

Effects of low-level hydroxy as a gaseous additive on performance and emission characteristics of a dual fuel diesel engine fueled by diesel/biodiesel blends

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ABSTRACT

In the present study, water electrolysis was employed for Hydroxy gas (HHO) production as a gaseous additive. The engine test was performed using the Diesel, B5, and B20 as pilot fuels. HHO was imported into the engine's combustion chamber at three volumetric flow rates of 3, 4, and 5 cc/s through the inlet manifold as the low-level HHO rate. The engine test setup was a single-cylinder dual-fueled diesel engine at a constant speed (1500 rpm) and full load condition. According to the results, HHO by 3 and 4 cc/s did not have a significant effect on BP, BTE, and BSFC. Using HHO gas by 5 cc/s significantly increased BP by about 2.5, 3.1, and 0.5% compared with Diesel, B5 and B20, respectively, and decreased BSFC by about 11, 7.8, and 13.5% compared with Diesel, B5, and B20, respectively. HHO gas by 5 cc/s significantly decreased CO₂ by about 7, 6.3, and 10.6% compared with Diesel, B5, and B20, respectively, and decreased CO emissions by about 6, 14.3, and 21.2% compared with Diesel, B5 and B20, respectively. However, the use of HHO gas and biodiesel increased NO_x emission by about 16, 13.7, and 10.5% compared with Diesel, B5, and B20, respectively.

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Introduction

Recently, fossil fuels and their impact on pollutions have led researchers to find clean fuel resources. Hydrogen is the only renewable fuel that does not have carbon content (Knop et al., 2008). Obviously, by reducing carbon in the fuel reduces engine emissions (except NO_x) (Saravanan et al., 2007). Hydrogen, as a clean and environmentally friendly fuel (Dincer, 2007; Yilmaz et al., 2010), is an accessible and endless fuel source (Arat, 2019). According to the International Energy Agency (IEA), 'Global Trends and Prospects for Hydrogen', the commercial value of hydrogen gas for 2022 is estimated to be more than 154 billion\$ (Arat, 2019).

Hydrogen can be generated by electrochemical, biological, and thermochemical methods. Figure 1 presents different hydrogen production methods. The most desirable method for producing hydrogen is water electrolysis (Baltacioglu et al., 2019) with renewable energy sources such as solar and wind resources (Trujillo-Olivares et al.,

2019). Solar energy and water are available almost worldwide (Cammack et al., 2001; Ramadhas, 2016). The cost of producing hydrogen must be reduced to the use of water electrolysis. Also, the durability, reliability, and safety of the system must be increased (Vickers, 2017; Yadav Milind et al., 2011).

In the water electrolysis process, hydrogen is produced along with oxygen. The generated gas is called hydroxy gas (HHO) (Arjun et al., 2019). The HHO can be produced from all surfaces of the electrodes using wet cell type generators. But the main problem with these generators is heat generation and reduction of the production yield. In dry cell type generators, water flows between the electrodes and produces less heat. These types of generators are more efficient type (Sudrajat et al., 2018). They usually use NaOH or KOH to ionize water as an electrolyte (Ismail et al., 2018).

Hydroxy gas contains 1 mol of hydrogen and 2 moles of oxygen (Selvi Rajaram et al., 2014). A diesel engine

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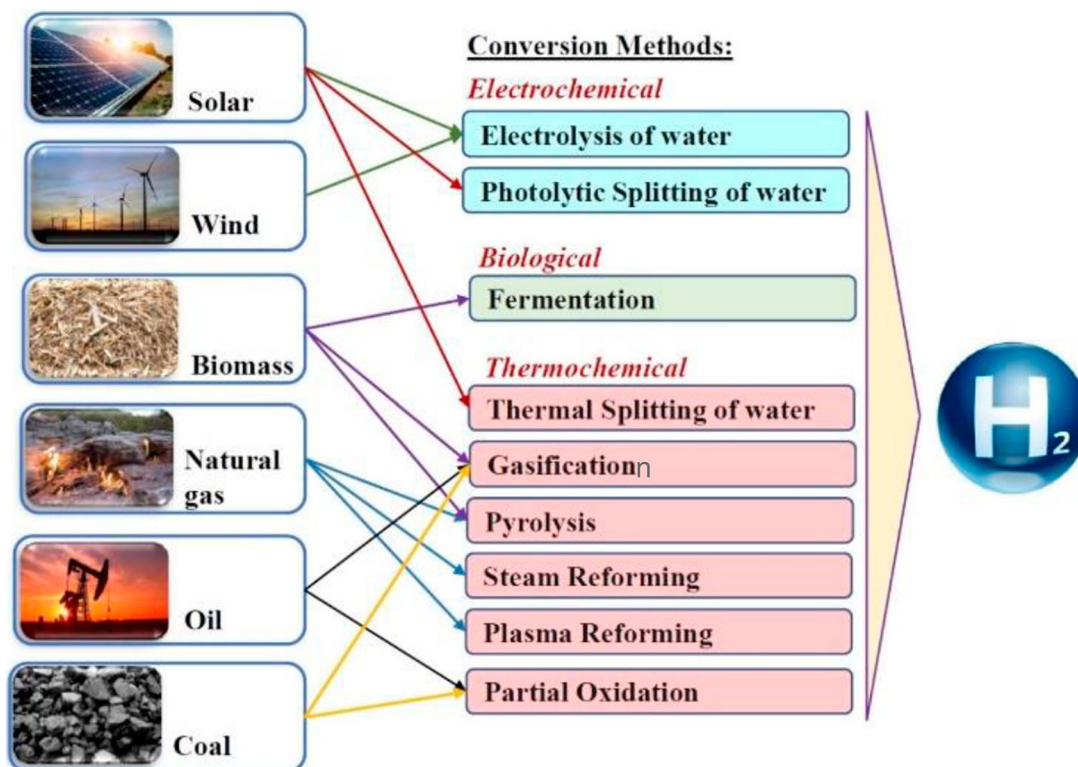


Figure 1. The different hydrogen production methods.

that uses diesel fuel with gaseous fuel, such as natural gas, biogas, or hydrogen, is called a ‘dual-fuel diesel engine’ (Akbarian et al., 2018). Studies indicate that HHO gas is more flammable than diesel fuel (Selvi Rajaram et al., 2014). Therefore, can improve the combustion process in diesel engines. The use of hydrogen increases the H/C ratio of the fuel and reduces carbon-based emissions (Szwaja & Grab-Rogalinski, 2009). Also, the diffusion rate of hydrogen gas in the air is extremely high, thus reducing the inhomogeneity of diesel fuel injection and creating a more uniform fuel–air mixture (Ismail et al., 2019).

Also, biodiesel fuel can improve diesel engines’ performance and emissions (Faizollahzadeh Ardabili et al., 2018). Like hydrogen, Biodiesel is a renewable and clean fuel (Reece & Peterson, 1995). The use of biodiesel significantly reduces greenhouse gas (GHG) emissions (Rimkus et al., 2018). Studies in the field of biodiesel combustion have shown that biodiesel fuel can reduce the emission of particulate matter (PM), unburned hydrocarbons (UHC), and carbon monoxide (CO) (Uludamar et al., 2016). Biodiesel produces lower brake power (BP) than diesel fuel due to the lower low heat value (LHV) compared with that of diesel fuel. Researchers are now looking to solve this problem. One way is to use additives

with high-energy content such as hydrogen (Arat, 2019; Rimkus et al., 2018).

Various studies have recently been developed on employing HHO gas with biodiesel fuel in a diesel engine (Table 1). As can be seen, almost all researchers agree that the use of HHO gas in diesel engines increases braking power (BP), braking torque (BT), and braking thermal efficiency (BTE), and reduces brake specific fuel consumption (BSFC). Most researchers also found that HHO gas in diesel engines reduces CO, UHC, and PM emissions and increases NO_x and CO₂ emissions.

Reviewing the articles showed that the use of HHO gas in diesel engines improves engine performance and reduces emissions. HHO gas is a new and sustainable energy source that can provide energy security in the present and future. According to the authors’ best knowledge, the effect of low-level HHO as an additive and the interactions of HHO and biodiesel has not been reported yet. In the present study, a dry cell HHO gas generator was designed and manufactured. Then, the effects of using HHO gas and diesel–biodiesel blends (B5 and B20) on a dual fuel diesel engine were investigated. The diesel engine was connected to an electric power generator and the electricity needed to produce HHO gas came from

Table 1. studies developed for employing HHO as a gaseous additive for biodiesel fuel in diesel engine.

Type of fuel blend	Biodiesel source	HHO or H ₂ flow	Type of engine	Test condition	Performance results			Emission results					Ref.
					BP	BSFC	BTE	CO	CO ₂	NOx	UHC	PM	
B10+HHO B10+H ₂	Sunflower oil biodiesel	10 L/min	4D34 mitsubishi diesel engine, 4 stroke, 4 cylinders, 89 kW, 3600 cc	Full load, 1200-2600 rpm	+13%	-2%	+9%	-25%	-8.72%	+20%	N.A.	N.A.	(Baltacioglu et al., 2016)
B10+E5 +HHO B15+E5+HHO	Castor oil biodiesel	1 L/min	L48N diesel engine, 4 stroke, single cylinder, 2.5 kW, 219 cc	Full Load, 1200-3200 rpm	+8.3%	N.A.	+ 2.82%	-8.39%	N.A.	+8.57%	N.A.	N.A.	(Baltacioglu et al., 2019)
H2+Diesel	-	10 L/min	Single cylinder, 4 stroke, diesel engine, 3.76 kW, 36.87 cc	25, 50, 75 and 100% loads, 1500 rpm	+29%	-27%	+24.5%	-17%	N.A.	+103%	-23%	N.A.	(Saravanan et al., 2007)
H2+Biodiesel	Pure jatropha oil	Hydrogen Mass Share 0-40%	Kirloscar AV1 diesel engine, single cylinder, 4 stroke, 3.7 kW	20, 40, 60, 80 and 100% loads, 1500 rpm	+14%	-2%	+7.3%	-34%	N.A.	N.A.	-30%	-16%	(Kumar et al., 2003)
H2+Diesel	-	2-9.5 L/min	Kirloscar AV1 diesel engine, single cylinder, 4 stroke, 3.7 kW	0, 25, 50, 75 and 100% loads, 1500 rpm	N.A.	-17.7%	+15%	↑ N.A.	-360%	+2%	+7%	N.A.	(Saravanan & Nagarajan, 2010)
H2+B90E10,	Tamanu methyl ester	4 L/min	Kirloscar AV1 diesel engine, single cylinder, 4 stroke, 3.7 kW	20, 40, 60, 80 and 100% loads, 1500 rpm	+14%	-2.3%	+11.65%	N.A.	+14%	-8.88%	-19%	N.A.	(Parthasarathy et al., 2016)
B80E20,B70E30 HHO + Diesel	-	1, 2 and 3 L/min	DEK TM (F-400) diesel engine, 1 cylinder, 4-stroke, 9.3Hp, 3500 rpm, 406 cc	750-3500 rpm	N.A.	-14%	N.A.	-23%	-7%	-15.5%	-22%	N.A.	(Trujillo-Olivares et al., 2019)
HHO + Biodiesel	Rapeseed methyl ester	HHO/Air: 14-18 Vol.%	1.9 TDI diesel engine, 4 cylinder, 4-stroke, 66 kW, 4000 rpm, 1896 cc	25, 50, 75 and 100% Loads, 1900-3700 rpm	N.A.	+12.9%	N.A.	-40%	N.A.	+17%	-26%	-45%	(Rimkus et al., 2018)
HHO + Diesel	-	5 L/min	In-line, direct-injection diese engine, 80 kW, 3567 cc	Low load, 1200-3000 rpm	N.A.	-14%	N.A.	-13.5%	N.A.	N.A.	-5%	N.A.	(Yilmaz et al., 2010)
HHO + B20	Chlorella protothecoides	-	4D34-2A Mitsubishi diesel engine, 89 HP, 3907 cc	low load, 1200-2700 rpm	+1.1%	N.A.	N.A.	-9.82%	-1.36%	N.A.	N.A.	N.A.	(E. J. I. j. o. h. e. Uludamar, 2018)
H2 + B20 H2+B10, B20	Karanja oil	Hydrogen Mass Share 0-40%	Kirloscar AV1 diesel engine, single cylinder, 4 stroke, 3.7 kW	20, 40, 60, 80 and 100% loads, 1500 rpm	N.A.	-2.41%	+2.61%	-6%	N.A.	+11.7%	-12.25%	-9%	(Thangaraj & Govindan, 2018)

5, 10% EGR

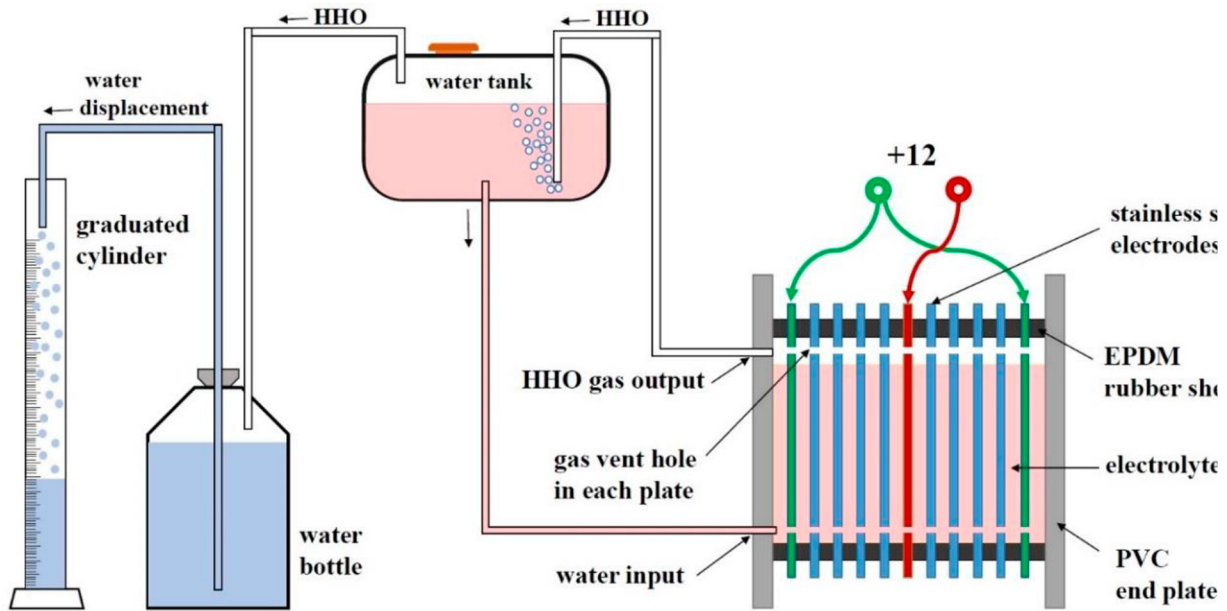


Figure 2. Schematic of the dry cell HHO generator.

the diesel engine. Therefore, net braking power (BP) was studied as a criterion for system evaluation.

Material and method

Design, manufacture, and evaluation of HHO generator

In this study, a dry cell type HHO generator was designed and manufactured. 38 electrode plates with dimensions of $20 \times 20 \times 1$ mm were made of stainless steel 316L. Among the electrodes were rubber gaskets (2 mm thick). The gaskets were made of corrosion-resistant rubber (Ethylene Propylene Diene Monomer), which prevented adjacent plates' contact. One plate was attached to the negative charge (cathode), and two plates to the positive charge (anode), and the rest were neutral. The electrodes from the top and bottom had holes 5 mm in diameter. The electrolyte flowed freely between all cells. The generated HHO gas was collected at the top of the generator through holes in the upper electrodes. The generated gas was passed through a trap of water to ensure system safety. Figure 2 presents a schematic of the HHO generator.

The alkaline electrolyte was prepared by adding NaOH to distilled water. The HHO generator had a capacity of 1.5 liters of electrolyte. The electrolysis process was performed using (~ 220 v) alternating current generated from the diesel engine. Using an AC to DC converter (A30 and V12 Model 12-360-5 China) AC power was converted to direct power. A KYORITSU KEW MATE 2000 multimeter measured the voltage and

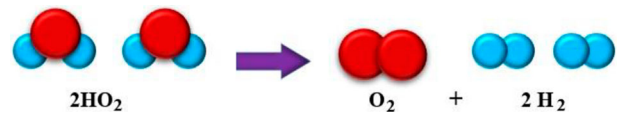


Figure 3. Decomposition of water molecules into HHO Gas.

current intensity. The amount of HHO gas produced was calculated by employing discharged water (using a graduated cylinder and chronometer) (Najafi & Ardabili, 2018).

The generator's efficiency is the ratio of the HHO gas energy produced to the electricity consumed (to produce it) (EL-Kassaby et al., 2016). The HHO gas contains 2 moles of hydrogen and 1 moles of oxygen (Figure 3), so the mole fraction of hydrogen and oxygen in it is 0.66 and 0.33, respectively. Thus, hydrogen accounts for 66% of the volume of HHO gas ($V_{H_2} = 0.66 \times V_{HHO}$). Since only H_2 gas is combustible, the efficiency of the HHO generator is calculated according to Equation (1):

$$\eta_{HHO} = \frac{V_{H_2} \times \rho_{H_2} \times LHV_{H_2}}{V \times I \times t} \quad (1)$$

That V_{H_2} is the volume of hydrogen (m^3) in the hydroxy gas, LHV_{H_2} is low heat value of hydrogen equal to 119.93×10^6 J/kg, and ρ_{H_2} is the density of hydrogen gas in conventional conditions equal to 0.0838 kg/ m^3 (Table 1). V is the voltage (volts), I the current of the current (amps) and t the time (seconds) which were measured experimentally.

Since the electrolyte concentration affects HHO production, directly, the amount of NaOH was added to

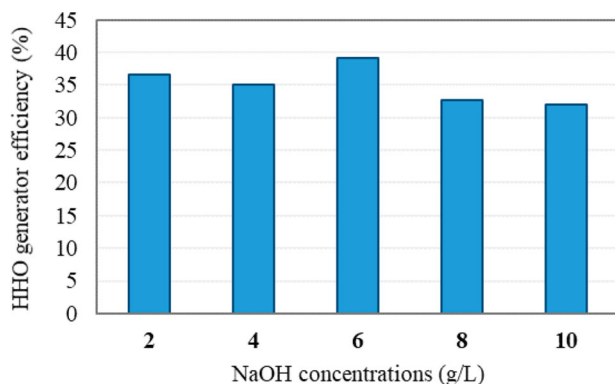


Figure 4. HHO gas generator efficiency at different catalyst concentrations.

distilled water at five levels of 2, 4, 6, 8, and 10 g/L. Figure 4 presents the efficiency of the HHO gas generator at different catalyst concentrations. It was observed that increasing the catalyst concentration increases the HHO gas generator's efficiency initially and then decreases. The highest efficiency of the HHO generator at 6 g/L concentration was 39.12%. Therefore, in this study 6 g/L concentration of NaOH catalyst was used.

Fuel preparation

In this study, biodiesel fuel was produced by transesterification using waste cooking oil (WCO), methanol alcohol (with alcohol to oil ratio 6:1), and NaOH catalyst (by 1% of the oil weight) at a temperature of 65°C for 30 min by the stirring intensity of 600 rpm (Faizollahzadeh

Ardabili et al., 2018; Hajlari et al., 2019). Finally, after neutralization and washing processes, biodiesel was generated with a purity of 98.5%. Figure 5 shows the biodiesel production steps. The thermochemical properties of biodiesel and diesel fuel were measured according to the ASTM standard. Table 2 presents the prepared fuels' properties.

Biodiesel and diesel fuels were blended at two ratios of 5 and 20% vol which were called B5 and B20, respectively. In each fuel sample, HHO gas was added at rates of 3, 4, and 5 cc/s (0.18, 0.24, and 0.3 L/min). B5, B20, and pure diesel (D) were used as control fuels. Table 3 shows the amount of diesel, biodiesel, and HHO fuels.

Engine test equipment

The engine tests were performed by a Kirloskar DA10 single-cylinder diesel engine (Figure 6). The specifications of the engine are described in detail in Table 4. The engine shaft was connected to a jbt-200 electric generator. The generator's legs were completely suspended, and its body was attached to a 200 kN load cell (model: LNron FG-5100) through an arm 30 cm long. The generated electricity was transmitted to a heater through a variable electrical resistance (model: TDGC2-5KVA). By changing the state of the variable electrical resistance, the engine was placed under load.

By measuring the force by the load cell (F), the braking torque of the relation $BT = 0.3 \times F$ was calculated. By measuring the rotational speed of the engine (by a magnetic sensor and Autonics MP5W-4N pulse meter), the

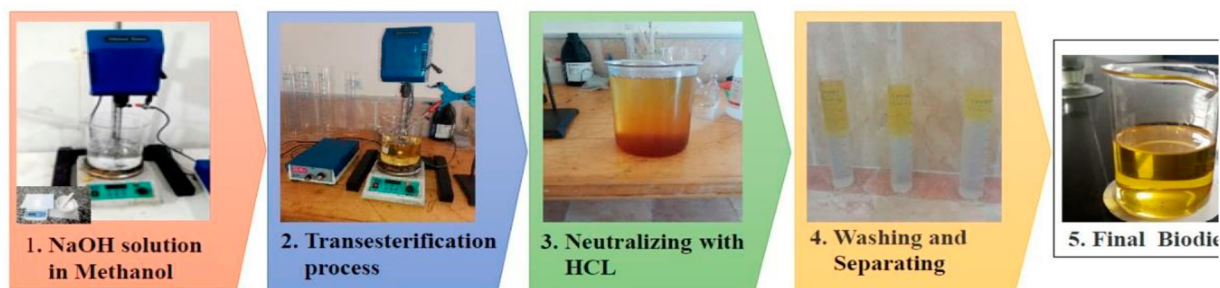


Figure 5. Biodiesel production process.

Table 2. Properties of biodiesel, diesel, and hydrogen.

Properties	Diesel	B5	B20	Biodiesel	Hydrogen ^a	ASTM Method
Density @ STD	0.84	0.8423	0.8491	0.8853	0.0838	D1298
Calorific value (MJ/kg)	42.49	42.43	40.01	39.77	119.93	D3338
Viscosity @ 40°C (mm ² /s)	3.95	4.05	4.25	4.39	-	D3338
Cetane number ^a (-)	50	51	523	55	10-May	D613
Auto ignition temperature ^b (°C)	280	-	-	415	585	-
Chemical Formula ^c	C ₁₄ H ₂₄	C _{14.2} H _{24.5} O _{0.1}	C _{14.8} H ₂₆ O _{0.4}	C ₁₈ H ₃₄ O ₂	H ₂ +0.5O ₂	-

^aSource: (<https://www.merckmillipore.com/INTL/en/product/12-Propanediol>; Riazi & Albahri, 2005).

^bSource: (Rimkus et al., 2018; Saravanan & Nagarajan, 2010; Uludamar, 2018; Yilmaz et al., 2010).

^cSource: (Jannatkhah et al., 2020).

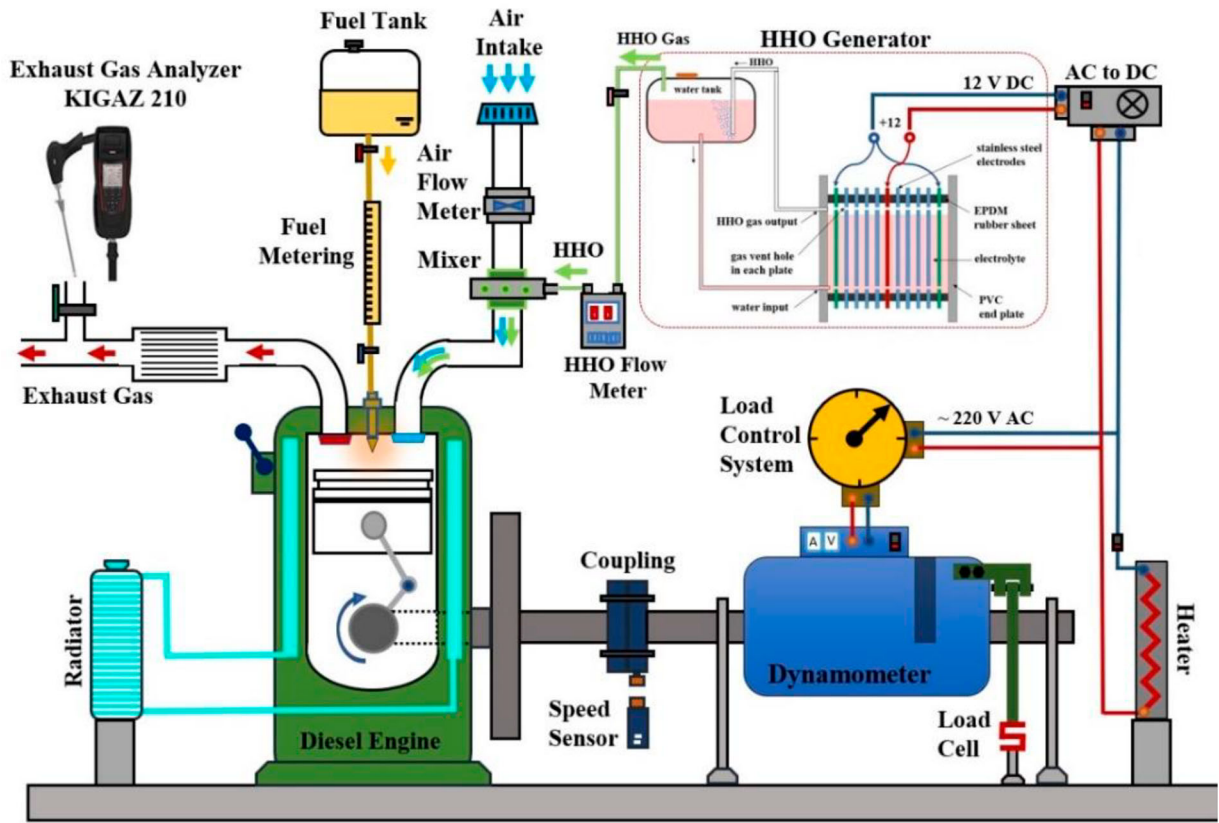


Figure 6. Schematic diagram of the diesel engine setup.

Table 3. The amount of diesel, biodiesel and HHO fuels.

N.	Biodiesel (cc)	Diesel (cc)	HHO (cc/s)	Sample Name
1	0	1000	0	D
2	0	1000	3	D _{HHO3}
3	0	1000	4	D _{HHO4}
4	0	1000	5	D _{HHO5}
5	50	950	0	B5
6	50	950	3	B5 _{HHO3}
7	50	950	4	B5 _{HHO4}
8	50	950	5	B5 _{HHO5}
9	200	800	0	B20
10	200	800	3	B20 _{HHO3}
11	200	800	4	B20 _{HHO4}
12	200	800	5	B20 _{HHO4}

Table 4. Kirloskar DA10 diesel engine specifications.

Bore × stroke	102 × 116 mm
Compression ratio	17.5
Displacement volume	0.948 L
Max. brake power @ 1500 rpm	7.4 kW
Brake mean effective pressure @ 1500 rpm	0.621 MPa
Cooling type	Water Cooling

braking power of Equation (2) was calculated:

$$BP = \frac{2\pi \times 0.3}{60 \times 10^3} \times F \times N \quad (2)$$

where F is the force (N), N is the rotational speed of the engine (rpm) and BP refers to the brake power (kW).

The flow of liquid fuel consumption (\dot{m}_f) was measured by a calibrated cylinder method. By measuring the fuel consumption time of 4 cc, the fuel consumption flow was calculated. A GS-84-04C G4 flowmeter measured the volumetric flow rate of hydroxy gas (HHO). KIGAZ 210 (Kimo Instruments “Chevry-Cossigny” France) portable gas analyzer was used to measure exhaust gases. The gas analyzer measured the CO₂, CO, and NO_x emissions values with an accuracy of 0.1 vol.%, 1, and 1 ppm, respectively.

In engine tests, diesel, B5, and B20 were the sources of energy. The electricity needed to produce HHO gas was provided by an electric generator connected to the engine. Therefore, if we consider the diesel-generator motor set as a thermodynamic system, the electricity required to produce HHO gas will be internal energy. Figure 7 shows the diesel-generator set as a thermodynamic system.

Special brake fuel consumption (g/kWh) was calculated from Equation (3):

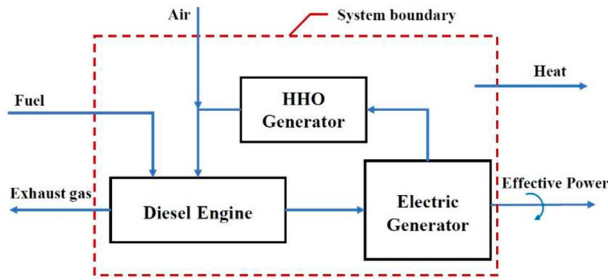
$$BSFC = 3.6 \times \frac{\rho_f \cdot \dot{V}_f}{BP} \quad (3)$$

where \dot{V}_f is volumetric of fuel consumption (cc/s) that is measured experimentally. ρ_f The density of diesel, B5 and

Table 5. Uncertainty analysis of the measurement parameters used in the study.

Parameter	Formula	Uncertainty
BP	$\delta_{BP} = \frac{2\pi \times 0.3}{60 \times 10^3} ((N \cdot \delta F)^2 + (F \cdot \delta N)^2)^{0.5} = \pm 47.75 \text{ (W)}$	$\pm 1.014 \text{ (\%)}$
BSFC	$\delta_{BSFC} = 3.6 \times \rho_f \left(\left(\frac{1}{BP} \cdot \delta \dot{V}_f \right)^2 + \left(\frac{-\dot{V}_f}{BP^2} \cdot \delta BP \right)^2 \right)^{0.5} = \pm 2.98 \text{ (g/kWh)}$	$\pm 1.0138 \text{ (\%)}$
BTE	$\delta_{BTE} = \frac{10^{-3}}{\rho_f \cdot LHV_f} \left(\left(\frac{-BP}{\dot{V}_f^2} \cdot \delta \dot{V}_f \right)^2 + \left(\frac{1}{\dot{V}_f} \cdot \delta BP \right)^2 \right)^{0.5} = \pm 0.461 \text{ (\%)}$	$\pm 1.275 \text{ (\%)}$
\emptyset	$\delta_{\emptyset} = AF_{st} \times \frac{\rho_f}{\rho_a} \times \left(\left(\frac{1}{\dot{V}_a} \cdot \delta \dot{V}_f \right)^2 + \left(\frac{-\dot{V}_f}{\dot{V}_a^2} \cdot \delta \dot{V}_a \right)^2 \right)^{0.5} = 0.027 \text{ (-)}$	$\pm 3.8 \text{ (\%)}$

$F = 100 \pm 1 \text{ (N)}, N = 1500 \pm 2.5 \text{ (rpm)}, \dot{V}_f = 0.36 \pm 0.01 \text{ (cc/s)} \text{ and } \dot{V}_a = 5.39 \pm 0.14 \text{ (L/s)}$

**Figure 7.** Diesel-generator engine as a thermodynamic system.

B20 fuels is 0.840, 0.8423 and 0.8491 kg/m³, respectively (Table 1).

Brake thermal efficiency (%) was calculated from Equation (4):

$$BTE = \frac{BP \times 10^{-3}}{\rho_f \cdot \dot{V}_f \cdot LHV_f} \quad (4)$$

where the LHV_f of the low heat value of diesel, B5, and B20 fuels is 42.49, 42.43, and 40.01 MJ/kg, respectively (Table 1).

Lambda (λ) for the HHO/Biodiesel/Diesel advantages of Equation (5) was calculated (Le Anh Tuan & Van Tai, 2011):

$$\lambda = \frac{\dot{m}_a}{\dot{m}_f (AF_{st})_f + \dot{m}_{HHO} (AF_{st})_{HHO}} \quad (5)$$

where, \dot{m}_a , \dot{m}_f and \dot{m}_{HHO} are the airflow, the liquid fuel rate, and the HHO mass flow rate (g/s), respectively.

$(AF_{st})_{HHO}$ is the stoichiometric ratio of air to HHO gas (= 0). $(AF_{st})_f$ is the stoichiometric ratio of air to fuels (D, B5, and B20), according to the chemical formula, they were calculated, which are 14.3, 14.19 and 13.91, respectively (Table 5).

Given that $\dot{m}_a = \rho_a \cdot \dot{V}_a$ and $\dot{m}_f = \rho_f \cdot \dot{V}_f$, the equivalence ratio (\emptyset) is the opposite of lambda ($\emptyset = \lambda^{-1}$). Therefore,

the equivalence ratio of Equation (6) was calculated:

$$\emptyset = (AF_{st})_f \times \frac{\rho_f \dot{V}_f}{\rho_a \dot{V}_a} \quad (6)$$

where \dot{V}_a and \dot{V}_f are the inlet airflow and the inlet fuel flow rate (cc/s), respectively, which is measured experimentally. ρ_a and ρ_f are air and fuel densities (kg/m³).

In all experimental tests, the accuracy of the measured data was validated. Due to device measurement error, data uncertainty was calculated according to Equation (7) (Barford, 1985; Kline, 1953):

$$\delta_R = \left[\left(\frac{\partial R}{\partial x_1} \delta_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \delta_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_N} \delta_N \right)^2 \right]^{0.5} \quad (7)$$

where δ_R is the amount of uncertainty, R is the response function, x_1, x_2, \dots and x_2 are independent variables, and $\delta_1, \delta_2, \dots$ and δ_n are symbols of the uncertainty of each independent variable.

The accuracy of measuring motor load (F), motor speed (N) and volumetric fuel consumption (\dot{V}_f) is ± 1 N, ± 5 rpm, and ± 0.1 cc/s, respectively. As a result, the uncertainty of BP, BSFC, and BTE was calculated to be 1.014%, 1.033%, and 1.275%, respectively (Table 5).

Engine tests were performed at full load and constant speed 1500 rpm. HHO gas was used in three levels 3, 4, and 5 cc/s as a supplement to diesel, B5, and B20 fuels. HHO gas entered the engine's combustion chamber through the inlet manifold. By changing the voltage of the electrolysis system and using the calibration table, the HHO gas flow rate was measured and controlled.

Table 6. Design summary.

Name	Units	Analysis	Minimum	Maximum	Mean	Std. Dev.	Ratio	Model
R1	BP	Polynomial	4418.45	4631.5	4524.56	68.95	1.05	Quadratic
R2	BSFC	Polynomial	213.99	258.55	236.22	13.5	1.21	Quadratic
R3	Nb	Polynomial	33.14	38.79	35.7	1.83	1.17	Quadratic
R4	O2	Polynomial	751.32	822.27	778.57	22.9	1.09	Quadratic
R5	CO	Polynomial	6.34	8.44	7.7	0.63	1.33	Quadratic
R6	CO2	Polynomial	486.46	554.4	521.91	22.43	1.14	Quadratic
R7	NOx	Polynomial	1.72	2.04	1.92	0.1	1.19	Quadratic

Results and discussion

Engine performance

Exhaust gas temperature

Figure 9 shows the temperature variation of the exhaust gases using HHO and various biodiesel–diesel fuel blends. According to Figure 8, biodiesel increases the EGT due to the complete combustion and higher heat release rate (MohamedMusthafa et al., 2011). EGT depends on the amount of oxygen in the fuel (Dhamodaran et al., 2017). Biodiesel contains 10–12% oxygen, while diesel fuel without oxygen (Faizollahzadeh Ardabili et al., 2018). The oxygen in biodiesel fuel causes complete combustion, increasing exhaust gas temperature (Ghazali et al., 2015). The biodiesel cetane number is higher than diesel (Table 2) (Faizollahzadeh Ardabili et al., 2019). As a result, biodiesel's use shortens the ignition delay time (Abu-Hamdeh & Alnefaie, 2015). Thus, some of the fuel that is not burned in the main combustion stage burns at the end of the combustion stage and releases the combustion chamber's temperature (Yu et al., 2002). Other researchers have reported expansion of exhaust gas temperature using biodiesel–diesel fuel blends (Abu-Hamdeh & Alnefaie, 2015; Banapurmath et al., 2008; Ghazali et al., 2015; Tamilselvan et al., 2017). Interestingly, the trend of changes in exhaust gas temperature (Figure 8) is consistent with the amounts of oxygen in fuels (Table 2). By adding HHO gas, the exhaust gas temperature increases (Kumar et al., 2003). Also, enriching the biodiesel–diesel fuel blends with high-calorie HHO gas (Table 2) causes more intense combustion and increases the combustion temperature in the cylinder (Kumar et al., 2003; Rahman et al., 2017). Also, the oxygen in HHO gas increases the combustion efficiency of biodiesel–diesel fuels, in which case the energy released rate from the fuels increases and the combustion temperature in-cylinder increases. In general, the simultaneous use of two fuels, HHO gas and biodiesel, in a dual-fuel diesel engine significantly increased the EGT. The highest amount of EGT was related to pilot fuel B20 by HHO rate 5 cc/s ($B20_{HHO5}$).

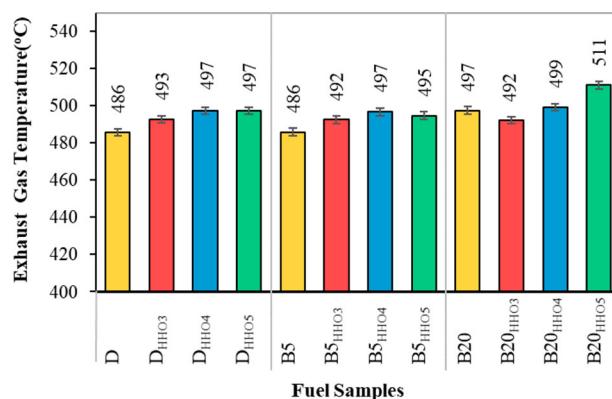


Figure 8. The effects of HHO gas and biodiesel/diesel blends on the exhaust gas temperature.

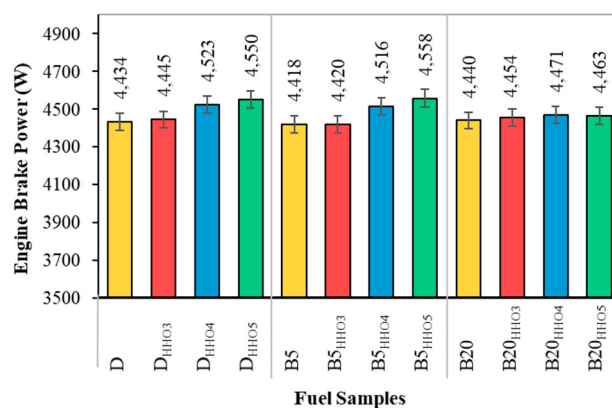


Figure 9. The effect of HHO gas and biodiesel/diesel blends on the variation of engine BP.

Engine brake power

Engine BP is the useful power of the engine output shaft. As shown in Figure 9, the engine's BP is generally increased by using HHO gas. Due to the uncertainty of the engine's BP (Table 5), the addition of HHO gas in the amount of 3 cc/s, did not have a significant effect on the BP compared to diesel, B5 and B20 fuels. But with the addition of 4 and 5 cc/s of HHO gas, the engine's BP increased compared to diesel and B5 fuels.

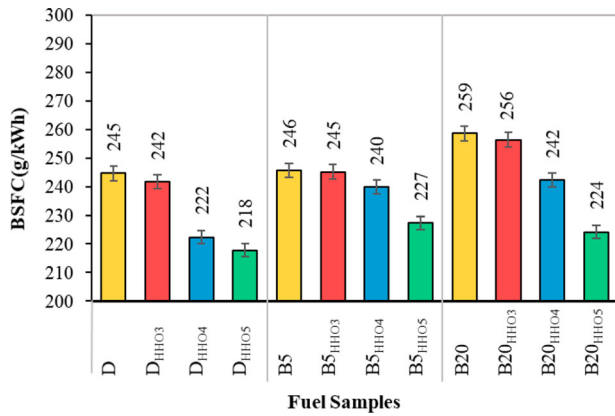


Figure 10. The effect of HHO gas and biodiesel/diesel blends on the variation of BSFC.

The highest BP increase is related to D_{HHO5} and $B5_{HHO5}$ fuels, which have increased by 2.61 and 3.16% compared to D and B5 fuels, respectively. This can be related to the higher calorific value of HHO gas (Table 2) (Sandalcı et al., 2019). Also, excess oxygen imported with HHO gas can complete combustion and thus increase BP (Baltacıoğlu et al., 2016). Masjuki et al. (2016) developed a study for comparing the effect of HHO with that of the Diesel and B20. According to the results, HHO increased BP about 2% in comparison with control fuel. The main reason was claimed to be the differences in the calorific value of the HHO and Diesel fuel (Masjuki et al., 2016). The similar findings also reported by Baltacıoğlu et al. (2019) in investigation of the effects of HHO at 1 L/min level on performance and emission characteristics of a diesel engine fueled by biodiesel and diesel as pilot fuels. According to the results, the presence of HHO significantly increased the BP compared with control fuel (Baltacıoğlu et al., 2019).

The calorific value of HHO gas is higher than that of Diesel, B5, and B20, and its use in a dual-fuel diesel engine can compensate for the low heat value of pilot liquid fuels (Deheri et al., 2020; Sandalcı et al., 2019). The results of Figure 10 show that using HHO gas increases the energy entering the engine, which compensates for the low energy of Diesel and B5 fuels and improves it. But, the use of the low value of HHO gas (3 cc/s) does not compensate for the low thermal value of B20 fuel. Therefore, it doesn't affect the production of BP. Also, the results showed that adding biodiesel to diesel fuel did not have a significant effect on BP. Data on the brake power of Diesel, B5, and B20 fuels are in the uncertainty range. The thermal value of biodiesel fuel is low, which reduces the BP. While biodiesel contains oxygen, it improves combustion and increases BP. As a result, with biodiesel's addition to diesel fuel, the BP generated does not change significantly.

Brake specific fuel consumption

The brake specific fuel consumption (BSFC) indicates the amount of fuel consumption on the mechanical energy produced by internal combustion engines. Variation of BSFC for different HHO gas and the biodiesel–diesel fuel blends is shown in Figure 10. As can be seen, the amount of BSFC increases as the amount of biodiesel in blend fuels increases. The BSFC for diesel, B5, and B20 was 245, 246, and 259 g/kWh, respectively. According to Table 5, BSFC data on diesel and B5 fuel do not differ significantly. But the amount of BSFC associated with B20 is significantly higher than diesel and B5 fuels. The main reason is biodiesel's low calorific value compared to diesel fuel (Table 2) (Faizollahzadeh Ardabili et al., 2018). As can be seen, the amount of BSFC for HHO-enriched fuels is lower than for Diesel, B5, and B20 fuels. This is due to the high heat value content of HHO gas compared to biodiesel and diesel fuels (Table 2), air-hydrogen mixing, and high hydrogen flame speed (Saravanan et al., 2008b), which has improved the combustion of the biodiesel–diesel fuel blends (Rahman et al., 2017). The results showed that adding 3 and 4 cc/s of HHO gas to D, B5, and B20 fuels did not make a significant difference in BSFC. But by adding 5 cc/s of HHO gas, the amount of BSFC is significantly reduced. The lowest BSFC values were for D_{HHO5} , $B5_{HHO5}$, and $B20_{HHO5}$ fuels, which were 218, 227, and 224 g/kWh, respectively. D_{HHO5} , $B5_{HHO5}$, and $B20_{HHO5}$ fuels reduced BSFC by 13.5%, 7.7%, and 11%, respectively, compared to D, B5, and B20 fuels. Therefore, in this study, the minimum amount of HHO gas that can significantly reduce the amount of BSFC was obtained, 5cc/s. Interestingly, the addition of HHO to B5 and B20 fuels corrects and improves biodiesel's low heat value, thereby reducing the amount of BSFC. The similar results were conducted by Masjuki et al. (2016) to compare the effect of HHO on the performance of a dual fuel diesel engine with that of the diesel and B20. According to the results, HHO successfully reduced the BSFC about 5% compared with the control fuel (Masjuki et al., 2016). Baltacıoğlu et al. (2019) reported a smooth reduction of BSFC by employing HHO at 1 L/min compared to the control fuel (Baltacıoğlu et al., 2019).

Brake thermal efficiency

The brake thermal efficiency (BTE) indicates the conversion of the thermal energy in the fuel into mechanical energy. Figure 11 shows the effect of HHO gas and biodiesel/diesel blends on the variation of BTE. As can be seen, the BTE is reduced by using biodiesel and increased by using HHO gas. Interestingly, these changes in BTE are consistent with the caloric content of biodiesel and

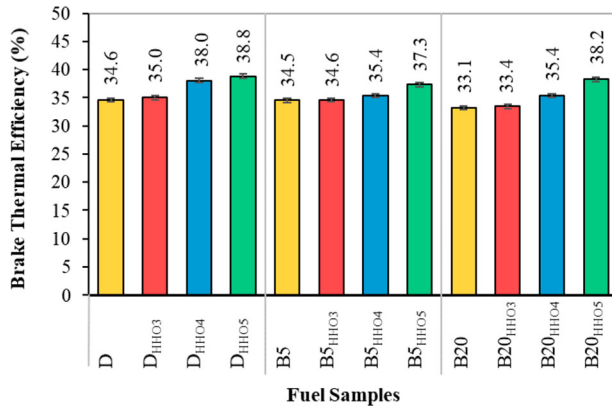


Figure 11. The effect of HHO gas and biodiesel/diesel blends on the variation of BTE.

HHO gas (Table 2). The BTE increases with HHO gas use, which is due to the better mixing of hydrogen-air and faster combustion and further diffusion of the flame (Saravanan et al., 2008a). Also, the oxygen in HHO gas causes complete combustion of biodiesel and Diesel (Kalam et al., 2003). Combustion of hydrogen produces higher temperatures than biodiesel and diesel fuels. Therefore, enriching biodiesel/diesel fuels with hydrogen increases the BTE (Baltacioglu et al., 2016; Yilmaz et al., 2010). The results showed that using HHO gas in the amount of 3 cc/s, increasing the BTE is not significant, but by increasing HHO by 4 and 5 cc/s, the BTE increases significantly. Baltacioglu et al. (2019) reported a considerable increase of BTE (by about 2.9%) in the presence of HHO at 1 L/min in comparison with the control fuel (Baltacioglu et al., 2019). The main reason was the higher calorific value of the Hydrogen which led to an increase in BTE value.

Equivalence ratio (ϕ)

Figure 12 shows the changes in the equivalence ratio using HHO gas and biodiesel/diesel fuel blends. Accordingly, with increasing HHO gas, the values of the equivalence ratio (ϕ) decrease. HHO gas causes better air-fuel mixing (Saravanan et al., 2008b). As a result, biodiesel/diesel fuel blends' combustion is improved (Rahman et al., 2017), reducing fuel consumption per kWh of braking power (Figure 11). Reducing the actual fuel consumption compared to its stoichiometric consumption reduces the equilibrium ratio (ϕ). As can be seen, adding 5 cc/s of HHO gas to D, B5, and B20 fuels significantly reduces the equivalence ratio's value. Adding 3 and 4 cc/s of HHO gas does not make a significant difference in ϕ . The lowest ϕ values were for D_{HHO5}, B5_{HHO5}, and B20_{HHO5} fuels, which were 0.642, 0.669, and 0.656, respectively.

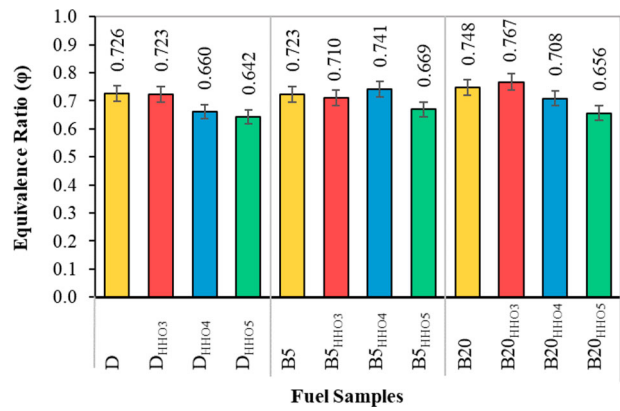


Figure 12. The effect of HHO gas and biodiesel/diesel blends on the variation of equivalence ratio.

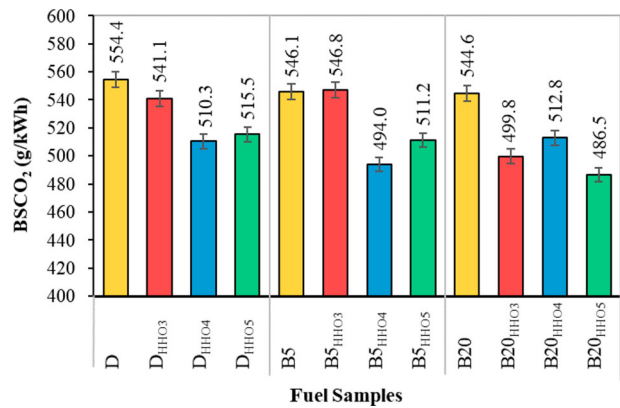


Figure 13. The effect of HHO gas and biodiesel/diesel blends on the variation of break specific CO₂.

Emission characteristics

Break specific CO₂ emissions

CO₂ is the most critical pollutant in the environment. Figure 13 shows break specific CO₂ emissions using HHO gas and biodiesel/diesel fuel blends. As can be seen, break specific CO₂ emissions increase significantly with HHO gas. The main reason for the increase break specific CO₂ emissions is the improvement in combustion (Aklouche et al., 2017). By injecting HHO gas, some oxygen gas enters the combustion chamber, and carbon oxidation is improved, resulting in more complete combustion (Deheri et al., 2020). The higher temperature in-cylinder is a sign of complete combustion (Figure 9) (Rahman et al., 2017; Verma et al., 2018). The results of this study showed that using HHO gas at values 4 and 5 cc/s significantly reduced break specific CO₂ emissions. The lowest emissions of break specific CO₂, related to D_{HHO4}, B5_{HHO4}, and B20_{HHO5} fuels, are 510.3, 494, and 486.5 g/kWh, respectively. B20_{HHO5} fuel significantly

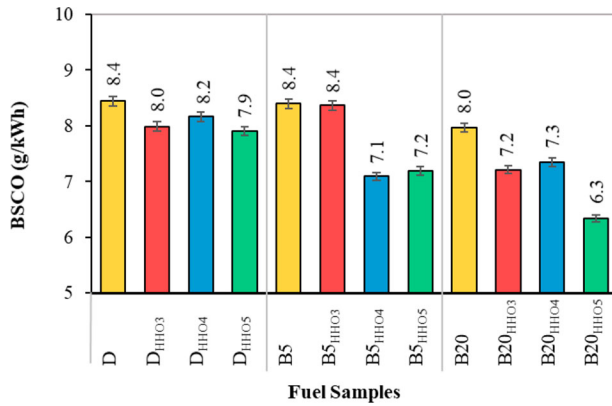


Figure 14. The effect of HHO gas and biodiesel/diesel blends on the variation of break specific CO.

reduces break specific CO₂ emissions by about 12.25% compared with diesel fuel as control.

Break specific CO emissions

CO is a toxic and dangerous gas which is generated by the incomplete combustion of hydrocarbon fuels (Akbarian et al., 2018). Figure 14 shows CO emissions using HHO gas and biodiesel/diesel fuel blends. Accordingly, break specific CO emissions are significantly reduced by using HHO gas, because HHO gas does not contain carbon (Baltacioglu et al., 2016). Also, break specific CO emissions depend on the fuel equivalent ratio (Saravanan et al., 2007). As shown in Figure 13, the values of the equivalence ratio (ϕ) decrease with increasing HHO gas. Decreasing the equivalence ratio means more inlet air into the cylinder. Obviously, despite the high oxygen content, the combustion in-cylinder is more complete and the break specific CO is reduced.

Also, because biodiesel fuel contains 10–12% oxygen, so by adding it to diesel fuel, the amount of oxygen in the combustion chamber increases, and as a result, the combustion is more complete, and CO emissions are reduced. The findings show that the simultaneous use of HHO gas and biodiesel intensifies the effect of increasing oxygen in the combustion chamber and significantly reduces break specific CO emissions. The highest break specific CO reduction was related to the B20_{HHO5} fuel, in which the ratio of biodiesel to diesel was 20:80, and the HHO gas flow rate was 5 cc/s. B20_{HHO5} fuel significantly reduces break specific CO emissions by about 25% compared to pure diesel fuel. Rimkus et al. (2018) also reported a significant reduction of CO emissions by employing 0.14–0.18 Vol.% of HHO in the engine's input air. According to the results, the presence of the HHO reduced the CO emission especially at higher engine

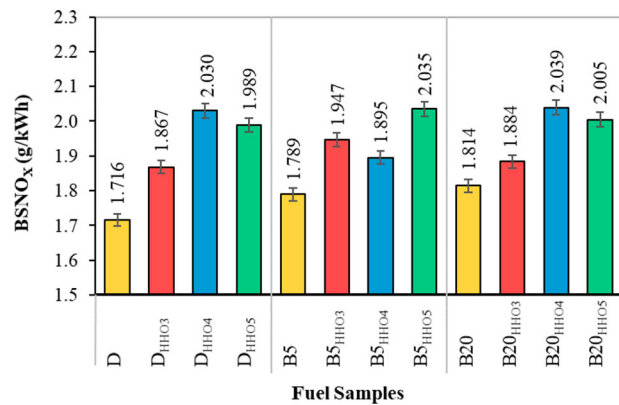


Figure 15. The effect of HHO gas and biodiesel/diesel blends on the variation of NO_x.

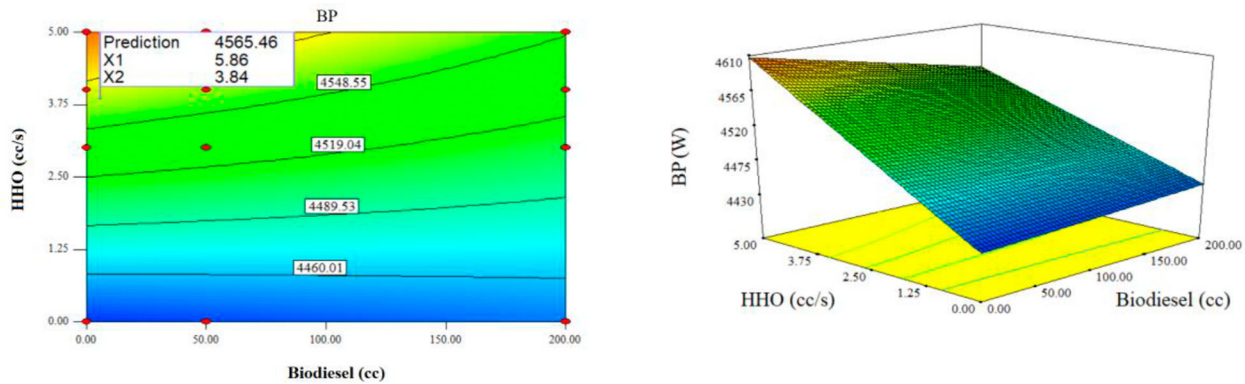
loads, due to the catalyzing effects of hydrogen in the fuel combustion (Rimkus et al., 2018).

Nitrogen oxides (NO_x)

NO_x play an essential role in creating and spreading environmental pollution due to their toxicity. The formation of NO_x during combustion depends on three factors: oxygen concentration, the temperature of the combustion chamber, and residence time (Premkartiikkumar et al., 2014). Figure 15 shows the NO_x emission using HHO gas in a biodiesel/diesel fuel blend. Accordingly, the amount of NO_x emissions increases significantly with HHO gas. The presence of HHO in the combustion chamber increases the intensity of combustion as well as increasing the temperature (Figure 8), resulting in NO_x emissions (Kumar et al., 2003). Also, the presence of oxygen in B5 and B20 fuels (Table 2) increases the concentration of oxygen in the combustion chamber [37], resulting in more intense combustion and increases NO_x emissions. On the other hand, the differences in cetane number of biodiesel and diesel (Table 2) affects the ignition delay (Heywood; Lavoie et al., 1970; Lyn & Valdmanis, 1968; Owen & Coley, 1995; Wong & Steere, 1982) and accordingly, increases the retention time of fuel in the combustion chamber and led to form more NO_x. The findings show that using of HHO gas and biodiesel simultaneously increases the NO_x emissions. The highest NO_x is for B20_{HHO4} fuel with 2.039 g/kWh, which is significantly higher than for B20 and D fuels. The increase of NO_x emission was also reported by Masjuki et al. (2016) for comparing the effect of HHO on the emission characteristics of a dual fuel diesel engine with that of the Diesel and B20. According to the results, HHO caused an increase in NO_x emission comparison with control fuel (Masjuki et al., 2016). Baltacioglu et al. (2019) reported an increase of NO_x emission by employing HHO at 1 L/min compared to the control fuel

Table 7. Optimization parameters.

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Biodiesel	is in range	0	200	1	1	3
HHO	is in range	0	5	1	1	3
R1	maximize	4418.45	4631.5	1	1	3
R2	minimize	213.993	258.546	1	1	3
R3	maximize	33.1446	38.7947	1	1	3
R5	minimize	6.34221	8.44311	1	1	3
R6	maximize	486.456	554.4	1	1	3
R7	minimize	1.71596	2.03913	1	1	3

**Figure 16.** the optimized levels for the performance and emission factors.

(Baltacıoğlu et al., 2019). In another study, Rimkus et al. (2018) investigated the effect of 0.14–0.18% of the volume of HHO in the input air to the engine. According to the results, the presence of the HHO increased the NOx emission especially in the lower engine loads. The main reason was the higher concentration of HHO in the combustion chamber that increases the combustion chamber's temperature and led to the formation of the NOx (Rimkus et al., 2018).

Optimization

The optimization process was performed by response surface methodology (RSM) as a mathematical-based analysis method. The RSM method's theoretical description is presented in our previous studies in (Faizollahzadeh Ardabili et al., 2018). The optimization was performed in terms of increasing the engine's performance and reducing engine exhaust emissions. In the optimization process, the biodiesel concentration (cc) in the pilot fuel samples and HHO rate (cc/s) were considered as the independent variables which affect the BP (W), BSFC (gr/kWh), and engine emissions (gr/kWh) as the dependent variables. Table 6 and Table 7 present the optimization parameters. Dataset was analyzed using Central Composite Design (CCD).

Figure 16 presents the optimal levels for the independent variables in the presence of the dependent variables.

According to Figure 16, the best condition for the highest performance as well as the lowest engine emission has happened in the biodiesel concentration of 5.86

cc and HHO rate 3.84 cc/s. this condition could successfully generate BP of 4565.46 W and efficiency of 36.75%, consume BSFC of 227.855 gr/kWh and produce engine emissions including O₂, CO, CO₂, and NO_x of 787.4, 7.96, 523.2, and 1.9 gr/kWh, respectively.

As is clear from Figure 16, increasing the HHO rate increases the BP but increasing the biodiesel concentration reduces the BP, especially at higher HHO rates. This can be due to biodiesel's lower heating value (Faizollahzadeh Ardabili et al., 2019). Increasing the HHO rate also reduces the BSFC value due to its higher heating value, but increasing the biodiesel concentration increases the BSFC, especially at higher HHO rates. Nb is also increased by increasing the HHO rate and reduced by increasing the biodiesel concentration.

HHO also affected the O₂ emission. By the way, increasing the HHO rate significantly increased O₂ emission. This phenomenon is also observed by Ismail et al., which is related to the extra oxygen content of HHO (Ismail et al., 2018). But, biodiesel did not indicate a significant effect on O₂ emission. Increasing the HHO rate and biodiesel concentration successfully reduced the CO emission. Uludamar also reported a reduction for CO and CO₂ emissions in the presence of HHO (Uludamar, 2018). The main reason was claimed to be the fast its fast flame expansion in the presence of HHO gas, and also lack of carbon in HHO reduced the availability of carbon in the combustion outcome (Jhang et al., 2016). Increasing the HHO rate also increased the NO_x emission. One of the main reasons for that is the higher temperature of

the combustion chamber in the HHO gas presence due to the faster burning rate. This was also reported by Zhou et al. (2014).

Conclusion

The present study's main aim is to investigate the performance and emission of a dual-fuel diesel engine using HHO as induced fuel and biodiesel/diesel blends as pilot fuel. Using HHO gas with 3 cc/s flow rate does not significantly affect BP, but using it in the amount of 4 and 5 cc/s increases the BP compared to diesel and B5 fuels. The highest BP increase is related to D_{HHO5} and B5_{HHO5} fuels, which increased by 2.61% and 3.16% compared to Diesel and B5 fuels, respectively. Adding 5 cc/s of HHO gas, reduced BSFC significantly. The lowest BSFC values for D_{HHO5}, B5_{HHO5}, and B20_{HHO5} fuels are 218, 227, and 224 g/kWh, respectively. Using HHO gas by 3 cc/s has no significant effect on the BTE, but HHO by 4 and 5 cc/s significantly increased the BTE of the engine. HHO gas by 4 and 5cc/s also reduced the CO₂ emissions significantly. Simultaneous use of HHO gas and biodiesel intensified the effect of increasing oxygen in the combustion chamber and significantly reduced CO emissions. The highest CO reduction was related to B20_{HHO5} fuel. The use of HHO and biodiesel gas in a dual fuel diesel engine increased the NO_x emission. The highest NO_x was related to B20_{HHO4} fuel by 2.039 g/kWh, which was significantly higher than for B20 and diesel fuel. According to the obtained results, the simultaneous use of HHO gas and biodiesel fuel in a dual fuel diesel engine enhances fuel combustion and improves performance and emissions of the engine. The minimum amount of HHO gas that has a significant effect on BSFC reduction and emissions is 5 cc/s. Therefore, the use of HHO gas can be considered as a promising technique to increase performance and reduce emissions of dual-fuel diesel engines, without any change in the structure of diesel engines.

Nomenclatures

ASTM	American Society for Testing and Materials
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
B5	Diesel fuel including 5% biodiesel
B20	Diesel fuel including 20% biodiesel
B20 _{HHO5}	20%Biodiesel+80%Diesel+5cc/s HHO
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
D	Diesel Fuel

DFDE	Dual Fuel Diesel Engine
GHG	Greenhouse gas
H ₂	Hydrogen
HHO	Hydroxy Gas
ICEs	Internal Combustion Engines
IEA	International Energy Agency
L/min	Liter per Minute
NO _x	Nitrogen Oxides
PM	Particulate Matter
Ppm	Parts per million
rpm	Revolutions per Minute
WCOME	Waste Cooking Oil Methyl Ester

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