosity increases the leakage likelihood in the fuel injection pump, resulting in reduced power. And ethanol also has a low flash point, which makes it highly flammable. Therefore, according to the NFPA regulations in the United States, diesel-ethanol blends should be classified as Class I liquid fuels, and appropriate measures should be taken in transportation, storage, and management. (Yahuza and Dandakouta, 2015). Ethanol has strong hygroscopicity, which makes it corrosive to metals such as aluminum, low-carbon steel, and copper (Thangavelu et al., 2016). However, Odziemkowska et al. (2016) and Pradelle et al. (2019) both tested the corrosiveness of ethanol blended fuels on copper metal, which is prone to corrosion. The research results showed that all samples had acceptable low corrosiveness and were within the PN-EN 590 standard for diesel. Moreover, when preparing multi-component mixed fuels by mixing ethanol with diesel, it is necessary to strictly control the ambient temperature as the solubility of ethanol is greatly affected by temperature. When the ambient temperature is above 10°C, diesel can dissolve a certain amount of ethanol. While the ethanol is prone to phase separation in diesel when the temperature is below 10°C (Hansen et al., 2005). Ge et al. (2022a,b) found that there was no stratification when bioethanol was blended with diesel at room temperature according to various volume ratios of ethanol in diesel from 5% to 15%. Shrivastava et al. (2021) researched the influences of diesel-biodiesel-ethanol ternary mixture on performance and emissions of a single-cylinder diesel engine under different compression ratios and loads at 1500 rpm. Based on the performance and emission characteristics, they reported that a mixture of 70% diesel, 20% biodiesel and 10% ethanol is the optimal combination compared to baseline of diesel. Ethanol contains up to 35 wt% oxygen, which can reduce CO and smoke emissions by improving fuel-air mixture ratio. In addition, ethanol has stronger cyclic changes compared to diesel, and its fuel-bound oxygen is stronger compared to other alcohol substitute fuels such as n-butanol (Rakopoulos et al., 2019). Moreover, ethanol has unique properties such as high latent heat of evaporation and high volatility, which play an important role in simultaneously improving NO_x and smoke emissions (Ge et al., 2022). To use a larger proportion of ethanol in the diesel engine, multiple application modes have been investigated, including direct injection in cylinder or intake manifold, and ethanol multicomponent fuel blends. Beatrice et al. (2020) found that 80% ethanol ratio can be effectively applied in a diesel engine with dual-fuel combustion method under high injection pressure conditions. Emiroğlu and Şen investigated the applied characteristics of different alcohol fuels such as butanol, ethanol and methanol on a single cylinder diesel engine. Compared with diesel, addition of alcohol fuels resulted in longer ignition delay, higher maximum in-cylinder pressure, lower CO and lower smoke emissions (Emiroğlu and Şen, 2018a).

Through reviewing above articles, it is found that most of the current research on ethanol is focused on the single-cylinder diesel engine under medium and high loads or medium and high speeds operating conditions, and the research on special conditions such as idling is still in a blank period. Although idling is not commonly used in actual on-road engine operations, it is necessary for most long-distance drivers to maintain a certain amount of

rest time. In addition, the engine often warms up under idling conditions in the cold winter. Research has shown that long-haul trucks are idling for 6 to 16 h a day (Rahman et al., 2013a). The in-cylinder temperature is very low under idling conditions, air flow is usually feeble, resulting in high fuel consumption and more harmful emissions (Ge et al., 2022; Vignesh et al., 2021). Hua et al. reported that the n-hexane, benzene and acrolein unregulated emissions from diesel engines are the highest under idle condition compared to maximum torque and nominal operation conditions due to incomplete combustion caused by a thinner mixture (Hua et al., 2020). Compared to hot idle conditions, diesel engines emit more CO, HC, NO_x and PM emissions due to lower combustion temperatures and delayed combustion processes under cold idle conditions. The exhaust temperature is only 100°C under cold idle condition, much lower than the 400°C under hot idle condition (Tipanluisa et al., 2021). Therefore, reducing idle emissions from diesel engines has become a hot topic.

In this study, the idle operation was defined as the engine running at the lowest speed with light load. This is consistent with the definition of other researchers (Rahman et al., 2013b, 2014). Low carbon anhydrous bioethanol was considered as a relatively inexpensive and practical alternative fuel compared to biodiesel for a diesel engine under idling conditions. The main aim of this work are as follows: 1) to study the application effects of bioethanol in a diesel engine under idling conditions, 2) to optimize the optimal blending ratio of diesel-bioethanol blends and corresponding engine operating conditions, and 3) to investigate the emission characteristics and generation mechanisms of NO_x and smoke. This study can provide some reference values for the control of idling emissions from diesel engines fueled with some low-carbon alternative fuels.

2. Experimental equipment and operational details

2.1. Experimental fuels

The ethanol used in this study was anhydrous bioethanol, which was purchased from local K company and prepared from corn starch as raw material. Although there are potential competition issues with human food resources in using corn starch to prepare bioethanol, the corn has abundant sources and is easier to convert into biofuels than lignocellulosic materials. And the preparation process is simple and cost-effective compared to using lignocellulosic biomass (Cripwell et al., 2020). In addition, corn is one of the most widely produced crops in the world, with an annual output of over 1 billion tons (García-Lara and Serna-Saldivar, 2019). The diesel was obtained from the S-oil petrol station near the university. Three diesel-bioethanol blended fuels including BE5, BE10 and BE15 were prepared using ultrasonic technology according to the volume ratios of 5%, 10%, and 15% ethanol in diesel. Table 1 lists the main properties of pure diesel and bioethanol. In Table 1, the bioethanol has lower cetane index and lower heating value, as well as higher latent heat of evaporation and higher oxygen content compared to diesel. These typical properties directly affect combustion and emission characteristics. For example, low cetane number can delay the start of combustion (SOC), high oxygen content can improve local hypoxia, and high latent heat of evaporation can diminish the maximum combustion temperature.

Table 1
Main physical properties of pure diesel and bioethanol.

Properties	Measurement unit	Diesel	Bioethanol
Cetane index	–	55.8	8
Density @ 15°C	kg/m ³	836.8	800
Flash point	°C	55	13
Viscosity @ 40°C	mPa s	2.719	1.1
Lower heating value	MJ/kg	43.96	28.18
Latent heat of evaporation	kJ/kg	250	840
Carbon	wt%	86.1	52.2
Hydrogen	wt%	13.9	13.1
Oxygen	wt%	0	34.7

2.2. Experimental methods

The main equipment of this experiment includes an inline four-cylinder diesel engine, a dynamometer, a combustion and emission analysis system, which are displayed in Fig. 1. Table 2 lists the engine's main performance parameters. A 230 kW dynamometer was used to measure the engine load. A Horiba MEXA analyzer was used to test CO, HC and NOx emissions. An OP-160 was used to analyze smoke emissions by calculating opacity. The combustion pressure was recorded by a Kistler 6056A piezoelectric sensor, the signal was amplified by a Kistler 5011B charge amplifier. An A&D GP-100K precision balance was employed to measure the fuel consumption.

2.3. Experimental conditions

To ascertain the impact of bioethanol on combustion and emissions from diesel engines under idle conditions, engine loads of 0, 15, 30 Nm were selected as several light loads. The speed under idling conditions was controlled at 750 rpm. To reduce experimental errors, recording experimental data was performed when the engine reaches a stable state of operation. That is, when the temperature of the cooling water reaches 85°C and remains constant, it is called a stable operating state. To reduce the influences of the previous fuel on the next experiment, a fuel pump was employed to remove the remaining fuel in the pipe and engine after each experiment. After all tests were completed, the fuel was replaced with the pure diesel and run for at least 30 min before turning off the engine.

3. Results and discussions

3.1. Combustion characteristics

3.1.1. Effects of engine loads on combustion pressure

Fig. 2 displays the influences of engine loads on combustion pressure for all diesel-bioethanol blends under idling conditions. The maximum

Table 2
Engine specifications.

Type	Turbocharged diesel engine
No. of cylinder	4
Injection mode	Direct injection
No. of injector nozzle holes	5
Bore (mm)	83
Stroke (mm)	92
Compression ratio	17.7:1
Rated power	82 kW @ 4000 rpm

combustion pressure for all tested fuels increased with increasing of load under idling conditions. As the load increases, the peak pressures in the cylinder for all tested fuels were delayed by 1~2°CA in terms of the crank angle. And the peak pressures occurred further away from the TDC. The start of combustion (SOC) had been slightly advanced with increasing of load. Similar results can be found in Zhu et al. (2011). The reason of this situation is that the increase in load leads to an increase in injection quantity, thereby increasing combustion temperature, combustion pressure and combustion duration. On the other side, adding 10% ethanol to diesel (BE10) had a significant increase in peak combustion pressure with load variation. Compared with the result at 0 Nm, the peak pressure for BE10 was increased by 12.13% and 23.51% at 15 Nm and 30 Nm, respectively. This may be attributed to the high volatility and high oxygen content of bioethanol, which plays a positive role in combustion at higher loads.

3.1.2. Influences of diesel-bioethanol blends on combustion pressure

Fig. 3(a)–(c) shows the influences of diesel-bioethanol blends on combustion pressure at different engine loads. All experimental fuels exhibited similar combustion pressure curves, with combustion pressure peaks on the left and right sides of the TDC caused by pilot injection and main injection, respectively. Under all load conditions, the peak combustion pressure of pure diesel (BE0) was the highest compared to diesel-

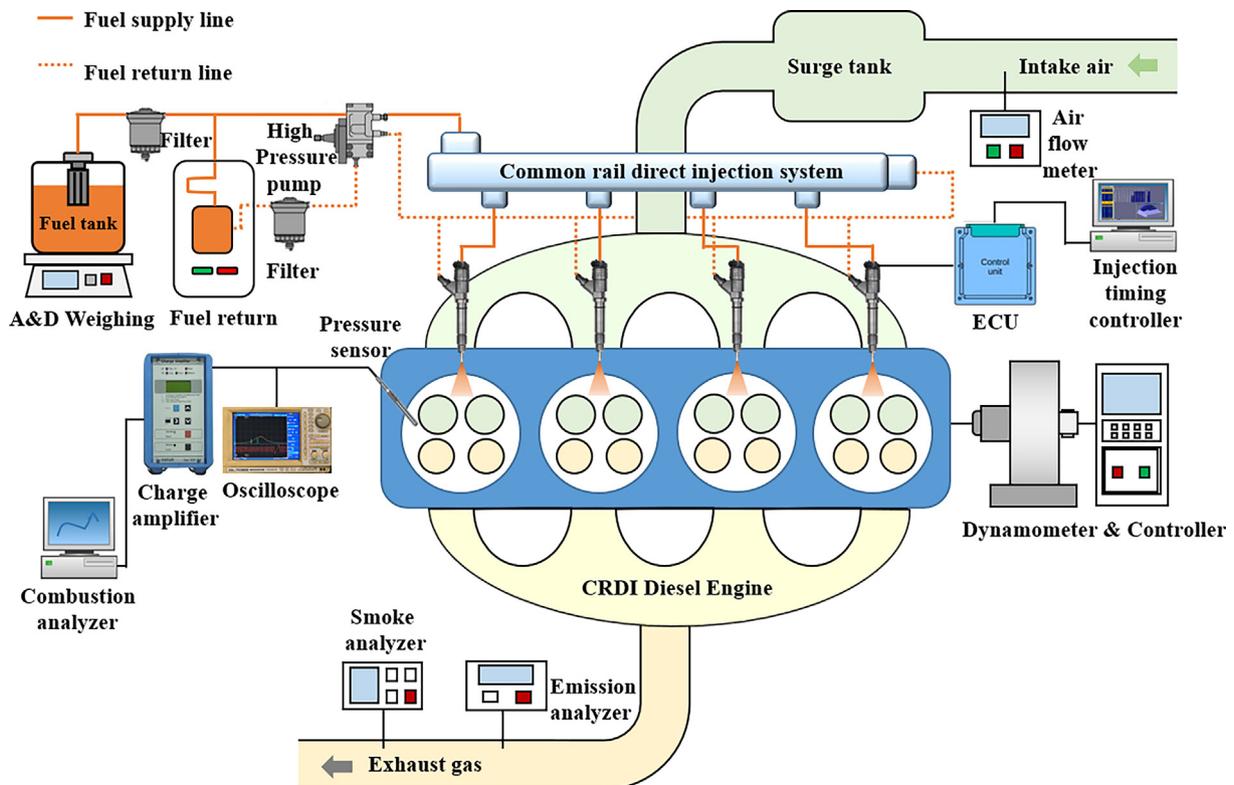


Fig. 1. Diesel engine bench setup.

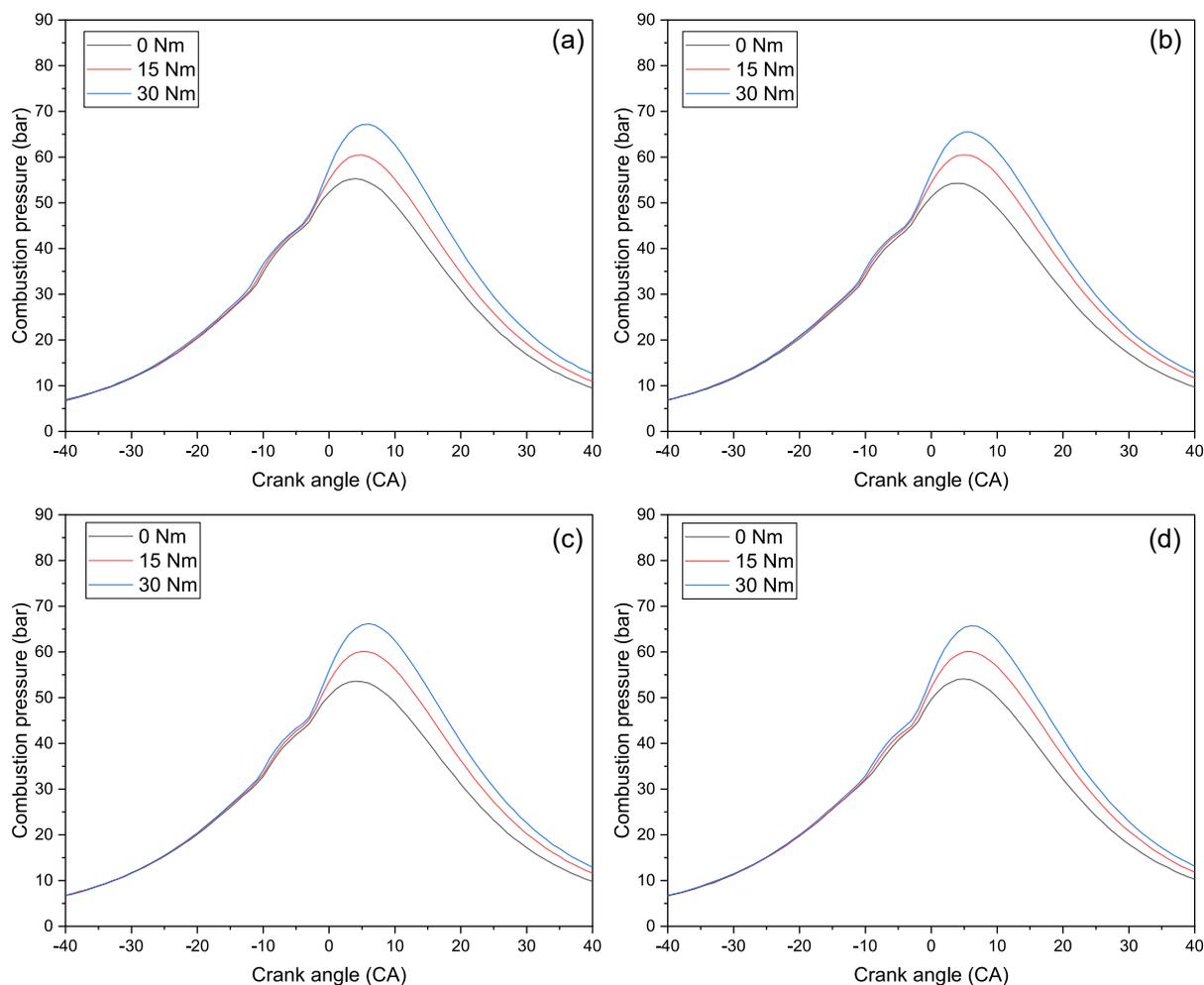


Fig. 2. Combustion pressure in the cylinder for (a) BE0, (b) BE5, (c) BE10 and (d) BE15.

bioethanol blends. Because the calorific value of bioethanol (28.18 MJ/kg) is much lower than that of diesel (43.96 MJ/kg). The low calorific value leading to low combustion pressure has also been proven in (Qi et al., 2010). In addition, it can be observed that the SOC of the diesel-bioethanol blended fuels was gradually delayed with increasing of the amount of bioethanol addition. This result is related to the low cetane number and high latent heat of evaporation of bioethanol. Low cetane number directly leads to poor ignition characteristics, while high latent heat of evaporation reduces cylinder temperature during fuel atomization, thereby weakening the chemical combustion performance. Firat et al. also demonstrated similar research results to this study. They reported that bioethanol with high latent heat of evaporation and low cetane number caused long ignition delay in diesel engines.

3.1.3. Effects of diesel-bioethanol blends and loads on peak combustion pressure

Fig. 3(d) presents the effects of diesel-bioethanol blends and engine loads on peak combustion pressure. From the figure, it is clear seen that the peak pressure in the cylinder showed a slight decrease trend with the increasing of bioethanol under each load condition. At 0 Nm, the peak pressures of BE0, BE5, BE10, and BE15 were observed to be 55.3, 54.3, 53.6 and 54.1 bar, respectively. At 15 and 30 Nm, the addition of bioethanol had less effect on the variation of peak pressure compared to the result at 0 Nm. Especially at 15 Nm, the peak variation caused by diesel-biodiesel blends was the smallest, with an average change rate of 0.44%, followed by 1.76% at 30 Nm and 2.35% at 0 Nm. In other words, the diesel-bioethanol blends had the least impact on the peak combustion

pressure under a light load of 15 Nm. As mentioned earlier, the decrease in peak pressure is related to the low calorific value and high latent heat of evaporation of bioethanol. On the other hand, the increase in load directly increased the peak combustion pressure, which was clearly observed in Fig. 3(d). Compared with the results at 0 Nm, the average peak pressure was increased by 11.00% and 21.77% at 15 and 30 Nm, respectively. Injecting more fuel resulted in an increase in peak combustion pressure at high load. Therefore, reasonable control of the addition ratio and injection quantity of bioethanol can effectively improve the peak combustion pressure.

3.1.4. Effects of engine loads on HRR

Fig. 4 reports the influences of engine loads on HRR of all tested fuels under idling conditions. The HRR curve, like the cylinder pressure curve, also had two peaks. The small peak on the left was caused by pilot injection, followed by the higher peak on the right caused by main injection. As shown in Fig. 4, the ignition delay and peak HRR were significantly shortened and increased with the increase of load, respectively. Especially for BE15, the engine load had the most significant impact on ignition delay. Because the lower cetane number and higher latent heat of evaporation properties of bioethanol leads to longer ignition delay, while the increase in load improves the air-fuel ratio, gas temperature, and other favorable conditions for combustion in the cylinder, thereby shortening the ignition delay. Ultimately, the “positive effect” caused by increased load has a faster response to the ignition delay for bioethanol blended fuels. As the load increases, the position corresponding to the HRR peak was delayed for pure diesel, while almost

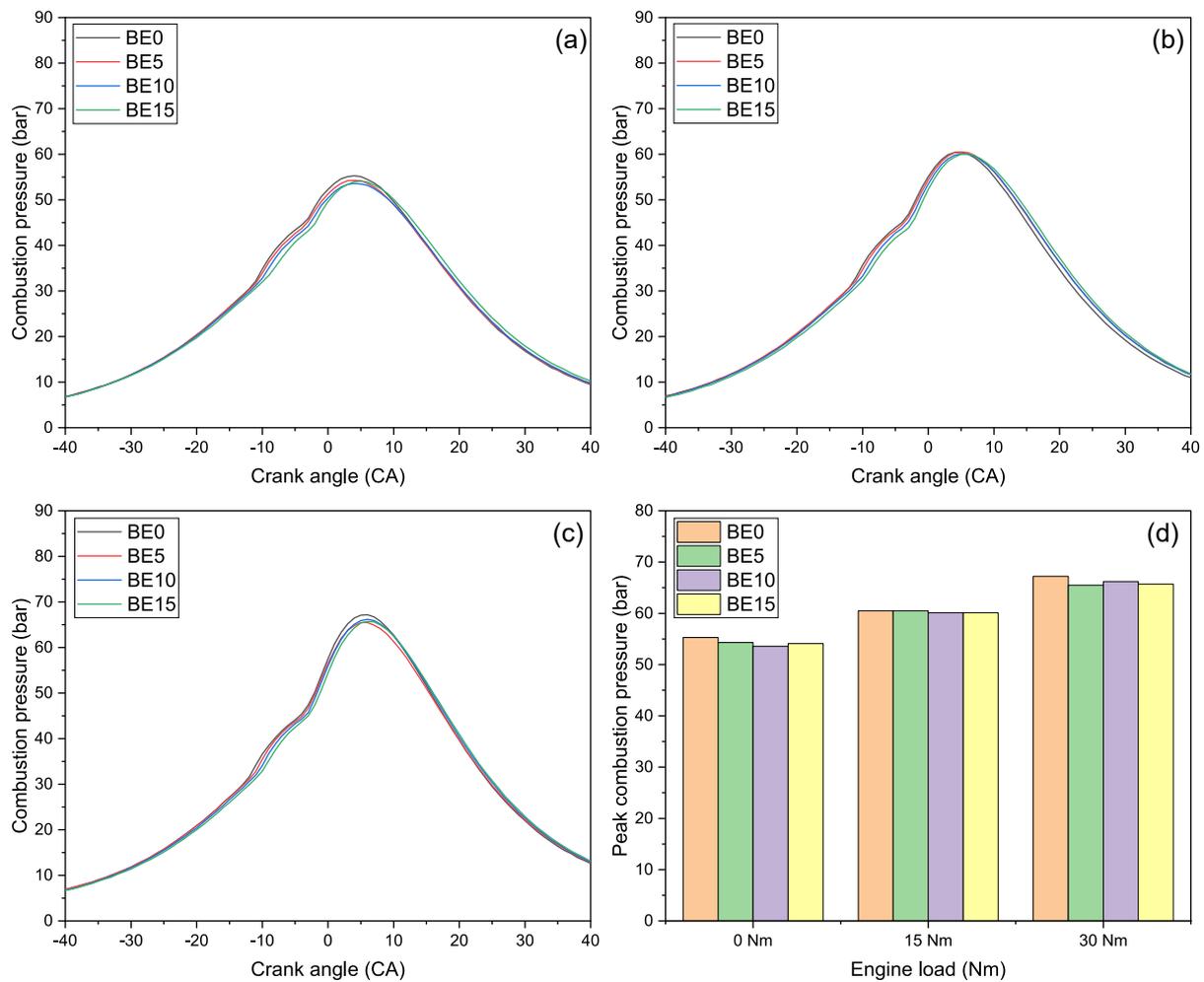


Fig. 3. Combustion pressure curves at (a) 0 Nm, (b) 15 Nm and (c) 30 Nm; (d) Peak pressures.

all diesel-bioethanol blends occurred at the same position. The increase in engine load resulted in an increase in peak HRR and a shortened ignition delay, which was also reported by [Chen et al. \(2022\)](#).

3.1.5. Influences of diesel-bioethanol blends on HRR

[Fig. 5\(a\)–\(c\)](#) shows the influences of diesel-bioethanol blends on HRR under idling conditions. Under all engine load conditions, the HRR of BE15 was the highest, with maximum values of 19.96, 23.67, and 28.81 J/CA at 0, 15, and 30 Nm, respectively. In the premixed combustion phase, it can be clearly seen that the ignition delay was further increased as the proportion of bioethanol mixture increases. In addition, the peak HRR caused by the pilot injection was the highest for pure diesel (BE0) compared to diesel-bioethanol blends. This is because the calorific value of bioethanol is low, and its latent heat of evaporation is high, resulting in a significant decrease in temperature during the atomization process of blended fuel in the combustion chamber, thereby increasing ignition delay and reducing the peak HRR in the premixed combustion phase. Similar results have also been reported by [Wang et al. \(2023\)](#). They also pointed out that the energy released by low calorific value fuels is low for the pilot injection stage with fixed injection quantity. However, for the main injection stage, the HRR peaks of most diesel-bioethanol blended fuels were higher than that of pure diesel due to the high oxygen content and high volatility of bioethanol ([Wang et al., 2023](#)). In addition, the long ignition delay caused by the low calorific value and high latent heat of evaporation of bioethanol allows sufficient time for the fuel and air to form a homogeneous mixture, promoting complete combustion and thus increasing the peak HRR.

3.1.6. Influences of diesel-bioethanol blends and loads on peak HRR

[Fig. 5\(d\)](#) shows the influences of diesel-bioethanol blends and engine loads on peak HRR. As shown in [Fig. 5\(d\)](#), the engine had a significant impact on the variation of peak HRR. The increase in engine load directly led to more fuel injection being used, thereby releasing more energy. Compared with the results at 0 Nm, the average peak HRR was increased by 35.33% and 69.42% at 15 and 30 Nm, respectively. The increase in load could improve the air-fuel ratio and cylinder gas temperature, thereby promoting complete fuel combustion and resulting in high peak HRR. The peak HRR of diesel-bioethanol blended fuels showed a gradually increasing trend only at 15 Nm. This can be explained by the fact that a load of 15 Nm belongs to intermediate operating conditions that are relatively favorable for the combustion of these diesel-bioethanol blended fuels, and the cylinder temperature and pressure under these conditions are also moderate. Under the “positive influence” of high oxygen content, high volatility and appropriate ignition delay properties of bioethanol, favorable combustion conditions are provided. Moreover, other researchers have pointed out that the low viscosity, low density and low surface tension of ethanol can form better fuel atomization and mixing, thereby accelerating combustion and releasing more heat ([Hulwan and Joshi, 2011](#)).

3.2. Engine performance

[Fig. 6](#) reports the influences of diesel-bioethanol blends and engine loads on the variation of indicated specific fuel consumption (ISFC). It was clearly observed that ISFC increased significantly with the increase

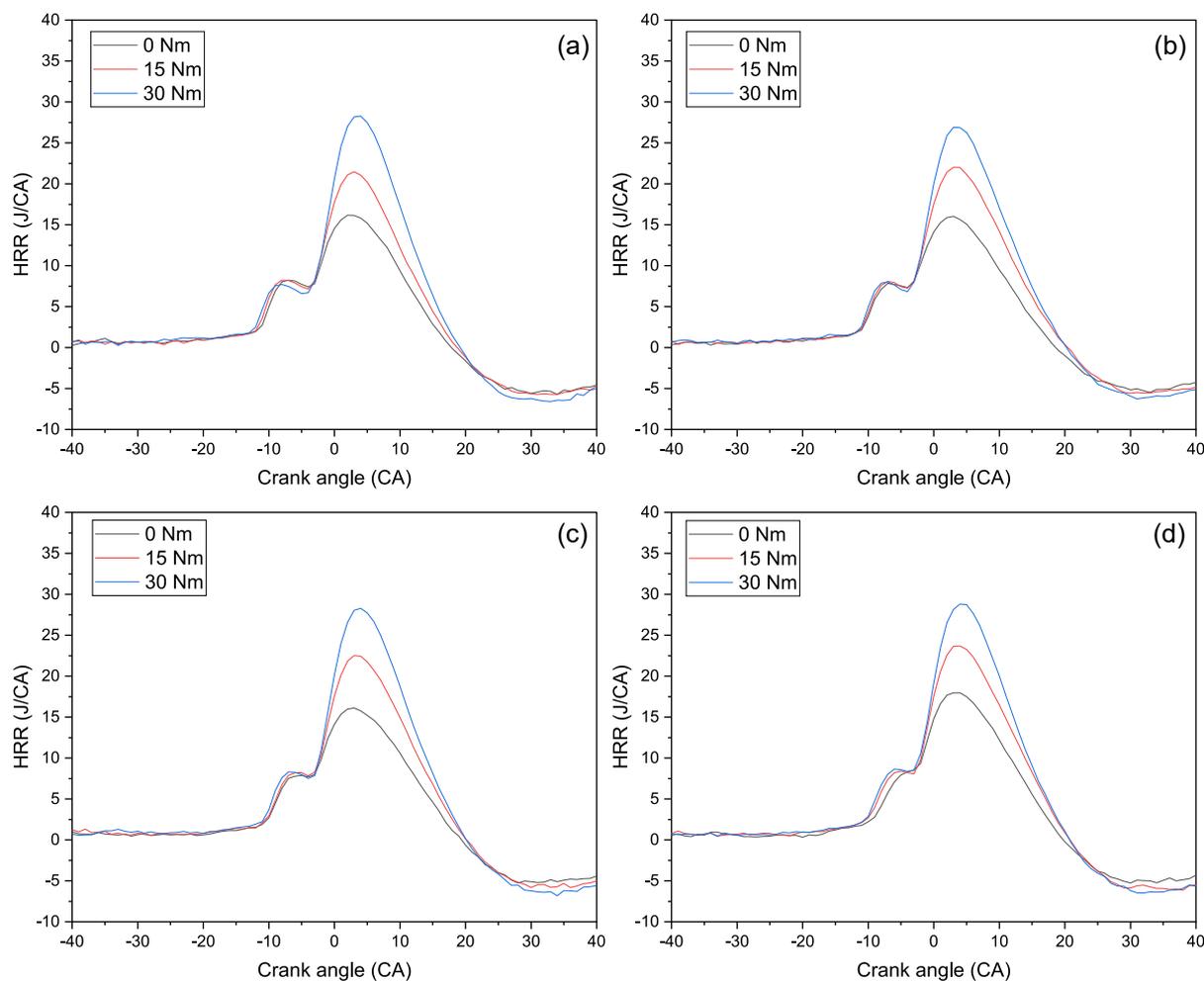


Fig. 4. HRR curves for (a) BE0, (b) BE5, (c) BE10 and (d) BE15.

of engine load for all tested fuels. Compared with the results at 0 Nm, the average ISFC for all tested fuels was increased by 20.56% and 69.28% at 15 and 30 Nm, respectively. The increase in ISFC may be related to the excessive injection of fuel into the combustion chamber caused by the increase in load. Excessive injection of fuel leads to an increase in total equivalence ratio and a decrease in combustion efficiency (Zhao et al., 2022). On the other side, the ISFCs of all diesel-bioethanol blends were higher than that of pure diesel due to the lower calorific value of bioethanol. It is worth noting that the addition of 5% and 10% bioethanol to diesel resulted in no significant increase in ISFC compared to pure diesel at 15 Nm. As mentioned earlier, 15 Nm may be a suitable operating condition for this study when using a suitable blended fuel of diesel-biodiesel in this diesel engine. Although bioethanol has a lower calorific value, its high oxygen content and volatility can improve the mixing uniformity between fuel and air, thereby increasing combustion efficiency and shortening the gap with pure diesel in ISFC.

3.3. Emission characteristics

3.3.1. CO emissions

The CO emissions of diesel-bioethanol blends under idling conditions are shown in Fig. 7. Overall, the addition of ethanol resulted in varying degrees of increase in CO emissions for most tested fuels, especially at 0 Nm, where CO emissions showed a continuously increasing trend. At 0 Nm, the CO emissions of the BE5, BE10 and BE15 were increased by 1.82%, 18.18% and 57.73% compared with that of BE0, respectively. In addition, CO emissions showed a decreasing trend as the load increased from 0 to 30 Nm. For all tested fuels, the CO emissions were reduced by

an average of 2.57% and 17.32% at 15 and 30 Nm compared to the result at 0 Nm, respectively. The reason for the slight increase in load leading to a decrease in CO emissions may be attributed to the slightly higher air-fuel ratio and high combustion temperature inside the cylinder. In addition, based on the fact that bioethanol contains approximately 35% oxygen, it is beneficial for improving the air-fuel ratio (Hulwan and Joshi, 2011). Therefore, a suitable combination of air-fuel ratio and combustion temperature resulted in minimal CO emissions, such as for BE5 and BE10 at 30 Nm. Several studies suggest that the higher oxygen content and lower carbon to hydrogen ratio resulting by adding appropriate bioethanol can promote further oxidation of CO under high engine loads due to high combustion temperature inside the cylinder (Caligiuri et al., 2019). The cooling effect inherent in bioethanol had a significant effect on the increase of CO emissions at 0 Nm. Because even with sufficient oxygen available for combustion at 0 Nm, lower temperature and delayed combustion could inhibit the oxidation of CO to CO₂. Therefore, in order to minimize CO emissions under idling conditions, the engine load can be appropriately increased.

3.3.2. HC emissions

Fig. 8 illustrates the influences of diesel-bioethanol blends on HC emissions under idling conditions. It is well-known that HC emissions are an unburned substance in fuel, which is mainly produced due to uneven mixture, cold cylinder wall, low heating value, low combustion temperature, wall wetting, residual fuel in the sac volume, and fuel sliding into cylinder gaps (Emiroğlu and Şen, 2018b; Fang et al., 2013; Park et al., 2011; Tutak et al., 2017). It can be clearly observed that with the addition of bioethanol in diesel, the HC emissions increased under the

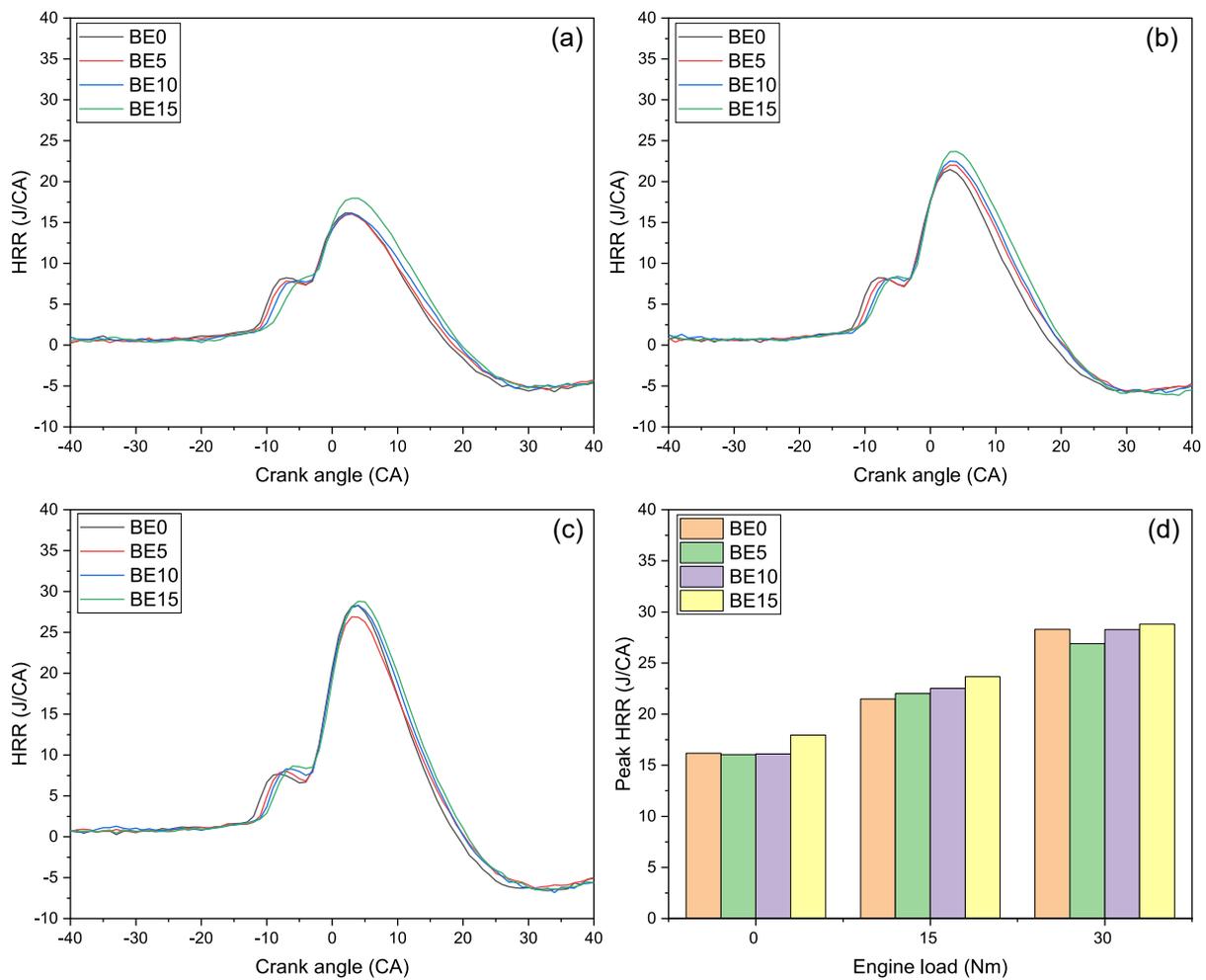


Fig. 5. HRR curves at (a) 0 Nm, (b) 15 Nm and (c) 30 Nm; (d) Peak HRR.

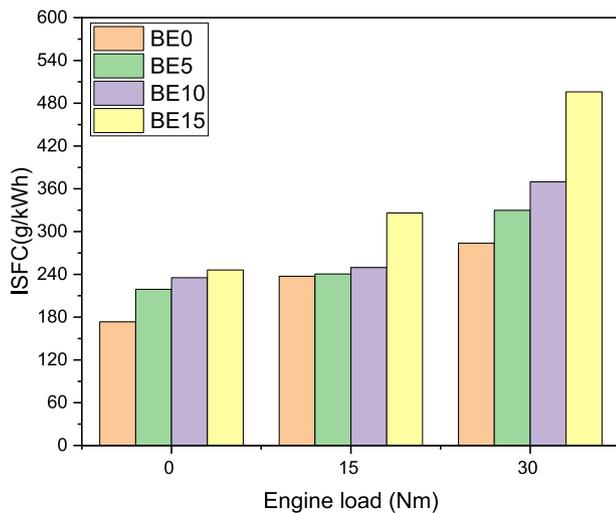


Fig. 6. ISFC for diesel-bioethanol blended fuels.

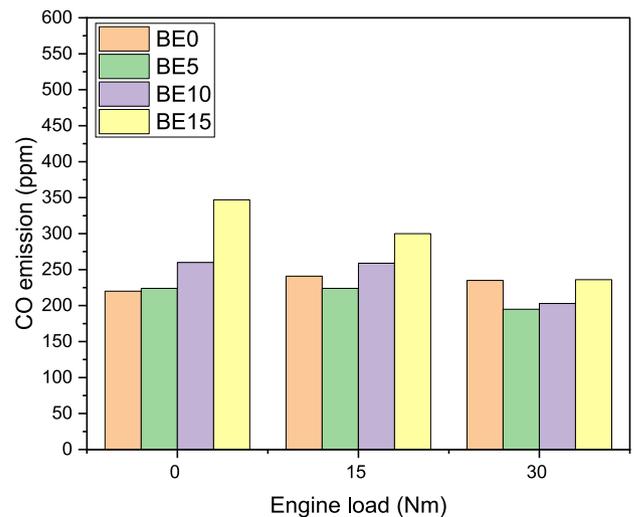


Fig. 7. Comparisons of CO emissions for diesel-bioethanol blended fuels.

same engine load conditions. The increase in HC emissions from bioethanol blended fuels may be related to the high latent heat of evaporation property of the bioethanol. The cooling effect caused by bioethanol during atomization reduces the cylinder wall temperature, resulting in a small amount of fuel coming into contact with the cold cylinder wall and causing misfire. In addition, the increase in HC

emissions caused by the addition of bioethanol may also be related to lower cetane number, longer ignition delay and lower heating value (Emiroğlu and Şen, 2018b; Park et al., 2011). Low cetane number and high heat of evaporation of bioethanol result in prolonged ignition delay and slow burning over late phases of the combustion (Labeckas et al., 2014). The fuel with low calorific value reduces energy release and

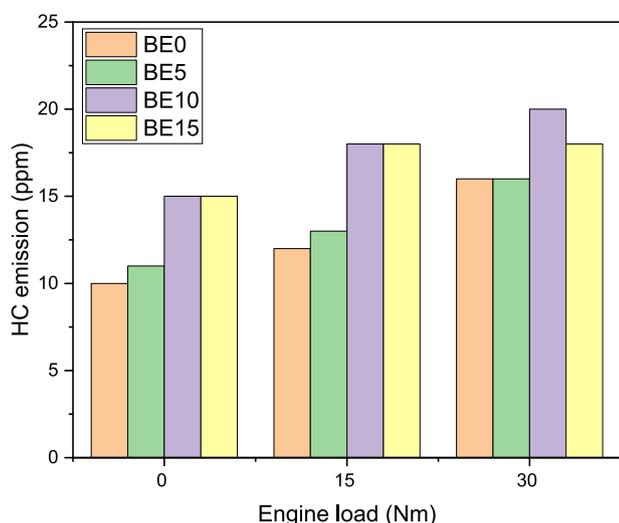


Fig. 8. Comparisons of HC emissions for diesel-bioethanol blended fuels.

combustion temperature, thereby increasing the generation of HC emissions (Emiroğlu and Şen, 2018b). On the other hand, an average increase of 19.61% and 37.25% was observed for all tested fuels at 15 and 30 Nm compared to 0 Nm, respectively. This may be mainly related to excessive fuel injection, which reduces the air-fuel ratio at low load. Similar findings were obtained in (Emiroğlu and Şen, 2018b; Qi et al., 2010). Therefore, the generation of HC emissions can be reduced by appropriately reducing the fuel injection amount under idling conditions.

3.3.3. NOx emissions

The emission results of NO_x of four tested fuels under idling conditions are presented in Fig. 9. Many researchers (Park et al., 2011; Zhang et al., 2022) have shown that the mechanism of NO_x generation in diesel engines mainly depends on the following three conditions: 1) combustion temperature in the cylinder, 2) local oxygen concentration, and 3) residence time in high-temperature regions. The NO_x emissions of diesel engines is mainly composed of 90%~95% NO formed within and beyond the flame front, with the rest being nitrogen dioxide (NO₂) (Labeckas et al., 2014). As shown in Fig. 9, NO_x emissions were significantly reduced with the addition of bioethanol, with a maximum decrease of 50% compared to pure diesel at 30 Nm for diesel-bioethanol blends. The reduction of NO_x with the increasing of bioethanol may be mainly related to the cooling effect caused by the high latent heat of evaporation of

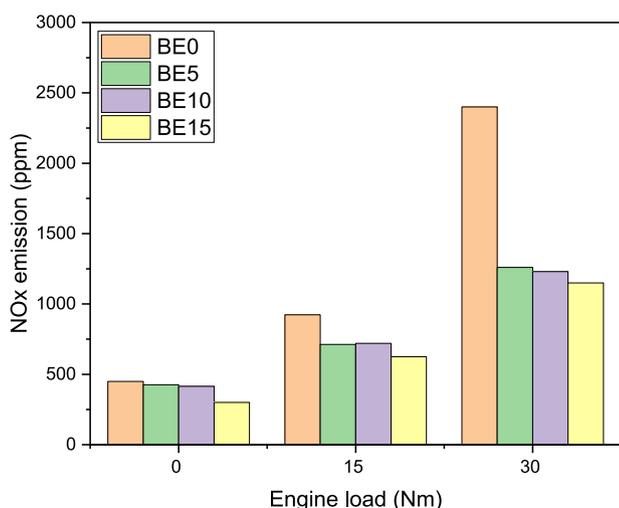


Fig. 9. Comparisons of NO_x emissions for diesel-bioethanol blended fuels.

bioethanol. Although bioethanol is a high oxygen low cetane fuel that can increase the formation of NO_x emissions by increasing local oxygen concentration and ignition delay, bioethanol also has a high latent heat of evaporation, and its cooling effect dominates, resulting in a decrease in the maximum combustion temperature inside the cylinder under the idling conditions. This result is consistent with the research findings from Guido et al. (2013). In summary, the addition of ethanol leads to an increase in NO emissions, which is related to the combined effects of high latent heat of evaporation, low calorific value, and low cetane number of bioethanol. High latent heat of evaporation and low calorific value play a cooling role in the fuel atomization process, reducing gas temperature and adiabatic flame temperature, and ultimately lowering the combustion temperature in the cylinder (Caligiuri et al., 2019; Labeckas et al., 2014). In addition, the lower cetane number of bioethanol may cause longer ignition delay, resulting in a thinner mixture, which in turn reduces combustion temperature and slows down the reaction rate of nitrogen and oxygen (Park et al., 2011). Moreover, bioethanol also has good volatility, which makes it easy to form a relatively homogeneous lean-mixture. Compared with conventional diesel fuel, the fuel spray cone angle of bioethanol is wider, which is beneficial to improving the mixing of air and fuel vapor, and contributing to a more uniform temperature distribution in the cylinder (Labeckas et al., 2014). On the other hand, the increase in load led to a significant increase in NO_x emissions under idling conditions. Compared to 0 Nm, an average increase of 87.37% and 279.64% was observed for all tested fuels at 15 and 30 Nm, respectively. Because more fuel was injected into the cylinder under high load, thereby increasing the combustion temperature and pressure inside the cylinder. Therefore, to reduce NO_x emissions under idling conditions, it can be achieved by appropriately adding bioethanol and reducing fuel injection quantity.

3.3.4. Smoke emissions

The emission results of smoke of four tested fuels under idling conditions are presented in Fig. 10. The particulate matter (PM) or smoke or soot emissions from diesel engines is mainly composed of carbon and some hydrogen adsorbed on the surface of particles (known as SOF, soluble organic fraction), which is usually formed through primary soot formation and soot oxidation. The former mainly depends on the molecular rate of collision and the concentration of fuel fragments, while the latter mainly depends on the active radical nuclei of fuel molecules in gas-phase collisions (Emiroğlu and Şen, 2018b; Hulwan and Joshi, 2011). For studying the smoke characteristics of diesel engines, soot or particles are considered the main substances that cause smoke opacity. The measurement of smoke opacity is calculated by using an opacity tester

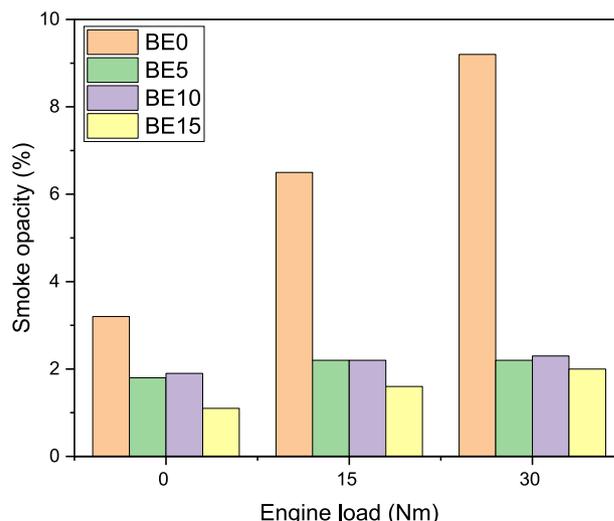


Fig. 10. Comparisons of smoke emissions under idling conditions.

with a light source and a photodetector to measure the degree of attenuation of light passing through the exhaust emissions.

As shown in Fig. 10, the smoke opacity of diesel-bioethanol blended fuels was much lower than that of pure diesel at the same load. As mentioned earlier, bioethanol has high oxygen content, which can greatly improve the problem of oxygen deficiency in local fuel rich areas. Moreover, bioethanol also has high latent heat of evaporation, high volatility, low cetane number and low calorific value, etc. With the help of these unique properties, a more homogeneous lean-mixture can be formed, thereby promoting complete combustion of the fuel and reducing the generation of smoke. In addition, the lower carbon to hydrogen ratio of bioethanol (seen in Table 1) is also one of the main reasons for reducing smoke emissions. The lower the carbon a fuel molecule contains, the lower the smoke formation (Emiroğlu and Şen, 2018b). Compared with pure diesel, diesel-bioethanol blended fuels reduced smoke emissions by 40%–80% under all load conditions. Especially at 15 and 30 Nm, the smoke emission reduction rate remained above 66%. The effect of diesel-bioethanol blends on reducing smoke emissions under high load was significantly better than that under low load, which has also been reported by Fang et al. (2013). The reduction of smoke emissions is also related to the source of OH in ethanol. During the formation of OH ($C_2H_5OH \rightarrow C_2H_4 + H_2O$, $H_2O + H \rightarrow OH + H_2$), active hydrogen atoms were converted into hydrogen molecules, thereby reducing the generation of soot (Zhu et al., 2011). Moreover, the addition of bioethanol can also reduce the initial radicals for the formation of aromatic rings, thereby reducing the precursor for the formation of smoke particles (Zhu et al., 2011). Under idling conditions, even with a slight increase in engine load, a significant increase in smoke emissions was observed. Compared with the results at 0 Nm, the smoke opacity was increased by an average of 56.25% and 96.25% at 15 and 30 Nm, respectively. The increase in load led to an increase in fuel injection quantity, thereby reducing the air-fuel ratio and resulting in incomplete combustion (Hulwan and Joshi, 2011). Therefore, the generation of smoke emissions under idling conditions can be effectively controlled by adding a certain amount of bioethanol to diesel fuel and appropriately reducing the load.

4. Conclusions

In the present work, the effects of diesel-bioethanol blends on combustion and emissions of a diesel engine under idling conditions were comparatively investigated. The main conclusions can be summarized as follows:

- i. The effect of engine load on combustion pressure and heat release rate (HRR) was much greater than that of diesel-bioethanol blends, while the addition of bioethanol had a smaller impact on combustion pressure changes than on HRR due to the combined effects of bioethanol's low cetane number, high latent heat of evaporation and good volatility.
- ii. Even a slight increase in load resulted in a significant increase of over 20% in indicated specific fuel consumption (ISFC) for all tested fuels on average. Overall, the addition of 5% and 10% bioethanol had little effect on the changes in ISFC at 15 Nm.
- iii. Although the addition of bioethanol is detrimental to the reduction of CO and HC emissions, it improved the NO_x and smoke trade-off relationship. The NO_x and smoke opacity were simultaneously reduced, with maximum reductions of 52.08% and 78.26% at 30 Nm, respectively.

5. Future works

Besides ethanol, methanol is also commonly used as a low-carbon fuel. Therefore, in future work, the combustion and emission characteristics of methanol and ethanol in diesel engines will be compared based on different blending ratios and operating conditions such as engine load,

speed, injection pressure, and injection timing. Future works are mainly focused on studying the effects of alcohol low-carbon fuel properties such as volatility, latent heat of evaporation, calorific value, cetane number, oxygen content and carbon hydrogen ratio on combustion and emissions, as well as exploring their influencing mechanisms.

CRediT authorship contribution statement

Jun Cong Ge: Data curation; Funding acquisition; Investigation; Methodology; Roles/Writing - original draft; **Lifeng Wang:** Funding acquisition; Investigation; Methodology; Writing - review & editing. **Hongliang Luo:** Funding acquisition; Investigation; Methodology; Resources; Writing - review & editing. **Nag Jung Choi:** Funding acquisition; Investigation; Methodology; Project administration; Resources; Writing - review & editing.

Declaration of competing interest

All authors of this article declare that there is no conflict of interest.

Acknowledgements

This study is financially supported by the Open Research Subject of Key Laboratory of Fluid Machinery and Engineering (Xihua University), Sichuan Province (LTJX-2024 002) and the National Key Laboratory of Marine Engine Science and Technology (LAB-2023-01) and the Open Fund of Key Laboratory of Oil & Gas Equipment, Ministry of Education (Southwest Petroleum University) (OGE202302-04) and the Fundamental Research Funds for the Central Universities (3072023CFJ0304).

References

- Abdellatif, T.M., Ershov, M.A., Kapustin, V.M., Abdelkareem, M.A., Kamil, M., Olabi, A., 2021. Recent trends for introducing promising fuel components to enhance the anti-knock quality of gasoline: a systematic review. *Fuel* 291, 120112.
- Basha, S.A., Gopal, K.R., Jebaraj, S., 2009. A review on biodiesel production, combustion, emissions and performance. *Renew. Sustain. Energy Rev.* 13 (6), 1628–1634. <https://doi.org/10.1016/j.rser.2008.09.031>.
- Beatrice, C., Denbratt, I., Di Blasio, G., Di Luca, G., Ianniello, R., Saccullo, M., 2020. Experimental assessment on exploiting low carbon ethanol fuel in a light-duty dual-fuel compression ignition engine. *Appl. Sci.* 10 (20), 7182.
- Bušić, A., Mardetko, N., Kundas, S., Morzak, G., Belskaya, H., Ivancić Santek, M., Komes, D., Novak, S., Santek, B., 2018. Bioethanol production from renewable raw materials and its separation and purification: a review. *Food Technol. Biotechnol.* 56 (3), 289–311.
- Caligiuri, C., Renzi, M., Bietresato, M., Baratieri, M., 2019. Experimental investigation on the effects of bioethanol addition in diesel-biodiesel blends on emissions and performances of a micro-cogeneration system. *Energy Convers. Manag.* 185, 55–65. <https://doi.org/10.1016/j.enconman.2019.01.097>.
- Campos-Fernández, J., Arnal, J.M., Gómez, J., Dorado, M.P., 2012. A comparison of performance of higher alcohols/diesel fuel blends in a diesel engine. *Appl. Energy* 95, 267–275.
- Chen, Q., Wang, C., Shao, K., Liu, Y., Chen, X., Qian, Y., 2022. Analyzing the combustion and emissions of a DI diesel engine powered by primary alcohol (methanol, ethanol, n-butanol)/diesel blend with aluminum nano-additives. *Fuel* 328, 125222. <https://doi.org/10.1016/j.fuel.2022.125222>.
- Cripwell, R.A., Favaro, L., Viljoen-Bloom, M., van Zyl, W.H., 2020. Consolidated bioprocessing of raw starch to ethanol by *Saccharomyces cerevisiae*: achievements and challenges. *Biotechnol. Adv.* 42, 107579.
- Devarajan, Y., 2019. Experimental evaluation of combustion, emission and performance of research diesel engine fuelled di-methyl- carbonate and biodiesel blends. *Atmos. Pollut. Res.* 10 (3), 795–801. <https://doi.org/10.1016/j.apr.2018.12.007>.
- E, J., Pham, M., Zhao, D., Deng, Y., Le, D., Zuo, W., Zhu, H., Liu, T., Peng, Q., Zhang, Z., 2017. Effect of different technologies on combustion and emissions of the diesel engine fueled with biodiesel: a review. *Renew. Sustain. Energy Rev.* 80, 620–647. <https://doi.org/10.1016/j.rser.2017.05.250>.
- Emiroğlu, A.O., Şen, M., 2018a. Combustion, performance and emission characteristics of various alcohol blends in a single cylinder diesel engine. *Fuel* 212, 34–40. <https://doi.org/10.1016/j.fuel.2017.10.016>.
- Emiroğlu, A.O., Şen, M., 2018b. Combustion, performance and exhaust emission characterizations of a diesel engine operating with a ternary blend (alcohol-biodiesel-diesel fuel). *Appl. Therm. Eng.* 133, 371–380. <https://doi.org/10.1016/j.applthermaleng.2018.01.069>.
- Erdoğan, S., Balki, M.K., Sayin, C., 2019. The effect on the knock intensity of high viscosity biodiesel use in a DI diesel engine. *Fuel* 253, 1162–1167. <https://doi.org/10.1016/j.fuel.2019.05.114>.

- Fang, Q., Fang, J., Zhuang, J., Huang, Z., 2013. Effects of ethanol–diesel–biodiesel blends on combustion and emissions in premixed low temperature combustion. *Appl. Therm. Eng.* 54 (2), 541–548. <https://doi.org/10.1016/j.applthermaleng.2013.01.042>.
- García-Lara, S., Serna-Saldivar, S.O., 2019. Corn History and Culture. *Corn*, pp. 1–18.
- Ge, J.C., Wu, G., Choi, N.J., 2022a. Comparative study of pilot–main injection timings and diesel/ethanol binary blends on combustion, emission and microstructure of particles emitted from diesel engines. *Fuel* 313, 122658. <https://doi.org/10.1016/j.fuel.2021.122658>.
- Ge, J.C., Wu, G., Yoo, B.-O., Choi, N.J., 2022b. Effect of injection timing on combustion, emission and particle morphology of an old diesel engine fueled with ternary blends at low idling operations. *Energy* 253, 124150. <https://doi.org/10.1016/j.energy.2022.124150>.
- Guido, C., Beatrice, C., Napolitano, P., 2013. Application of bioethanol/RME/diesel blend in a Euro5 automotive diesel engine: potentiality of closed loop combustion control technology. *Appl. Energy* 102, 13–23. <https://doi.org/10.1016/j.apenergy.2012.08.051>.
- Hansen, A.C., Zhang, Q., Lyne, P.W.L., 2005. Ethanol–diesel fuel blends — a review. *Bioresour. Technol.* 96 (3), 277–285. <https://doi.org/10.1016/j.biortech.2004.04.007>.
- Hua, Y., Liu, S., Li, R., Mei, L., 2020. Experimental study of regulated and unregulated emissions from a diesel engine using coal-based fuels. *Fuel* 280, 118658. <https://doi.org/10.1016/j.fuel.2020.118658>.
- Hulwan, D.B., Joshi, S.V., 2011. Performance, emission and combustion characteristic of a multicylinder DI diesel engine running on diesel–ethanol–biodiesel blends of high ethanol content. *Appl. Energy* 88 (12), 5042–5055. <https://doi.org/10.1016/j.apenergy.2011.07.008>.
- Kang, Y.-H., Zhang, X.-Q., Gao, J., Wei, X.-Y., Xue, C.-H., Li, Y.-J., Gao, Y., Liu, G.-H., Bai, J.-J., Ma, X.-R., 2021. Deep hydroconversion of ethanol-soluble portion from the ethanols of Hecaoguo subbituminous coal to ultra-clean liquid fuel over hierarchical porous zeolite Y supported Ni–Co nanoparticles. *J. Energy Inst.* 99, 88–96.
- Khouani, Z., Nazemi, F., Shafiei, M., Aghbashlo, M., Tabatabaei, M., 2019. Techno-economic aspects of a safflower-based biorefinery plant co-producing bioethanol and biodiesel. *Energy Convers. Manag.* 201, 112184. <https://doi.org/10.1016/j.enconman.2019.112184>.
- Labeckas, G., Slavinskas, S., Mažeika, M., 2014. The effect of ethanol–diesel–biodiesel blends on combustion, performance and emissions of a direct injection diesel engine. *Energy Convers. Manag.* 79, 698–720. <https://doi.org/10.1016/j.enconman.2013.12.064>.
- Lu, J., 2011. In: *Environmental Effects of Vehicle Exhausts, Global and Local Effects: a Comparison between Gasoline and Diesel*.
- Mizik, T., Gyarmati, G., 2021. Economic and sustainability of biodiesel production—a systematic literature review. *Cleanroom Technol.* 3 (1), 19–36.
- Odziemkowska, M., Matuszewska, A., Czarnocka, J., 2016. Diesel oil with bioethanol as a fuel for compression-ignition engines. *Appl. Energy* 184, 1264–1272. <https://doi.org/10.1016/j.apenergy.2016.07.069>.
- Othman, M.F., Adam, A., Najafi, G., Mamat, R., 2017. Green fuel as alternative fuel for diesel engine: a review. *Renew. Sustain. Energy Rev.* 80, 694–709. <https://doi.org/10.1016/j.rser.2017.05.140>.
- Park, S.H., Youn, I.M., Lee, C.S., 2011. Influence of ethanol blends on the combustion performance and exhaust emission characteristics of a four-cylinder diesel engine at various engine loads and injection timings. *Fuel* 90 (2), 748–755. <https://doi.org/10.1016/j.fuel.2010.08.029>.
- Petrauskienė, K., Skvarnavičiūtė, M., Dvarionienė, J., 2020. Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania. *J. Clean. Prod.* 246, 119042. <https://doi.org/10.1016/j.jclepro.2019.119042>.
- Pradelle, F., Leal Braga, S., Fonseca de Aguiar Martins, A.R., Turkovics, F., Nohra Chaar Pradelle, R., 2019. Experimental assessment of some key physicochemical properties of diesel-biodiesel-ethanol (DBE) blends for use in compression ignition engines. *Fuel* 248, 241–253. <https://doi.org/10.1016/j.fuel.2019.03.087>.
- Qi, D.H., Chen, H., Geng, L.M., Bian, Y.Z., 2010. Experimental studies on the combustion characteristics and performance of a direct injection engine fueled with biodiesel/diesel blends. *Energy Convers. Manag.* 51 (12), 2985–2992. <https://doi.org/10.1016/j.enconman.2010.06.042>.
- Rahman, S.M.A., Masjuki, H.H., Kalam, M.A., Abedin, M.J., Sanjid, A., Imtenan, S., 2014. Effect of idling on fuel consumption and emissions of a diesel engine fueled by Jatropha biodiesel blends. *J. Clean. Prod.* 69, 208–215. <https://doi.org/10.1016/j.jclepro.2014.01.048>.
- Rahman, S.M.A., Masjuki, H.H., Kalam, M.A., Abedin, M.J., Sanjid, A., Sajjad, H., 2013a. Impact of idling on fuel consumption and exhaust emissions and available idle-reduction technologies for diesel vehicles – a review. *Energy Convers. Manag.* 74, 171–182. <https://doi.org/10.1016/j.enconman.2013.05.019>.
- Rahman, S.M.A., Masjuki, H.H., Kalam, M.A., Abedin, M.J., Sanjid, A., Sajjad, H., 2013b. Production of palm and Calophyllum inophyllum based biodiesel and investigation of blend performance and exhaust emission in an unmodified diesel engine at high idling conditions. *Energy Convers. Manag.* 76, 362–367. <https://doi.org/10.1016/j.enconman.2013.07.061>.
- Rakopoulos, C.D., Rakopoulos, D.C., Kosmadakis, G.M., Papagiannakis, R.G., 2019. Experimental comparative assessment of butanol or ethanol diesel-fuel extenders impact on combustion features, cyclic irregularity, and regulated emissions balance in heavy-duty diesel engine. *Energy* 174, 1145–1157. <https://doi.org/10.1016/j.energy.2019.03.063>.
- Roy, M.M., Wang, W., Alawi, M., 2014. Performance and emissions of a diesel engine fueled by biodiesel–diesel, biodiesel–diesel-additive and kerosene–biodiesel blends. *Energy Convers. Manag.* 84, 164–173. <https://doi.org/10.1016/j.enconman.2014.04.033>.
- Shrivastava, K., Thipse, S.S., Patil, I.D., 2021. Optimization of diesel engine performance and emission parameters of Karanja biodiesel-ethanol-diesel blends at optimized operating conditions. *Fuel* 293, 120451. <https://doi.org/10.1016/j.fuel.2021.120451>.
- Thangavelu, S.K., Ahmed, A.S., Ani, F.N., 2016. Impact of metals on corrosive behavior of biodiesel–diesel–ethanol (BDE) alternative fuel. *Renew. Energy* 94, 1–9.
- Tipanluisa, L., Fonseca, N., Casanova, J., López, J.-M., 2021. Effect of n-butanol/diesel blends on performance and emissions of a heavy-duty diesel engine tested under the World Harmonised Steady-State cycle. *Fuel* 302, 121204. <https://doi.org/10.1016/j.fuel.2021.121204>.
- Tutak, W., Jamrozik, A., Pyrc, M., Sobiepański, M., 2017. A comparative study of co-combustion process of diesel-ethanol and biodiesel-ethanol blends in the direct injection diesel engine. *Appl. Therm. Eng.* 117, 155–163. <https://doi.org/10.1016/j.applthermaleng.2017.02.029>.
- Vignesh, R., Ashok, B., Jeevanantham, A.K., Jacob, A., Bhembre, R.D.P., Sharma, S.S., Hire, K.R.B., 2021. Enhancement of idling characteristics using multi-objective approach in light-duty diesel Vehicle fuelled with orange peel biofuel. *Fuel* 291, 120222. <https://doi.org/10.1016/j.fuel.2021.120222>.
- Wang, X., Gao, J., Chen, Z., Chen, H., Zhao, Y., Huang, Y., Chen, Z., 2022. Evaluation of hydrous ethanol as a fuel for internal combustion engines: a review. *Renew. Energy* 194, 504–525. <https://doi.org/10.1016/j.renene.2022.05.132>.
- Wang, X., Geng, C., Dong, J., Li, X., Xu, T., Jin, C., Liu, H., Mao, B., 2023. Effect of diesel/PODE/ethanol blends coupled pilot injection strategy on combustion and emissions of a heavy duty diesel engine. *Fuel* 335, 127024. <https://doi.org/10.1016/j.fuel.2022.127024>.
- Yahuza, I., Dandakouta, H., 2015. A performance review of ethanol-diesel blended fuel samples in compression-ignition engine. *J. Chem. Eng. Process Technol.* 6 (5), 1–6.
- Ying, W., Genbao, L., Wei, Z., Longbao, Z., 2008. Study on the application of DME/diesel blends in a diesel engine. *Fuel Process. Technol.* 89 (12), 1272–1280.
- Zhang, Z., Tian, J., Li, J., Lv, J., Wang, S., Zhong, Y., Dong, R., Gao, S., Cao, C., Tan, D., 2022. Investigation on combustion, performance and emission characteristics of a diesel engine fueled with diesel/alcohol/n-butanol blended fuels. *Fuel* 320, 123975. <https://doi.org/10.1016/j.fuel.2022.123975>.
- Zhao, W., Yan, J., Gao, S., Lee, T.H., Li, X., 2022. The combustion and emission characteristics of a common-rail diesel engine fueled with diesel and higher alcohols blends with a high blend ratio. *Energy* 261, 124972. <https://doi.org/10.1016/j.energy.2022.124972>.
- Zhu, L., Cheung, C.S., Zhang, W.G., Huang, Z., 2011. Combustion, performance and emission characteristics of a DI diesel engine fueled with ethanol–biodiesel blends. *Fuel* 90 (5), 1743–1750. <https://doi.org/10.1016/j.fuel.2011.01.024>.