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Effect of Injection Timing on Performance and Emissions of a CRDI Diesel Engine Using Biodiesel-n-Octanol Blend Fuel

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Abstract

The global pursuit of sustainable energy and environmental conservation has led to a growing interest in renewable fuel sources. Among the primary consumers of energy are the agriculture, industrial, and transportation sectors, which concurrently represent major contributors to environmental degradation due to their high reliance on fossil fuels. Diesel engines, which are extensively utilized across these sectors, emit significant quantities of harmful pollutants as a result of fossil-based fuel combustion. In this context, biodiesel emerges as a viable and environmentally sustainable alternative to conventional diesel fuels. It can be synthesized from various feedstocks, including waste cooking oils and vegetable oils, thereby offering dual benefits: effective waste oil management and the utilization of renewable, plant-derived resources. This study aims to examine the impact of biodiesel produced from waste oils, as well as its blend with n-octanol, on the performance and emission characteristics of a diesel engine. Experimental tests were conducted at a constant engine speed of 150 rpm, under two different injection timing settings and four distinct engine load conditions (25%, 50%, 75%, and 100%). At standard injection timing, engine power of B95O5 decreased by 6.8% compared to B100. While there was no significant change in exhaust gas temperature, BSFC decreased by approximately 1.7%. With increasing injection timing, a slight decrease in engine power of B95O5 (0.9%) was measured, while EGT decreased by 5.5% and BSFC by approximately 6%. The greatest reduction in HC emissions compared to B100 was achieved with B95O5 +2CA with 4.5%. CO_2 increased by 9.4% in the same fuel operation. Again, NO emissions increased by 5.6% compared to B100 in the same fuel operation.

Keywords: CRDI, Biodiesel, n-octanol, Injection timing

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Biyodizel-n-Oktanol Karışımı Yakıt Kullanan CRDI Dizel Motorun Performansı ve Emisyonları Üzerinde Enjeksiyon Zamanlamasının Etkisi

Özet

Sürdürülebilir enerji ve çevre koruma hedeflerine ulaşmak için yenilenebilir yakıt kaynaklarına olan ilgi her geçen gün artmaktadır. Enerji tüketiminin en büyük payı tarım, sanayi ve ulaşım sektörlerinde gerçekleşmektedir. Dolayısıyla bu sektörler, çevresel tahribatta da önemli bir rol oynamaktadır. Dizel motorlar, bu sektörlerde yaygın olarak kullanılmaktadır. Fosil kaynaklı yakıtlarla çalıştıkları için önemli miktarda zararlı emisyonu çevreye salmaktadırlar. Biyodizel, bu motorlar için mükemmel bir alternatif yakıttır. Çeşitli atık yağlardan ve bitkisel yağlardan üretilebilir. Biyodizel, hem atık yağların değerlendirilmesindeki rolü hem de bitkisel kaynaklı üretimi sayesinde çevre dostu bir yakıt olarak kabul edilebilir. Bu çalışmada, atık yağlardan üretilen biyodizel ve n-oktanol karışımının motor performansı ve emisyonlar üzerindeki etkileri incelenmiştir.

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Testler, sabit 1500 dev/dak motor hızında, iki farklı enjeksiyon zamanlaması ve dört farklı yük koşulunda (%25, %50, %75 ve %100) gerçekleştirilmiştir. Standart enjeksiyon zamanlamasında, B100 yakıtı, B95O5 karışımına kıyasla daha iyi motor performansı ve daha düşük egzoz emisyon değerleri sergilemiştir. B100 ile enjeksiyon zamanlaması öne alındığında motor performansı düşmüş, egzoz emisyonları ise artmıştır. Ancak B95O5 test yakıtında enjeksiyon zamanının öne alınması, hem motor performansını hem de egzoz emisyonlarını iyileştirmiştir.

Anahtar Kelimeler: CRDI, Biyodizel, n-oktanol, Enjeksiyon zamanlaması

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1. Introduction

Diesel engines are widely used in transportation and industrial applications due to their high efficiency, durability, and low fuel consumption [1]. However, the environmental impact of fossil-based diesel fuels and growing sustainability concerns have accelerated the search for alternative fuels [2], [3]. In this context, renewable fuels such as biodiesel stand out due to their cleaner combustion characteristics and potential for carbon neutrality.

Biodiesel, produced from biological sources such as vegetable oils, animal fats, or waste oils, can be used either in its pure form or blended with conventional diesel [4]. Biodiesel offers significant advantages in terms of emission reduction when used in appropriate proportions with diesel fuel. However, when this proportion is increased or used in pure form, it has been reported to increase brake specific fuel consumption (BSFC) and NOx emissions [5], [6]. To overcome these problems, various fuel additives such as methanol, ethanol, butanol, octanol, etc. are generally used to improve the properties of biodiesel and provide optimum engine performance. This study examines the effects of biodiesel and fuel additives on engine performance, emissions, and fuel characteristics. Additionally, it evaluates the influence of different additives on the physicochemical properties and combustion behavior of biodiesel-diesel blends [7].

n-Octanol (1-octanol), being a long-chain alcohol with favorable combustion properties, offers several advantages as a fuel additive in both gasoline and diesel engines, including performance enhancement and emission reduction [8]. n-Octanol possesses a high cetane number, oxygen content, and energy density [9], [10], [11]. These characteristics enable better fuel ignition, reduced engine knocking, and lower CO and particulate matter emissions. Due to its high energy density, it increases engine power output. n-Octanol forms more homogeneous blends with biodiesel.

Chaurasiya et al. [12], reported that the n-butanol blended fuel with modified injection timing resulted in reduced BSFC. They observed no significant changes in EGT for any of the tested fuels. The researchers documented that the lowest emissions were achieved with the n-butanol additive.

Nayak et al. [13], investigated the performance impact of diesel, biodiesel, and t-butyl peroxide blends under different injection timings in a compression ignition engine. Their experimental results demonstrated that advancing the injection timing improved both engine performance and emissions, while simultaneously reporting an increase in NOx emissions.

Nghia et al. [14], experimentally investigated the effects of injection timing on engine performance and exhaust emissions in a CRDI-equipped diesel engine using biodiesel-blended fuels. Their results demonstrated correlations between biodiesel blend ratios, injection advance, and engine parameters.

Another study concerning injection timing was conducted by Kant et al. [15], They investigated the effects of hydrogen-enriched biodiesel blends on diesel engine performance and emissions under various injection parameters. Their results indicated that an injection advance of 23 degrees before top dead center (23° CA bTDC) provided optimal engine performance and exhaust emissions.

In their experimental study, Damotrohan et al. [16], analyzed a single-cylinder CI engine operating on n-octanol/biodiesel blends, demonstrating that optimized injection timing at peak load delivered performance and emission levels approaching those of baseline diesel fuel.

A review of the literature reveals limited research on the effects of biodiesel–n-octanol blended fuels under varying injection timings on engine performance in CRDI diesel engines. The objective of this study is to evaluate the impact of pure biodiesel (B100) and a 5% n-octanol–biodiesel blend (B95O5) on engine performance and exhaust emissions under different injection timings in a CRDI-equipped diesel engine.

2. Materials And Method

In this experimental study, biodiesel was supplied by "DP Tarımsal Enerji Sanayi ve Ticaret A.Ş". The n-octanol blended with biodiesel was purchased from MERCK and has a purity of over 99%. By adding 5% n-octanol by volume to pure biodiesel (B100), the B95O5 test fuel was prepared. The properties of these test fuels are given in Table 1.

Table 1. Physical and chemical properties of B100, n-octanol, and B95O5 fuels

Parameters	B100	n-Octanol	B95O5
Density (kg/m^3)	883.70	830	881.02
Cetane number	51.30	-	50.7
Lower heating value (MJ/kg)	39.54	39.55	39.54
Viscosity (mm^2/s at 40℃)	4.367	5.6	-
Flash point (℃)	171	86	-
Boiling point (℃)	-	195	-

The test setup consists of a single-cylinder CRDI diesel engine, an eddy current dynamometer, an electronic control unit (ECU), air-fuel measurement units, and engine oil/coolant conditioning systems. The test engine is water-cooled, and auxiliary systems maintain constant oil and coolant temperatures. Table 2 lists the test equipment and their accuracies. The test setup is given in Figure 1.

Table 2. Test devices and their accuracy

Measurmenet	Equipment	Accuracy
Torque	HBM torque flange	±0.1%
Engine speed	AVL encoder	≤ ±0.1 CA
Injection timing	Angle enkoder	±0.1CA
Engine coolant and oil conditioner	AVL-577	±1K
Fuel consumption	AVL-735	<0.15%
Temperature sensors	PT100 (Type K)	< ±1%

Figure 1. Engine test setup

Prior to testing, the engine oil, coolant, and fuel temperatures stabilized at 90°C, 70°C, and 20°C respectively using conditioning systems. These temperatures remained constant throughout the experiments. The engine was then operated until it reached steady-state conditions. Preliminary tests with diesel fuel determined that the engine achieved maximum torque at 1500 rpm. All experiments were conducted at a constant speed of 1500 rpm under four different load conditions (25%, 50%, 75%, and 100%). To ensure data reliability, each test was repeated three times. Prior to commencing the experiments, the engine speed corresponding to maximum torque was determined. The engine's maximum torque was measured at 1500 rpm. At this speed, the engine's maximum power output corresponds to 100% throttle position (full load condition). In this study, “load” represents the test engine's pedal position percentage; thus, the four load percentages correspond to throttle position percentages. The test system automatically adjusts fuel injection timing and pressure maps according to different load and speed conditions. For instance, in this test engine at 1500 rpm and 50% load, the fuel system operates with -11.2° CA (crank angle) main injection and -17.5° CA pilot injection timing. In this study, experiments were carried out by disabling the pilot injection. The change of injection pressure and advance depending on the load at a constant speed of 1500 rpm of the test engine is given in Table 3. In the experimental study, two fuels (B100 and B95O5) were first tested under standard injection timing, followed by testing with the injection timing (advance) retarded by 2 degrees.

Table 3. Injection pressure and injection timing of the test engine depending on the load at 1500 rpm

Engine load (%)	Injection pressure (bar)	Injection timing (CA)
25	750	15
50	900	16
75	1300	17
100	1600	18

3. Results & Discussion

In this section, the test results of pure biodiesel and biodiesel blended with n-octanol in a CRDI diesel engine, both at standard injection timing and at an advanced injection timing of 2 CA, were discussed and compared with literature studies. Engine performance parameters such as engine power, brake-specific fuel consumption (BSFC), and exhaust gas temperature were measured. As for exhaust emissions, hydrocarbon (HC), nitrogen oxide (NO), and carbon dioxide (CO_2) were measured.

3.1 Engine Power

Figure 2 shows the variation of engine power with engine load for B100 and B95O5 fuels under two different injection timings. The power values of both fuel types increased with increasing load. As engine load increases, a greater quantity of fuel must be injected into the cylinder to maintain the same engine speed. The increase in engine power with load is attributed to this higher fuel quantity. At standard timing, B100 fuel produced higher engine power than B95O5 under all load conditions. This result is attributed to n-octanol's higher viscosity. For B100 operation at 25% and 50% loads, advancing the timing by 2°CA resulted in higher engine power, while at 75% and full load conditions, lower power was obtained. This is believed to be due to the CRDI engine's electronic control unit (ECU) optimizing injection timing and pressure according to load conditions. For B95O5 operation with +2°CA timing, higher engine power was measured compared to standard injection timing. N-octanol has high viscosity. The extended injection duration facilitates sufficient fuel vaporization and promotes homogeneous mixture formation, serving as the key determinant for the observed increase in power. These results show good agreement with previous studies [17], [18].

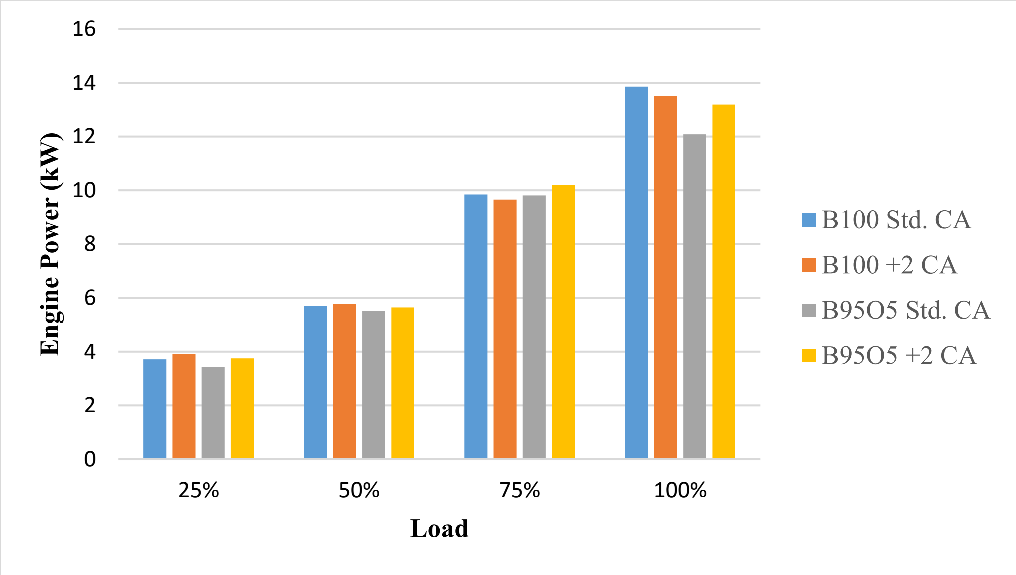

Figure 2. Variation of engine power depending on load at two different injection timings

3.2. Brake Specific Fuel Consumption

BSFC (Brake Specific Fuel Consumption) is defined as the fuel consumption rate per unit engine power output. Therefore, BSFC depends on engine power. Figure 3 presents the variation of BSFC for B100 and B95O5 under two different injection timings across four different engine load conditions. As engine load increased, BSFC decreased for both standard and +2°CA injection timings. This reduction is attributed to improved combustion phenomena resulting from increased in-cylinder temperatures.

For B100 operation, at 25% and 50% load conditions, BSFC was higher with standard injection timing compared to +2°CA timing. Under these load conditions, lower engine power output resulted in increased BSFC. At 75% and full load conditions, BSFC decreased as engine power was higher with standard injection timing.

For B95O5 operation, advancing the injection timing reduced BSFC. The higher engine power output achieved with advanced timing led to this BSFC reduction. These results are consistent with findings from previous studies[15].

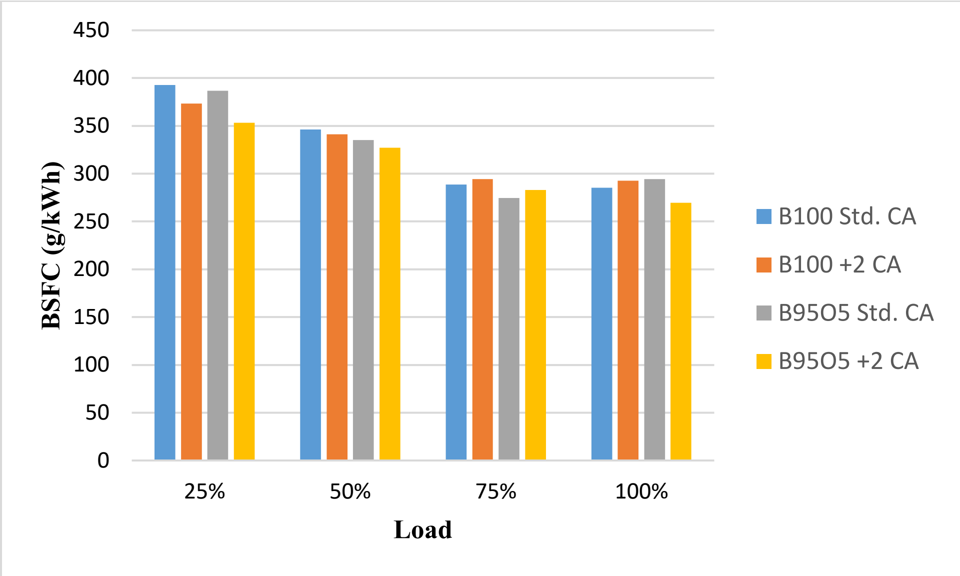

Figure 3. Variation of BSFC depending on load at two different injection timings

3.3. Exhaust Gas Temperature

Figure 4 shows the variation of exhaust gas temperature (EGT) with engine load. In all test conditions, EGT increased with increasing load. As engine load rises, more fuel participates in the combustion process within the cylinder. Consequently, more energy is released, increasing the in-cylinder temperature, which in turn raises EGT values.

On average, EGT values were measured to increase by 7.1% in the study with B100+2 CA, by 5.5% in the study with B95O5 +2 CA, and by 0.1% in the study with B95O5, compared to B100. The lowest EGT was measured for B95O5 with standard injection timing. This is likely due to the blended fuel's higher viscosity and the alcohol's cooling effect. Because high viscosity worsens the evaporation ability of the fuel, it can also negatively affect the combustion process. In B100 operation, advancing the injection timing increased EGT. The primary reason for this is the sufficient time available for fuel vaporization. Having enough time for evaporation in the cylinder causes the fuel vapor to form a better mixture with the air. B95O5 operation showed the same trend as B100 when injection timing was advanced. In general, it can be concluded that advanced injection timing improves combustion and increases EGT.

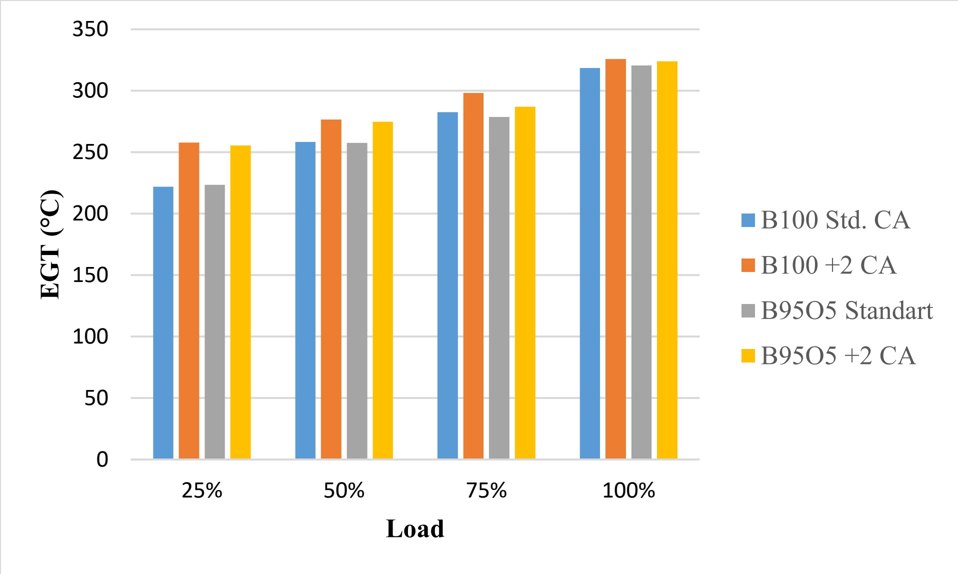

Figure 4. Variation of EGT depending on load at two different injection timings

3.4. HC Emissions

HC emissions typically occur as a result of incomplete combustion of fuel. Factors such as crevice volumes inside the cylinder, fuel type, combustion temperature, and oxygen concentration (oxygen content in the fuel and the fuel/air ratio) influence the formation of HC emissions. Figure 5 shows the variation in HC emissions depending on engine load. As the load increases, the injection of a greater amount of fuel into the cylinder raises HC emissions for both fuels and both injection timings. When operating with B100, advancing the injection timing increased HC emissions by 25% under full load conditions. This increase is thought to be related to the fuel's residence time inside the cylinder. At other loads, no significant change was observed. When operating with B95O5, HC emissions were higher at all loads under standard injection timing. This is attributed to noctanol's high viscosity worsening fuel atomization and the cooling effect of the alcohol. In the operation with B95O5, increasing the injection timing provided the necessary time for fuel atomization, evaporation, and mixing with oxygen, resulting in a reduction in HC emissions[13].

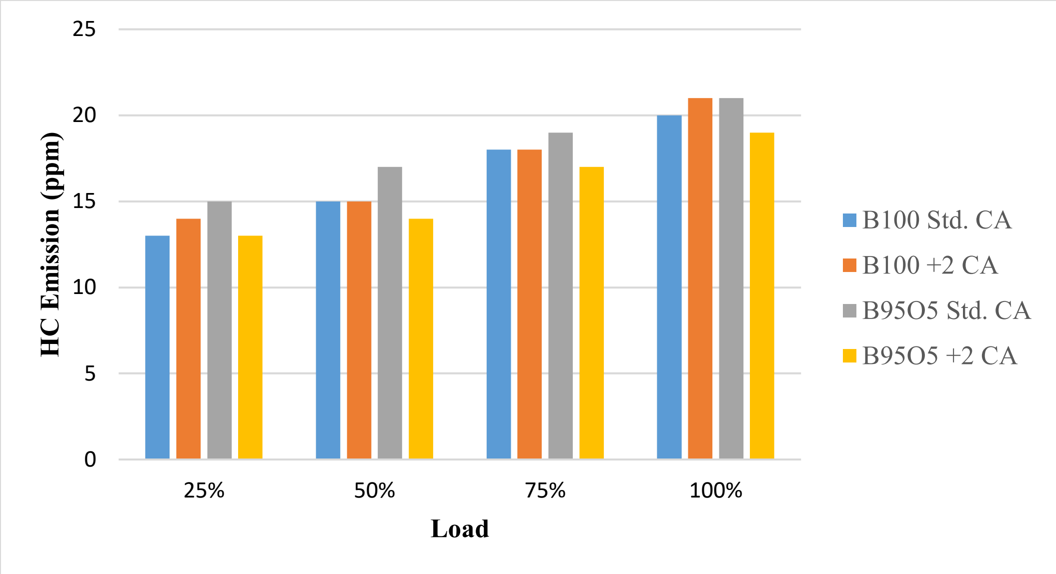

Figure 5. Variation of HC emission depending on load at two different injection timings

3.5. NO Emissions

NO emissions are generally dependent on the presence of oxygen in the cylinder and high temperatures. Figure 6 shows the variation in NO emissions for B100 and B95O5 test fuels under standard and +2°CA (crank angle) injection timings, based on engine load. As the engine load increased, NO emissions rose for both B100 and B95O5 fuels under both injection timings. This increase in NO emissions is attributed to higher in-cylinder temperatures under load.

When operating with B100, advancing the injection timing increased NO emissions. This rise is due to the increase in in-cylinder temperature. In contrast, NO emissions decreased when operating with B95O5. This reduction is linked to n-octanol's cooling effect and its high viscosity, which lowers combustion temperature. However, advancing the injection timing caused a slight increase in NO emissions, as more fuel participated in the combustion process[13].

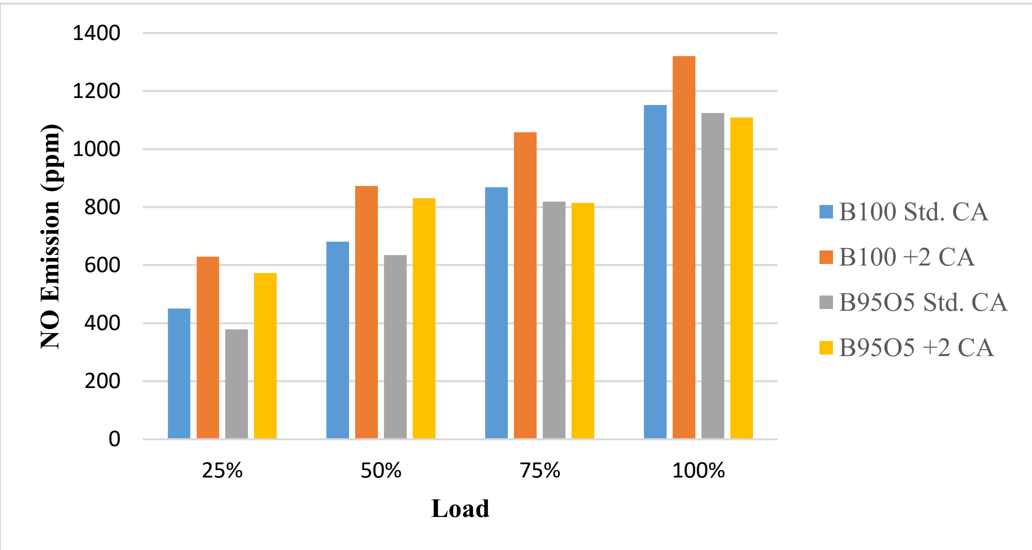

Figure 6. Variation of NO emission depending on load at two different injection timings

3.6. CO_2 Emissions

CO_2 is a reaction product formed after complete combustion of fuel. Figure 7 shows the variation of CO_2 emissions depending on engine load. As the engine load increased, the injection of more fuel into the cylinder resulted in higher CO_2 emissions for both test fuels and both injection timings.

In tests with pure biodiesel, higher CO_2 emissions were achieved with standard injection timing, while increasing the injection timing led to a reduction in CO_2 emissions. This reduction can be explained as a consequence of the increase in NO emissions. Because the oxygen in the cylinder is consumed in the formation of NO emissions.

When operating with the blended fuel, CO_2 emissions remained low at standard injection timing. This is thought to be due to B95O5's high viscosity and cooling effect, which deteriorate combustion. Advancing the injection timing improved the complete combustion rate by providing sufficient time for the combustion process (atomization, evaporation, and mixing with oxygen), resulting in higher CO_2 emissions.

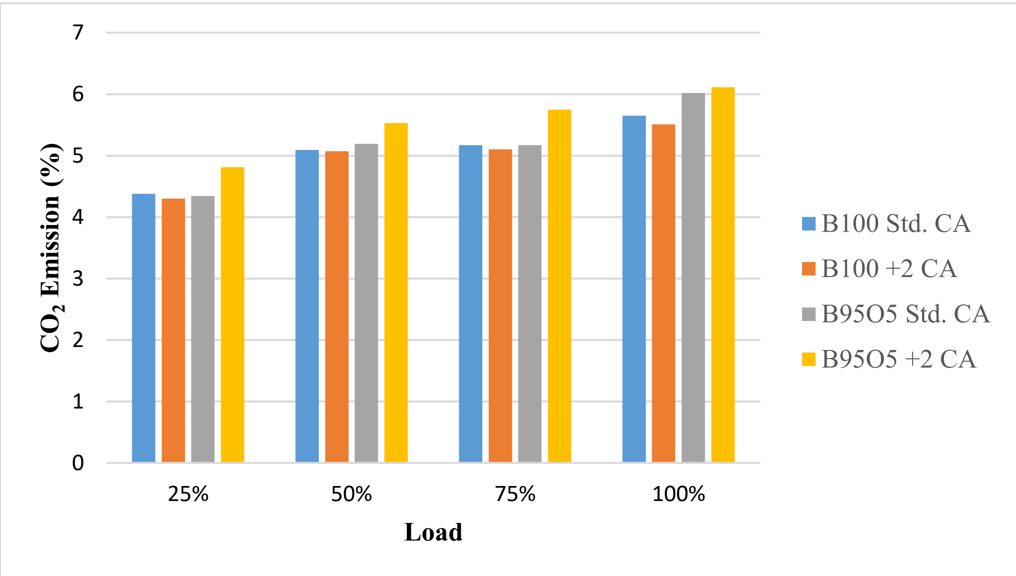

Figure 7. Variation of CO_2 emission depending on load at two different injection timings

4. Conclusion

In this study, the effects of injection timing variation on engine performance and exhaust emissions were investigated using B100 and B95O5 fuels in a CRDI diesel engine. The engine was tested at a constant speed of 1500 rpm under 25%, 50%, 75%, and full load conditions, yielding the following results:

- At standard injection timing, engine power, BSFC and EGT values of B95O5 decreased by 6.8%, 1.7% and 0.1% on average, respectively, compared to B100. When the injection timing was increased, engine power and BSFC decreased by approximately 0.8%, while EGT increased by 7.1% compared to B100. When these parameters were evaluated on a load basis, it was seen that they did not have a certain stability.

- When the results are evaluated in terms of emissions, HC emissions of B95O5 in standard advance increased by 9.1% compared to B100, while NO emissions decreased by 6.2%. CO_2 emissions increased by 2.1%. B100 +2 CA increased HC emissions by 3% and NO emissions by 23% compared to B100. CO_2 emissions decreased by 1.5%. When the injection timing of the blended fuel was increased compared to B100, HC emissions decreased by approximately 4.5%, while NO and CO_2 emissions increased by 5.6% and 9.4%, respectively.
- In conclusion, advancing the injection timing in pure biodiesel-n-octanol fuel blends generally improved engine performance. In terms of emissions, HC emissions decreased, while NO and CO_2 increased. Future research could examine the effects of different n-octanol/biodiesel blend ratios. Similarly, different types of higher alcohols (butanol, pentanol, hexanol, etc.) and their ratios can be used. In addition, various injection strategies (injection pressure, injection timing, pilot injection, etc.) can be included to test engine performance and emissions.

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