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Research Article

Effect of Adding Combustion Air on Emission in a Diesel Dual-Fuel Engine with Crude Palm Oil Biodiesel Compressed Natural Gas Fuels

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Abstract. A diesel dual-fuel engine uses two fuels designed to reduce the consumption of fossil fuels. Generally, the specific fuel consumption of diesel dual-fuel engines has increased. However, in combination with alternative fuels, namely compressed natural gas injected through air intake, the use of diesel fuel can be reduced. However, using two fuels in a diesel dual-fuel engine increases the equivalent ratio; therefore, the air and fuel mixture becomes richer because the air entering the cylinder during the intake stroke is partially replaced by compressed natural gas. This results in incomplete combustion and increases exhaust emissions, particularly hydrocarbon (HC) and carbon monoxide (CO) emissions. This study aims to improve the combustion process in dual-fuel diesel engines by improving the air-fuel ratio; thus, it can approach the stoichiometric mixture by adding combustion air forcibly to produce complete combustion to reduce CO and HC emissions. An experimental approach using a single-cylinder diesel engine modified into a diesel dual-fuel engine powered by crude palm oil biodiesel and compressed natural gas was adopted. The combustion air was forcibly added to the cylinder using an electric supercharger at different air mass flow rates ranging from 0.007074 to 0.007836 kg/s and different engine loads (1000 to 4000 watts). The results indicated that adding more air to the cylinder could produce complete combustion, reducing the emission levels produced by a diesel dual-fuel engine. An air mass flow rate of 0.007836 kg/s can reduce CO, HC, and particulate matter emissions by averages of 60.55%, 49.63%, and 86.87%, respectively, from the standard diesel dual-fuel engine. Increasing in the amount of oxygen concentration improves the quality of the air-fuel ratio, which results in improved combustion and thereby reducing emissions.

Keywords: Carbon monoxide, combustion air, emissions, hydrocarbon

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1. Introduction

A diesel dual-fuel engine is designed to reduce the consumption of fossil fuels by using two different current fuels. This involves using alternative fuels such as biodiesel and compressed natural gas (CNG) in the system (Channappagoudra, 2020; Gharehghani *et al.*, 2015; Imran *et al.*, 2014; Y. Liu *et al.*, 2015; Paul *et al.*, 2014; Tarabet *et al.*, 2014). Previously, various studies have explained the possibility of using biodiesel and CNG fuels in diesel engines through a dual-fuel system. It was observed from the explanation of Ryu (Ryu, 2013) that carbon dioxide (CO_2), nitrogen oxide (NO_x), and particulate matter (PM) emissions were lower in diesel dual-fuel engines compared to standard diesel engines, but carbon monoxide (CO) and hydrocarbon (HC) emissions were higher. Additionally, Tarabet *et al.* (2014) explained that the use of biodiesel as a pilot fuel improved the combustion stability in diesel dual-fuel engines, and HC and CO emissions reduced as a load was added using either biodiesel or pure diesel as the pilot, but the values were higher compared to those recorded in a standard diesel engine.

Moreover, Imran *et al.* (2014) demonstrated that the thermal efficiency of diesel dual-fuel engines using biodiesel and CNG is higher than that of standard diesel engines, and the same trend was observed for the HC emissions (Hiremath *et al.*, 2017; Mousavi *et al.,* 2016; Papagiannakis *et al.,* 2017). Hiremath *et al.* (2017) explained that thermal efficiency was lower while CO and HC emissions increased in dual-fuel diesel engines, but NOx and PM emissions decreased. Channappagoudra *et al.* (2020) explained that the thermal efficiency and heat release rate in diesel dual-fuel engines are lower than those in standard diesel engines. Moreover, there was a significant increase in all engine loads with HC and CO

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emissions. Shim *et al.* (2020) explained that the dual-fuel PCCI combustion model diesel engine produces high concentrations of CO and HC, reducing thermal efficiency. Pathak *et al.* (2021) explained that diesel dual-fuel engines have higher CO and HC emissions than diesel engines.

These previous studies demonstrated the possibility of improving combustion stability to produce high thermal efficiency in diesel dual-fuel engines with biodiesel and CNG, but the concentrations of CO and HC were higher than those of standard diesel engines (Gharehghani *et al.*, 2015; Hiremath *et al.,* 2017; Mousavi *et al.,* 2016; Papagiannakis *et al*., 2017). Therefore, it is necessary to regulate the emission of diesel dual-fuel engines with biodiesel and CNG through the addition of combustion air to improve the air-fuel ratio (AFR) towards ensuring complete combustion. Banapurmath *et al.* (2015) added a turbocharger to a diesel dual-fuel engine fueled by rice bran oil methyl ester (RBOME) biodiesel and producer gas, and the thermal efficiency increased while the CO and HC emissions decreased significantly with the addition of combustion air. Moreover, Nayak *et al.* (2013) added a turbocharger to a diesel dual-fuel engine fueled with Karanja biodiesel and CNG, reducing CO, HC, and smoke emissions due to the addition of combustion air. Peng *et al.* (2018) tested by varying the excess air using the throttle control method on a diesel dual-fuel engine. Increasing the excess air ratio can increase power and fuel consumption, specifically at low and medium loads. This indicates that adding combustion air to the cylinder can increase thermal efficiency as well as decrease CO and HC emissions.

Based on the problems in the diesel dual-fuel engine, this study adds combustion air to a diesel dual-fuel engine fueled by crude palm oil (CPO) biodiesel and CNG using the forced method through an electric supercharger system. The novelty of this research is the addition of combustion air through a controlled mechanism using an electric supercharger; thus, the mass flow rate of the air can be determined. Previous research used a combustion air addition method using a turbocharger (Banapurmath, 2015) and an air compressor (Nayak *et al*. 2013); therefore, the air entering the cylinder cannot be conditioned. Additionally, previous studies that added combustion air to a diesel dual-fuel engine used RBOME biodiesel and producer gas fuels (Banapurmath, 2015) as well as Karanja biodiesel and CNG fuels (Nayak *et al*. 2013), whereas this study used CPO and CNG biodiesel fuels. This study is important because of the significant increase in CO and HC emissions using dual fuels owing to a decrease in combustion air due to the substitution of CNG fuel through the intake manifold. This study aims to reduce the high concentrations of CO, HC, and PM emissions produced by a diesel dual-fuel engine by increasing the amount of air entering the cylinder forcibly using an electric supercharger to obtain an AFR close to stoichiometry to produce complete combustion. This research hypothesizes that adding combustion air into the cylinder can improve the AFR so that it is close to a stoichiometric mixture to produce complete combustion, which reduces CO and HC emissions in diesel dual-fuel engines. A diesel dual-fuel engine with a single cylinder equipped with forced air addition using an electric supercharger system to improve the AFR be ideal. It can improve combustion to reduce CO, HC, and PM emissions at different engine loads.

2. Materials and Methods

2.1 Testing Engine

This study was conducted using a standard diesel engine with a single cylinder and four strokes, as indicated in the detailed engine specifications listed in Table 1. Moreover, a naturally aspirated intake system was used in the engine, and an electric supercharger was added to force the combustion air into the cylinder. Additionally, the electric supercharger could be adjusted to the speed of the rotor by adjusting the voltage.

2.2 Fuel

The fuels used in the diesel dual-fuel engine include CPO biodiesel and CNG fuels. Their characteristics are listed in Table 2 (Sudarmanta *et al.,* 2021; Yang *et al.,* 2014). The CPO biodiesel fuel (B100) acts as an ignition fuel, and the CNG fuel acts as the main fuel in the diesel dual-fuel engine. Biosolar fuel (B30) is a mixture of CPO biodiesel and diesel, where the percentage of fuel is 30% CPO biodiesel and 70% diesel fuel. Biosolar fuel (B30) was only tested on a single-fuel engine (SF biosolar) as a control variable; this fuel has also been tested on vehicles in previous studies (Karuana *et al.,* 2020; Solikhah *et al.,* 2020).

2.2 Experimental Setup

The standard single engine was modified into a diesel dual-fuel engine with the CNG fuel fed through the inlet using an injection system controlled by an electronic control unit. The injection timing (IT) and duration injection (DI) of the CNG were 110^0 ATDC and 70^0 CA (low load), 90^0 CA (medium load), and 110^0 CA (high load) (Yuvenda et al., 2019, 2020). The CPO biodiesel fuel was injected directly into the combustion chamber at a pilot injection timing of 17^0 BTDC (Sudarmanta *et al.,* 2021; Trihatmojo *et al.*, 2019). Moreover, the combustion air was forcibly added at different variations, as summarized in Table 3, using an electric supercharger mounted at the engine inlet. Notably, the mass flow rate of standard air without an electric supercharger was 0.007074 kg/s.

Table 1
Specifications for the diesel dual-fuel engine.

Descriptions	Characteristics	
Type	One cylinder, four-stroke	
Production date	2009	
Combustion system	Direct injection	
Bore x Stroke (m)	0.82 x 0.78	
Displacement (cm^3)	411	
Max. output (kW/rpm)	5.22/2200	
Rated output (kW/rpm)	4.47/2000	
Max. torque (kg-m/rpm)	2.6/1900	
Compression ratio	18:1	
Pilot injection timing (PTI)	13^0 BTDC	
Cooling systems	Water cooling	
Valve timing	Open	Close
Intake	30^0 BTDC	50^0 ABDC
Exhaust	55^0 BBDC	35^0 ATDC

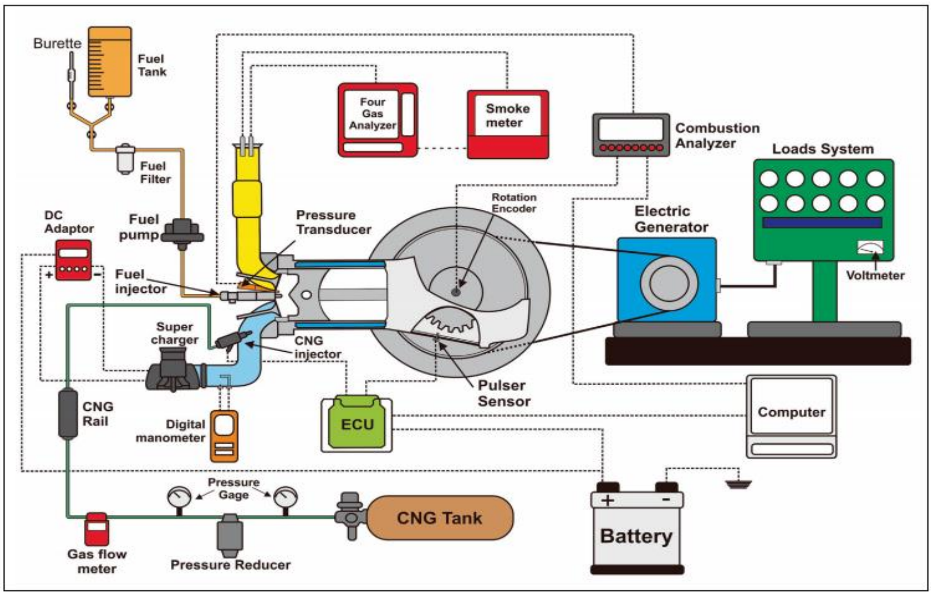

Fig. 1 Experimental setup of the diesel dual-fuel engine

Table 2
Characteristics of fuels

Properties	Biosolar (B30)	CPO Biodiesel	CNG
Density at 15 ^{0}C (Kg/m^3)	860	875	0.72
Kinematic viscosity at 40 ^{0}C (mm^2/s(cSt))	2.0	4.5	-
Cetane number (min)	51	58	-
Octane number	-	-	120
Flashpoint (^{0}C, min)	55	140	700
Sulphur content (%)	0.30	0.01	-
Low heating value (kJ/kg)	45,470	39,910	45,800
Carbon content (%)	-	74.3	-
Hydrogen content (%)	-	13	-
Oxygen content (%)	-	12.7	-

Source: Solikhah et al. (2020); Sudarmanta et al. (2021); Yang et al. (2014)

Table 3
Research variables on diesel dual-fuel engine

Load (watt)	PTI (^{0}BTDC)	IT of CNG (^{0}ATDC)	DI of CNG (^{0}CA)	Air mass-flow rate (kg/s) (1x10^{-3})
1000	17	110	70	7.074 - 7.836
1500	17	110	70	7.074 - 7.836
2000	17	110	90	7.074 - 7.836
2500	17	110	90	7.074 - 7.836
3000	17	110	90	7.074 - 7.836
3500	17	110	110	7.074 - 7.836
4000	17	110	110	7.074 - 7.836

Table 4
Specifications of the gas analyzer.

Descriptions	Characteristics
Type	Stargas 898
Production date	2004
Temperature (^{0}C)	25
Relative humidity (%)	40
Carbon monoxide (vol %)	3,498
Carbon dioxide (vol %)	12.5
Hydrocarbon (ppm vol)	1464
Diesel smoke tester	optional

The HC and CO emissions for each variation of combustion air were measured using the STARGAS 898 analyzer. In contrast, the PM emission was determined using the TEXA OPABOX auto power at different engine loads with the specifications of the gas analyzer listed in Table 4.

The test scheme for the diesel dual-fuel engine is presented in Fig. 1. The dual-fuel diesel engine is coupled to an electric generator, which was used to condition the load given to the engine using a 500 W lamp. The test parameters are listed in Table 3, where for each engine load, combustion air variations are conducted in the form of air mass flow rate using electric supercharger equipment. Five data collection points with variations in the air mass flow rate of 0.007074 kg/s, 0.007273 kg/s, 0.007401 kg/s, 0.007618 kg/s, and 0.007836 kg/s were taken for each load; thus, the total data are 35.

3. Results and Discussion

The exhaust emissions were analyzed after adding combustion air to the diesel dual-fuel engine using an electric supercharger.

3.1 CO emissions

CO emissions are caused by incomplete combustion owing to a lack of oxygen. In a diesel dual-fuel engine, a mixture of fuel and air allows a rich mixture to form, particularly at high loads (Hosmath *et al.,* 2016; Liu *et al.,* 2013; Lounici *et al.,* 2014). This is because of the use of additional fuel other than diesel fuel for ignition, namely natural gas, which is injected through the air inlet so that the proportion of air is reduced in the cylinder (Khan *et al.,* 2015; Li *et al.,* 2016). Thus, the amount of oxygen available in the cylinder is also significantly reduced so that the AFR is low (Alrazen *et al.,* 2016; Li *et al.,* 2016). This phenomenon was also observed in a study by Kalsi & Subramanian (2016) where there was a decrease in the airflow rate with an increase in the substitution of CNG into the cylinder. The CO emission levels of the diesel dual-fuel engine are higher compared to that of the standard diesel engine (SF biosolar and SF biodiesel), as shown in Fig. 2 (Liu *et al.,* 2013; Mousavi *et al.,* 2016; Papagiannakis *et al.,* 2010).

Fig. 2 shows the CO emission as a function of engine load at different variations of combustion air. This phenomenon was also demonstrated in previous studies (Lounici *et al.,* 2014; Papagiannakis *et al.,* 2010). This is because of poor combustion quality owing to low oxygen availability, increasing the concentration of CO emissions. It was discovered that the CO emissions decreased significantly with the addition of engine load on all variations of combustion air, and the lowest average value of 0.063% was obtained at the highest air added with an air mass flow rate of 0.007836 kg/s. This was a 60.55% reduction from the standard diesel dual-fuel engine (air mass flow rate of 0.007074 kg/s). This proves that the quality of combustion improves with the addition of forced combustion air to increase the amount of oxygen in the cylinder. This was also shown in previous studies (Baskar & Senthilkumar, 2016; Hassan, Zainal, & Miskam, 2011; Hassan, Zainal, Aizat, *et al.,* 2011; He *et al.,* 2022; Mahmood *et al.,* 2022; Palaniswamy *et al.,* 2016; Peng *et al.,* 2018). Moreover, adding combustion air affected the CO concentrations in all engine loads. Hassan *et al.* (2011) explained that increasing the air density in the cylinder can increase combustion efficiency, reducing CO emissions.

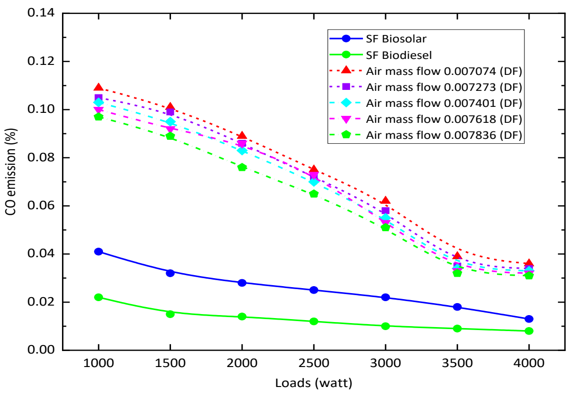

Fig. 2 Graph of CO emissions of engine load function with variations in combustion air in the diesel dual-fuel engine.

Theoretically, the formation of CO is affected by the AFR. Excess air results in high carbon dioxide (CO^2) formation (Heywood, 1988). Mahmood *et al.* (2022) explained that when the air concentration is richer in the ratio of the fuel mixture, all the C can be converted to CO_2, and it does not form CO.

Adding more combustion air increases the volumetric efficiency, increasing the temperature and pressure at the end of the compression step. This further increases the combustion rate and produced maximum combustion, which is characterized by an increase in the rate of heat released, leading to a high combustion temperature that makes it easier for the CO molecules to decompose and oxidize with oxygen to form CO_2 (Baskar & Senthilkumar, 2016; Peng *et al.,* 2018; Sarkar & Saha, 2018). Baek *et al.* (2021) explained that the addition of combustion air decreased CO emissions because of the increased combustion.

3.2 HC emissions

HC emissions are produced from fuels that are not burned during combustion (Heywood, 1988); in this case, they are biodiesel and CNG fuels. Similar to CO emissions, HC emissions from diesel dual-fuel engines are higher compared to those from standard diesel engines (SF biosolar and SF biodiesel), as shown in Fig. 3 (Liu *et al.,* 2013; Mousavi *et al.,* 2016; Papagiannakis *et al.,* 2010). The HC emissions produced by diesel dual-fuel engines are dominated by unburned CNG fuel (Liu *et al.,* 2013; Yang *et al.,* 2014). This is because CNG fuel acts as the primary fuel; therefore, the amount of CNG fuel entering the cylinder and the potential for not burning are greater.

Figure 3 shows that the HC emissions decreased significantly as the engine load increased for all variations of combustion air. This phenomenon was also demonstrated in previous studies (Hassan *et al.,* 2011; Lounici *et al.,* 2014; Papagiannakis *et al.,* 2010). The increase in engine load increases the combustion pressure and temperature; thus, the rate of ignition velocity increases as a result of increasing the amount of fuel so that more fuel is burned, specifically CNG fuel (Liu *et al.,* 2013).

Moreover, Fig. 3 shows that increasing the amount of combustion air in the cylinder reduces HC emissions, which occur at all engine loads. This phenomenon has also been demonstrated in previous studies (Hassan *et al.,* 2011; Hassan *et al.,* 2011; Papagiannakis *et al.,* 2010; Peng *et al.,* 2018). It was observed from the figure that the addition of combustion air affects the concentration of HC in all engine loads. The lowest average HC emission value was obtained at 97.28 ppm at the highest increase in the air with an air mass flow rate of 0.007836 kg/s. The average reduction for a standard diesel dual-fuel engine was 49.63%. This is attributed to the increase in the proportion of oxygen owing to the addition of combustion air into the cylinder, increasing the amount of oxygen mixed with CNG fuel and CPO biodiesel (Baskar & Senthilkumar, 2016; Sudarmanta *et al.,* 2021). This made the fuel burn more and reduced the production of HC emissions (Liu *et al.,* 2015; Yuvenda *et al.,* 2020). Notably, the reduction is caused by the improvement in the AFR, which leads to complete combustion (Peng *et al.,* 2018). Baek *et al.* (2021) explained that the addition of combustion air decreased HC emissions in diesel engine.

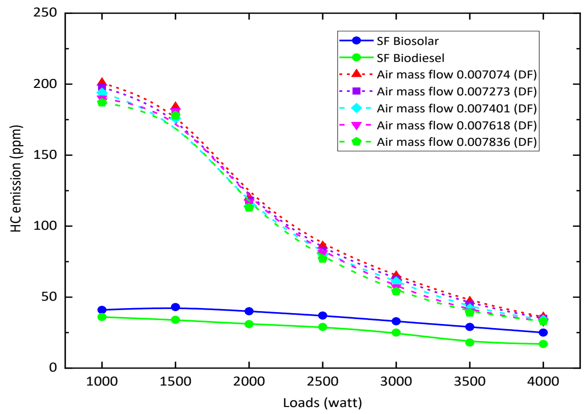

Fig. 3 Graph of HC emissions of engine load function with variations in combustion air in the diesel dual-fuel engine.

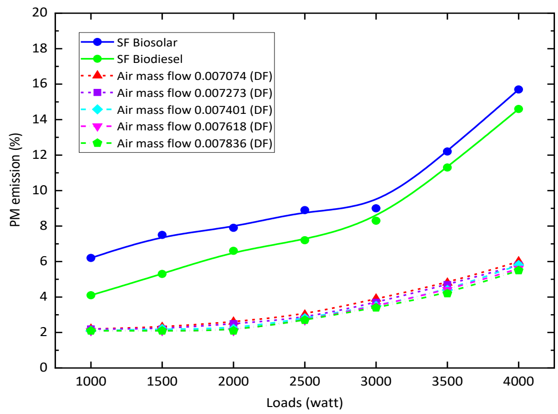

Fig. 4 Graph of PM emissions of engine load function with variations in combustion air in the diesel dual fuel engine.

3.2 PM emissions

In diesel dual-fuel engines, more PM is produced from diesel/biodiesel fuel, which acts as an igniter (Papagiannakis *et al.,* 2010, 2017; Papagiannakis & Hountalas, 2004). PM is produced because diesel fuel is part of the paraffin family, whereas CNG fuel is low in paraffin (Papagiannakis & Hountalas, 2004; Yang *et al.*, 2014). Similarly, biodiesel fuel produces high PM owing to its high aromatic content of biodiesel fuel (Asokan *et al.,* 2019). Hosamani & Katti (2018) explained that PM emissions from biodiesel fuel are higher compared to those from diesel fuel because biodiesel fuel has high viscosity and poor evaporation. This affects the air-fuel mixture, as does the combustion process. Raman *et al.* (2019) described the increase in PM emissions using biodiesel fuels owing to poor atomization and evaporation.

Figure 4 shows that PM emissions also increase significantly with an increase in engine load, and this phenomenon is also shown in previous studies (Papagiannakis *et al.*, 2010, 2017; Papagiannakis & Hountalas, 2004). The increase in engine load causes an increase in pilot fuels (biosolar and biodiesel fuels), increasing the concentration of PM (Papagiannakis *et al.*, 2017). Figure 4 also shows that adding combustion air into the cylinder affects the PM concentration at all engine loads. The lowest average value was 3.15% at the highest proportion of air added with an air mass flow rate of 0.007836 kg/s. Therefore, an average reduction of 86.87% was recorded from a standard diesel dual-fuel engine. Notably, a decrease in HC emissions reduced PM emissions because biodiesel fuel burned more during premix combustion owing to an increase in the amount of biodiesel fuel mixed with air (Bari & Hossain, 2019; Gharehghani *et al.,* 2015; Yuvenda *et al.*, 2019). Baek *et al.* (Baek *et al.,* 2021) also reported that the PM emissions decreased with an increase in the volume of air entering the cylinder. (Baskar & Senthilkumar, 2016; He *et al.,* 2022) explained that increasing the oxygen-fuel ratio can increase the oxidation of the fuel, suppressing the formation of soot.

The limitation of the gas analyzer is that it cannot provide information about NO_x emissions, and this study will be equipped with these data in the future. For further research, it is necessary to analyze the combustion performance of a diesel dual-fuel engine with numerical simulation methods using computational fluid dynamics on variations in load and engine speed. Therefore, overall information regarding the characteristics of combustions and emissions in a diesel dual-fuel engine can be obtained.

4. Conclusion

In this study, research has been conducted by varying the combustion air in a diesel dual-fuel engine with CPO biodiesel and CNG fuels, and it is concluded that a dual-fuel diesel engine can be operated using CPO biodiesel as pilot fuel and CNG as the primary fuel, which can be used as an alternative fuel. The use of CPO biodiesel fuel (B100) in diesel engines (single fuel) results in lower emissions (CO, HC, and PM) than the use of biosolar fuel (B30) for all given engine loads. The addition of combustion air using an electric supercharger with an air mass flow rate of 0.007836 kg/s can reduce CO, HC, and PM emissions by averages of 60.55%, 49.63%, and 86.87%, respectively, from a standard diesel dual-fuel engine.

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Conflicts of Interest: The authors declare no conflict of interest.

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