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Experimental Assessment of the Impact of Biodiesel Blends and Methanol on Emissions and Performance in a Semi-Industrial Boiler

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ABSTRACT

Recently, there has been a growing interest in biodiesel due to its utilization of renewable resources, which is particularly significant given the increasing depletion of fossil fuel stocks. The utilization of Cresson weed in biodiesel fuel production is a pioneering application of botanical herbs within the biodiesel industry. This study compares the combustion characteristics of biodiesel fuel B10, B20, B40, B60, and D80B10M10 blends with petroleum diesel. This analysis examined the combustion process across various equivalence ratios in semi-industrial boilers. The study examined the combustion efficiency, flue gas emissions (CO, CO_2, T exhaust, and HC), as well as flame length. The obtained findings show that adding more biodiesel fuel to diesel fuel increases its combustion efficiency above and beyond what is possible with regular diesel fuel at high energy levels. In addition, blends like B60 and other mixtures like D80B10M10 emit lower levels of pollutants, such as CO, than diesel as well as increase T exhaust and CO_2, which indicates the completion of combustion.

Keywords: semi-industrial boiler; renewable energy; biodiesel; emission; combustion efficiency; methanol.

INTRODUCTION

The boiler is one of the industrial machines with the highest fuel consumption. The boiler fuel considerations include steam demand, fuel prices, availability, and supply guarantees. The number of oil-fired boilers in the industrial and commercial sectors is much lower than in other fuel types, such as natural gas, coal, and biomass. Still, the quantity of diesel fuel used for a boiler remains high in terms of consumption volume. The concerns about the limited availability of fuel and the volatility of oil prices call for the continued diminution of petroleum oil consumption. Because it does not harm the environment and is a renewable resource, the biofuel obtained from biomass is currently the most promising alternative fuel source. Biofuel is any liquid or gaseous fuel derived from biomass, such as biodiesel, methanol, and biogas (Launhardt & Thoma, 2000). Biodiesel, a liquid alternative fuel for diesel engines and industrial burners, is generated from organic oils and lipids and has the qualities that closely resemble those of diesel fuel (Elkelawy et al., 2021). According to the Organization for Economic Cooperation and Development (OECD) and the Food and Agriculture Organization of the United Nations (FAO), the output of biodiesel will be projected to exceed 41.4 billion liters by 2025 (Tabatabaei, 2018). Increasing biodiesel utilization across all user sectors is one effective strategy. The biodiesel usage target for the industrial and commercial sectors is 5% in 2013, 10% at the beginning of 2016, 20% in 2020, and 25% in 2025. Presently, the application is less practical than intended, as demonstrated by the fact that only a few users have adopted biodiesel as boiler fuel. The concerns regarding engine compatibility and the cost of biodiesel influence this condition (Komariah, 2014). The use of biodiesel in boilers has been shown to have positive effects on minimizing emissions (Komariah et al., 2013);

however, biodiesel has been found to be inferior to diesel oil in terms of boiler performance. Heravi et al. (2015) studied how using a variety of vegetable oils in a biodiesel-gasoil combination affected the emissions produced by the boiler. Sunflower and corn biodiesel mixed with gasoil were characterized by the highest NOx, SO_2, and temperature levels. Several factors, including the physicochemical qualities and molecular structure of biodiesel, the adiabatic flame temperature, the experimental settings employed, and the operational systems, contribute to the varying outcomes of NOx generation. Bhele et al. (2016) investigated the effect of Jatropha biodiesel and diesel mixes on air-blast burner emissions through laboratory testing. On the basis of on their findings, they concluded that switching to biodiesel decreases the primary emissions of CO, CO_2, UbH, and PM while increasing NOx emissions. On the basis of these findings, biodiesel is used instead of conventional fuels in industrial burners in power plants. Malik et al. (2017) investigated a conventional solid spray fuel nozzle and an open-ended combustion chamber to examine the efficiency and emissions of three different biodiesel/diesel equivalency ratios compared to pure diesel. They found that biodiesel fuel blends combust at a lower temperature and produce fewer pollutants than regular diesel fuel at all equivalency ratios. Combustor wall temperature and emission concentration were also decreased when the percentage of biodiesel fuel in conventional diesel fuel mixtures was increased (Norwazan et al., 2018)**.** In the present study, the combustion and emission properties of blends of jatropha oil biodiesel and diesel fuels (B5, B10, B15, B20, and B25) were examined using a swirl burner. The investigation revealed a notable reduction in emissions of hydrocarbons (HC), carbon dioxide (CO_2), and carbon monoxide (CO). However, the elevated oxygen concentration present in biodiesel fuel resulted in an increase in NOx emissions across all fuel blends. The use of B25 results in significant decreases in carbon monoxide (CO), sulfur dioxide (SO_2), and unburned hydrocarbon (UHC) emissions by 42%, 33%, and 50%, respectively. Pollutant emissions from diesel and biodiesel fuels result in inefficient combustion. Researchers combining biodiesel with conventional diesel improved the chemical and physical properties of fuel. Using additives is an alternative method for enhancing the emissions and performance of diesel-biodiesel mixtures. One of the promising liquid alternative fuels for diesel engines and industrial burners is biodiesel, derived from organic oils and lipids and has similar properties to diesel fuel. Ghorbani et al. (2011) compared B5, B10, B20, B50, B80, and B100 combustion with petroleum diesel at two energy phases in an experimental boiler with large input air fluxes. The distinction was made based on combustion efficiency, pollution of flue gas (CO, CO_2, NOx, and SO_2), and the effect of ventilation at two energy ranges: 219 kJ/h and 249 kJ/h. The results indicate that energy efficiency of diesel was slightly greater than that of biodiesel at higher levels but that biodiesel is more efficient at lower levels. The study by Al-Esawi (2016) examined the combustion characteristics and emissions of 75 percent diesel fuel and 25 percent biodiesel fuel blends in three swirl angles. The results showed reduced carbon monoxide, unburned hydrocarbon, and particulate emissions when the rotating flow was increased. The NOx emissions were marginally more significant for all biodiesel fuel types than diesel fuel combustion (Amirnordin et al., 2013). A UTHM biodiesel pilot plant study determined biodiesel purity and analyzed its effects on oil burner emissions. The biodiesel mixtures containing 5%, 10%, and 15% diesel showed an 87% reduction in hazardous emissions compared to pure diesel. This suggests that palm oil biodiesel mixtures can reduce the emissions from combustion systems. Veski (2002) stated that the optimal air-to-boiler ratio must be set in order to maintain maximal boiler efficiency. Elkelawy et al. (2022) found that biofuel mixtures significantly reduced emissions compared to diesel oil alone. The CO emissions decreased by 19%, 69%, and 65% for D50B50, D50B50E15, and D50B50E25 fuels, respectively. The HC emissions decreased by 18%, 37%, and 28%, while smoke opacity decreased by 10%, 70%, and 40%. Biofuel can be used in industrial furnaces without modification and combined with petroleum diesel in any proportion. The research article by Rahim et al. (2016) emphasizes the CO_2 emissions caused by the combustion of biodiesel and diesel fuel mixtures. The oxygen in biodiesel fuels is responsible for the increased CO_2 emissions. During discharge, oxygen reacts with unburned carbon atoms, increasing CO_2 formation. The increased CO_2 emissions indicate more complete combustion and decreased CO concentration. According to researchers' findings, it has been shown that the system's performance improves when the cetane number increases and methanol is introduced for fuel blending (Allawi et al. 2020, Allawi, 2016).

The study results presented previously indicated (Rahim et al., 2016) that the use of biodiesel blends in a liquid fuel burner resulted in reduced emissions of NOx, carbon dioxide, and soot compared to the use of pure diesel fuel.

MATERIALS

In this study, conventional petroleum was combined with Cresson oil biodiesel fuel. The biodiesel is produced by transesterification with alkali. These oils are obtained from botanical herbs. In addition, diesel fuel is obtained from an Al-Dura Oil Refinery. Methanol (alcole metallic p.a. 99.8+% CH_3OH) and potassium hydroxide (KOH) are used in the biodiesel production procedure. Table 1 presents the fatty acid methyl esters (FAME) in the biodiesel, as determined by utilizing gas chromatography-mass spectrometry (GC-MS). The chromatogram obtained for Cresson biodiesel is depicted in Figure 1. The chromatogram exhibits 15 distinct peaks, each corresponding to the identification of the esters present in the produced biodiesel.

Biodiesel production

Figures 2 and 3 present streamlined flowcharts that depict the biodiesel manufacturing method employed in the current research investigation.

Physical attributes

The physical characteristics of biodiesel, such as its viscosity, heating value, flash point, and cetane index, were determined using the methods described in Table 2.

Table 1. The FAME content of Cresson biodiesel

Compounds detected	Molecular formula	Composition (%)	#Peaks
Methyl tetradecanoate	C15H30O2	0.26	1
9-Hexadecenoic acid, methyl ester,	C16H30O2	0.31	2
Hexadecanoic acid, methyl ester	$C_{17}H_{34}O_2$	14.85	3
Pentadecanoic acid	C15H30O2	0.12	4
9,12-Octadecadienoic acid, methyl ester	C19H34O2	59.66	5
Heptadecanoic acid, 16-methyl-, methyl ester	C19H38O2	4.01	6
9,12- Octadecadienoic acid (Z,Z)-, methyl ester	C19H34O2	0.58	7
9,12-Octadecadienoic acid (Z,Z)-, methyl ester	C19H34O2	0.16	8
cis-5,8,11-Eicosatrienoic acid methyl ester	C21H36O2	0.14	9
9-Octadecenoic acid (Z)-, methyl ester	C19H36O2	12.52	10
Methyl 18-methylnonadecanoate	C21H42O2	3.21	11
Dodecyl cyclohexane carboxylate	C19H36O2	0.18	12
Erucic Acid	C22H42O2	3.23	13
Methyl 20-methyl-heneicosanoate	C23H46O2	0.59	14
Benzene, 1-methyl-3,5-bis(1-methylethyl)-	C13H20	0.15	15

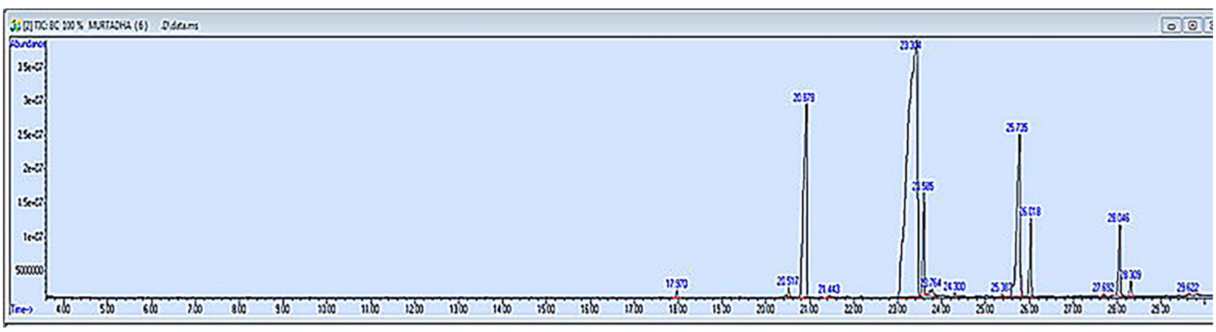

Fig. 1. GC–MS chromatogram of Cresson biodiesel

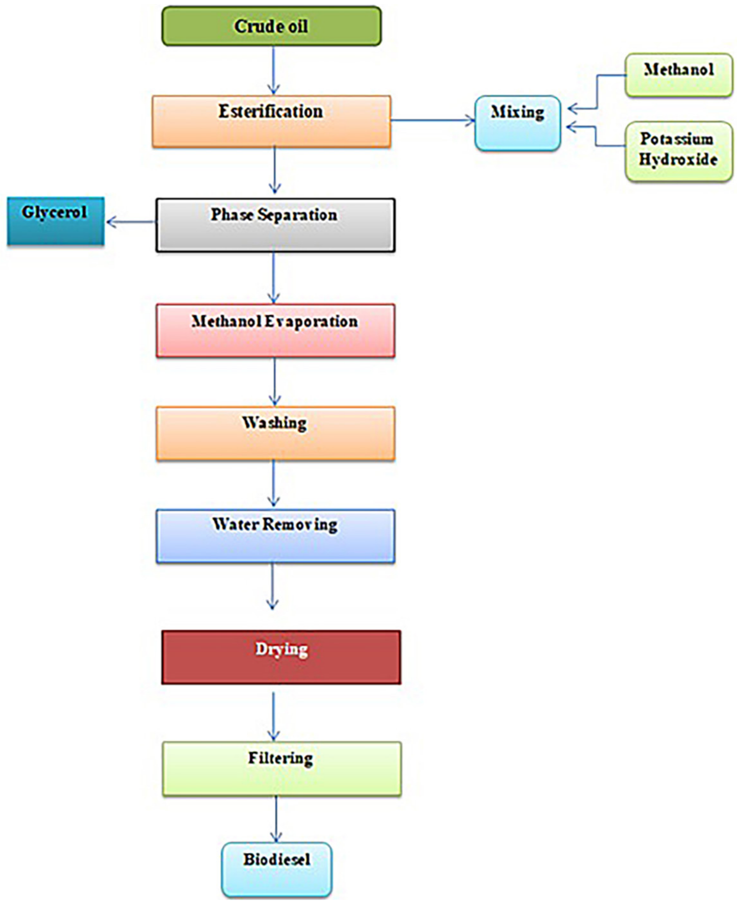

Fig. 2. Flow chart of biodiesel manufacturing

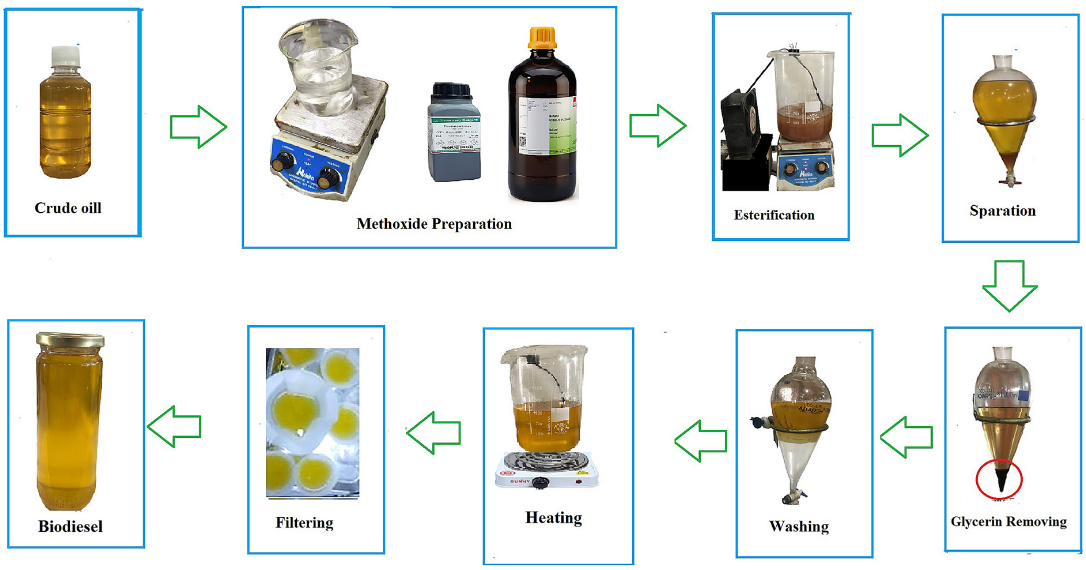

Fig. 3. The steps in making biodiesel (the esterification process)

EXPERIMENTAL SETUP

Experiments were conducted in the combustion laboratory of the Mechanical Engineering Department, College of Engineering, Mustansiriyah University, Iraq, under atmospheric conditions (P = 1 bar and T = 298 K). The experimental setup consists of a TVCC unit (Figures 4 and 5), which is a computer-controlled laboratory unit. The purpose of the TVCC unit is

Table 2. Physical properties of biodiesel and petroleum fuels

Property	unit	Diesel	BC10	BC20	BC40	BC60
Density at 15 ºC	kg/m³	831	835.9	841.8	853.6	865.4
Kinematic viscosity at 38.8 ºC	mm²/s	2.51	2.81	3.05	3.54	3.98
Flash point temperature	ºC	62	77	89	101.5	118
Fire point temperature	ºC	73	95	111.5	123.5	136
Calorific value	MJ/kg	46.5	45.8	45.1	43.6	42.2
Cetane number	-	46.3	47.9	50.9	54.2	55.9

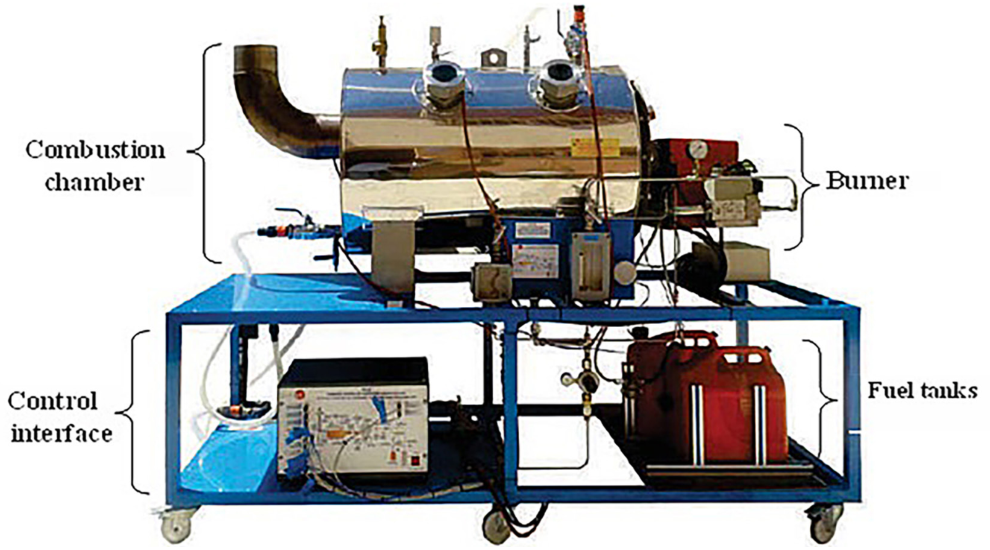

Figure 4. TVCC laboratory equipment

to study the operation of an industrial burner in a controlled laboratory environment, with conditions as close as possible to those found in the industry. The dimensions and specifications for the TVCC unit are provided in Table 3.

Emissions measurements

The TBMC-AGE Exhaust Gas Analyzer is a specialized device utilized to quantify and examine the constituent elements present in exhaust gases discharged due to combustion procedures. This instrument is commonly employed in various applications such as internal combustion engines, industrial furnaces, boilers, and other systems involving combustion. The analyzer facilitates the assessment of combustion efficiency, the evaluation of the environmental impact of emissions, and the verification of conformity with emission norms and standards. The TBMC-AGE conducts a range of measurements to offer significant insights into the exhaust gases

Table 3. The parameters of specifications of the TVCC unit

Technical characteristics of the TVCC unit	Range	Accuracy
Power output up to	150 kW	-
Flow rate of fuel	4-38 kg/h.	±2%
Cooling water flow inlet	1.5 to 30 L/min	±3%
The appropriate fuel viscosity for oil: kerosene, diesel or other light fuel	0.011-0.055 cm²/s at 40ºC	-
Approximate density	790-840 kg/m³	
Flow sensor, range	3-21 m³/h.	±2.5%
Air inlet (by means of a differential pressure sensor)	0-1 PSI	±0.20%

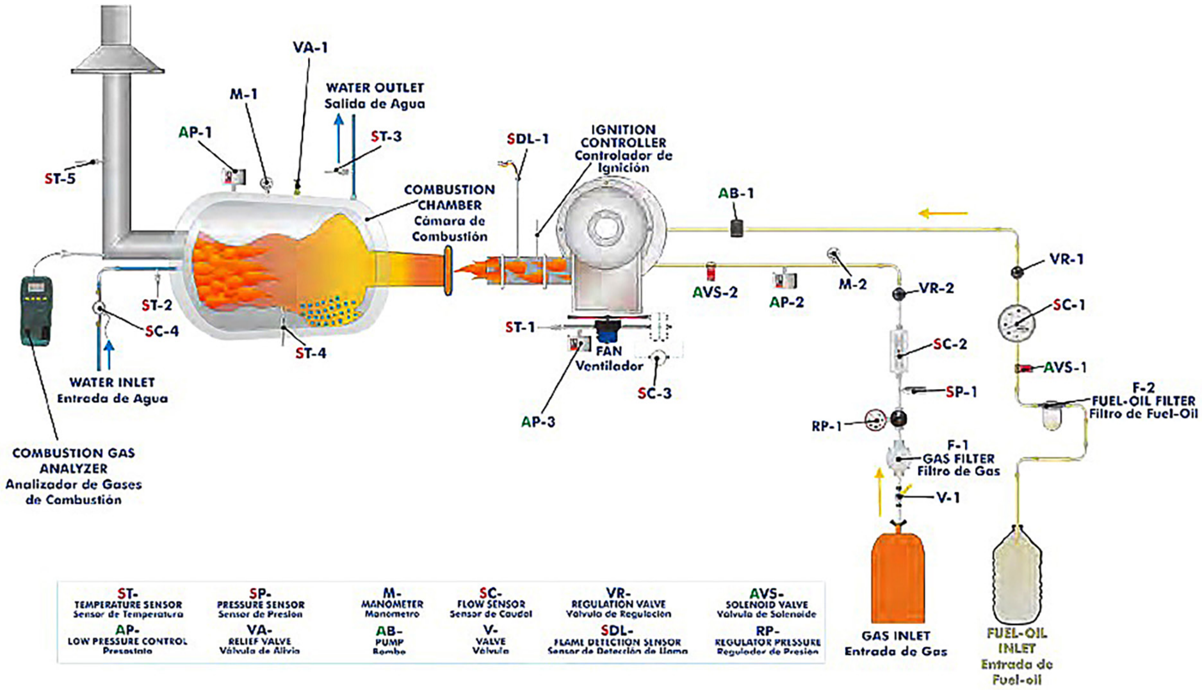

Figure 5. The schematic diagram for the TVCC equipment

generated during the combustion process. Specifications of the TBMC-AGE Exhaust Gas Analyzer are given in Table 4.

RESULTS AND DISCUSSION

A laboratory experiment is conducted with and without methanol on prepared diesel and vegetable oil biodiesel fuel samples, and the corresponding combustion and emission parameters are determined. The volume ratios of the various fuel types utilized in the investigations are displayed in Table 5. The results of an investigation into the variable equivalence ratio of an industrial burner are presented in the sections that follow.

Exhaust temperature

Figure 6 show the relationship between exhaust temperature and equivalence ratio. The exhaust temperature ranged from 500 to 695°C when utilizing 100% diesel fuel. In contrast, when 10% biodiesel was used, the exhaust temperature ranged from 515 to 700°C. When the biodiesel concentration was increased to 60%, the exhaust temperature ranged from 530 to 720°C. On the basis of the data presented in Figure 5, it can be observed that an increase in the equivalence ratio leads to a corresponding elevation in the exhaust temperature for all fuel types. The increase in temperature observed can be attributed to the larger volume of the fuel-air mixture, resulting in an elevated combustion temperature. This phenomenon arises due to the liberation of a significant quantity of heat by the extra fuel present in the combination. Furthermore, as the concentration of biodiesel in the mixture increases, there is a corresponding increase in the exhaust temperature. The greater oxygen content present in biodiesel can be attributable to this phenomenon when compared to standard diesel (Elkelawy et al., 2022).

Combustion efficiency

The concept of combustion efficiency is concerned with optimizing exhaust gas emissions through reducing carbon monoxide outputs. The impact of the equivalency ratio on combustion efficiency across various blends of biodiesel, ranging from 10% to 60%, is depicted in Figure 7. The data indicates that there is a positive correlation between the increase in both biodiesel blend ratios and equivalency ratios as well as the improvement in efficiency (Stephen, 2000)

CO emissions

The emission of an industrial burner's refers to the discharge of pollutants, notably carbon monoxide (CO), into the exhaust gases during

Table 4. The parameters of specifications of the TBMC-AGE

Technical characteristics of the TBMC-AGE, exhaust gas analyzer	Resolution	Accuracy	Range
Carbon monoxide (CO)	+/- 0.02% abs	+/- 3% rel	0-15%
Carbon dioxide (CO_2)	+/- 0.3% abs	+/- 3% rel	0-20%
HC	+/- 8 ppm abs	+/- 3% rel	0-3000 ppm vol
Oxygen (O2)	+/- 0.1% abs	+/- 5% rel	0-25%
Lambda	-	-	0-9.999 rmp
Oil temperature	-	-	0-200°C

Table 5. Types of fuels tested in the study

Test fuel	Diesel volume	Biodiesel volume	Methanol volume
D 100	100%	NIL	NIL
D90B10	90%	10%	NIL
D80B20	80%	20%	NIL
D60B40	60%	40%	NIL
D40B60	40%	60%	NIL
D80B10M10	80%	10%	10%

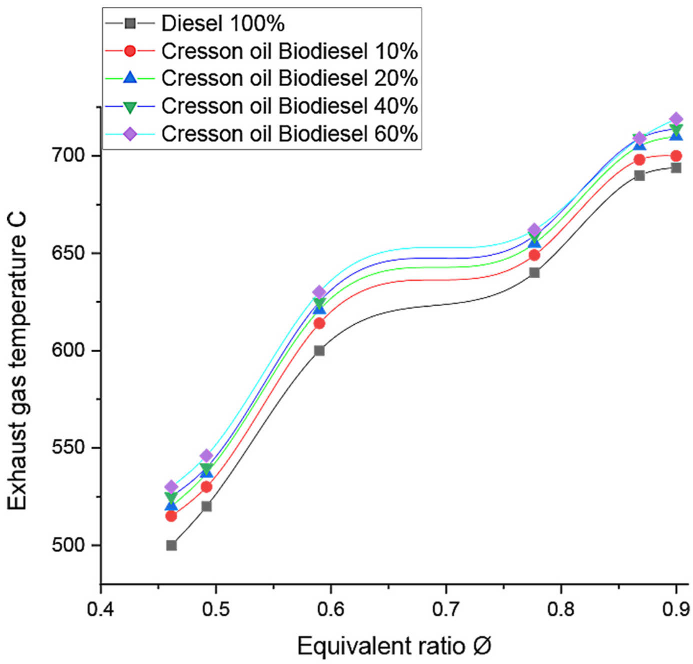

Fig. 6. Exhaust temperature versus equivalence ratio at different percent of biodiesel blend

combustion. Figure 8 depicts the measured carbon monoxide (CO) emissions for various biodiesel mixes ranging from (10% to 60%) and D80B10M10. Observations indicate that biodiesel emits fewer pollutants than diesel. The higher CO concentration of diesel results from the higher carbon content by volume ratio of diesel compared to biodiesel. The rapid influx of air extinguished the flame and unevenly dispersed the fuel throughout the chamber. Furthermore, the flame temperature is lowered by the increased air-to-fuel ratio (Bazooyar et al., 2014). Because higher oxygen content reduces CO emissions in the exhaust, increasing the quantity of methanol in the fuel has the opposite effect. Higher oxygen concentrations increase the likelihood of complete combustion and decrease the possibility of CO generation. However, the physical and chemical

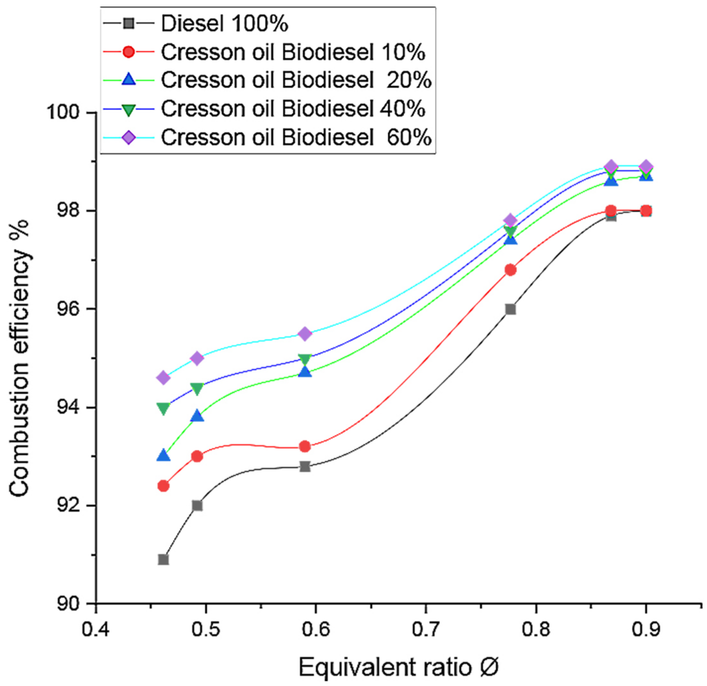

Fig. 7. Combustion efficiency versus equivalence ratio at different percent of biodiesel blend

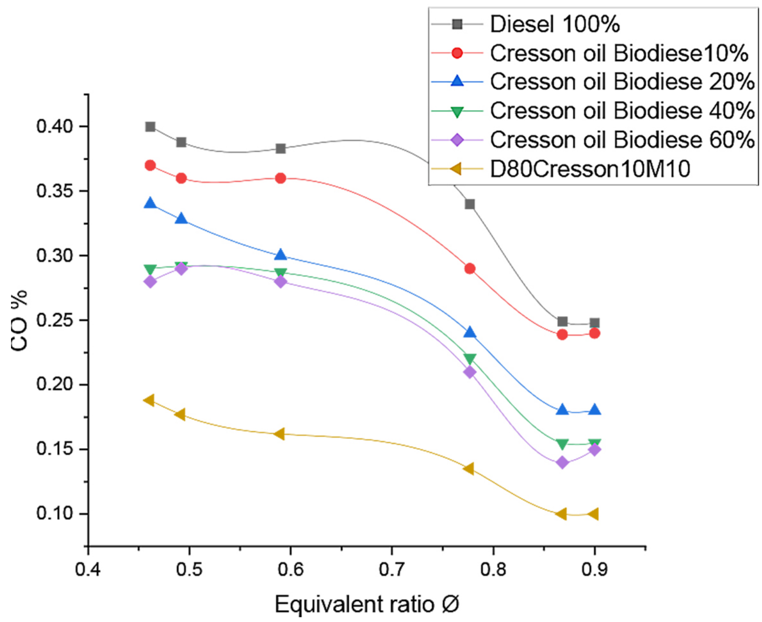

Fig. 8. Carbon monoxide versus equivalence ratio at different percent of biodiesel blend

features of the additives explain the wide range of CO emissions seen in composites that incorporate them (Rakopoulos, 2013). The study findings suggest that using a combination of n-butanol and methanol in diesel-biodiesel blends has the potential to enhance the reduction of carbon monoxide (CO) and hydrocarbon (HC) emissions compared to pure diesel fuel and this is consistent with Amiri & Shirneshan (2020)

CO_2 emissions

The analyzer calculated the CO_2 value for biodiesel and diesel fuel based on the oxygen measurement. The variation of CO_2 versus equivalence ratio for various biodiesel mixes ranges from (10% to 60%). It is depicted in Figure 9. On the basis of the trajectory of the results, the CO_2 emission of biodiesel is slightly higher than

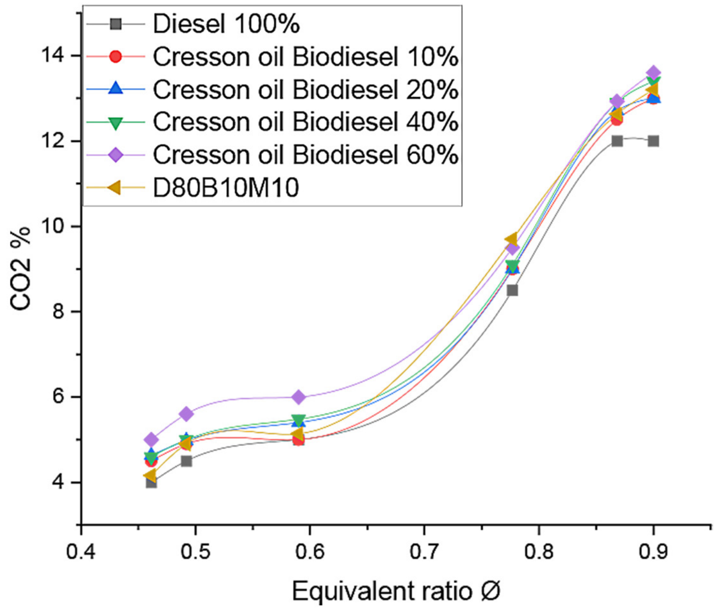

Fig. 9. Carbon dioxide versus equivalence ratio at different percent of biodiesel blend

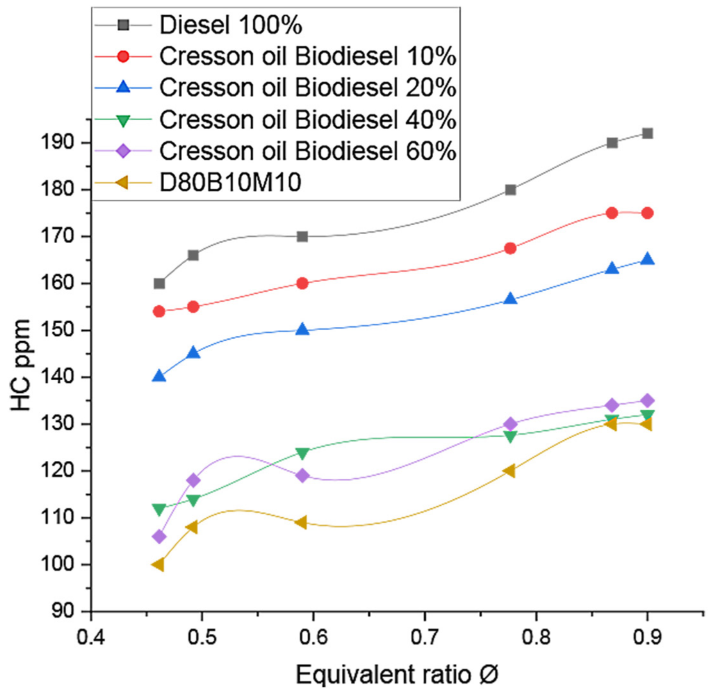

Fig. 10. Unburned hydrocarbon versus equivalence ratio at different percent of biodiesel blend

that of diesel due to the oxygen and carbon atoms present in the fuel. The CO_2% increases along with the equivalence ratio from (0.7 to 0.9). Pure diesel exhibited the lowest CO_2 emissions, whereas the D70B25M5 blend (a specific composition of diesel and biodiesel) showed the maximum CO_2 emissions. In addition, the study revealed that the addition of methanol to diesel-biodiesel mixtures increased CO_2 emissions. This increase in emissions is due to oxygen in these fuel combinations (McCarthy et al., 2011; Amiri & Shirneshan, 2020).

Unburned hydrocarbon

Figure 10 depicts the measured hydrocarbons (HC) emissions for various biodiesel mixes ranging from (10% to 60%) and D80B10M10. Using oxygenated fuels, such as biodiesels, can improve

Fuel sample	Flame structure	The length of the flame cm
Diesel		60 cm
BC 10		56 cm
BC 20		53cm
BC 40		50cm
BC 60		48 cm

Fig. 11. The flame structure of biodiesel blends

combustion efficiency by supplying the necessary oxygen for fostering combustion. When oxygenated fuels are utilized, the combustion process becomes completer and more efficient, reducing unburned hydrocarbons in the exhaust gases. By providing additional oxygen atoms, the oxygen content of these fuels promotes improved combustion. This excess oxygen contributes to the complete oxidation of hydrocarbon molecules, thereby decreasing the formation of unburned hydrocarbons. In other words, when there is a sufficient supply of oxygen, the combustion process is more effective at breaking down hydrocarbon molecules, thereby reducing the number of unburned hydrocarbons in the product gases. The reduced UHC emissions are due to the O_2 content of biodiesel fuel, which aids biodiesel combustion. This is the result shown in Figure 10 for the tested fuels, which is also consistent with the results reported in the research presented by (Kwanchareon et al., 2007). However, some researchers (Žaglinskis et al., 2016; Yilmaz et al., 2018) have demonstrated that the behavior of HC emissions from diesel fuels compounded with alcohol is distinct.

FLAME COLOR AND SHAPE

Figure 11 depicts the flame length and ignition temperature of a mixture of petroleum diesel (B0) and various biodiesel ratios (B10, B20, B40, and B60). During the experimental period, the biodiesel blend composed entirely of biodiesel, known as B100, did not endure combustion. Furthermore, as the biodiesel content in the mixture increased, there was a perceptible reduction in the length of the flame. It must be noted that 100 percent diesel fuel displayed a faint orange flame. Observations revealed that the luminosity of yellow flame increased proportionally with increasing biodiesel content. In addition, the increased stability of the flame coincided with the furnace stabilization. Biodiesel fuels with 20%, 40%, and 60% biodiesel content showed a significant flame brilliance and clarity increase at various comparable ratios. This phenomenon is attributable to complete combustion, which substantially decreases unburned hydrocarbon emissions across all flame types, according to the results for the pollutants mentioned in the preceding statistics. In their study, Bhele et al. (2018) reported a comparable finding wherein they utilized a biodiesel blend sourced from Jatropha as a fuel for a gas turbine compressor. The flame length was noticeably reduced as the proportion of biodiesel in the blend increased. This phenomenon is characterized by a decrease in flame height corresponding to an increase in the proportion of biodiesel, and this is consistent with Sitanggang et al. (2022).

CONCLUSIONS

This study examined and compared the combustion performance, features, and emissions of diesel and biodiesel fuel blends. The studies were conducted under identical operating conditions within a flame tube boiler initially configured to utilize diesel as its typical fuel source. The study yielded some positive outcomes, which are summarized as follows. The findings from the emissions analysis, which encompassed the measurement of carbon monoxide nd hydrocarbon, indicate that the utilization of biofuel blends in conjunction with diesel oil resulted in a notable reduction in emissions compared to the use of diesel oil alone at all equivalent ratios. The 60% biodiesel blend exhibited the highest exhaust temperature, but these temperatures declined as the quantity of biodiesel was reduced to 10% compared to pure diesel. Flame length decreases with increasing biodiesel blends. As the proportion of biodiesel in the blends rose, there was a noticeable combustion efficiency increase at all equivalence ratio levels. Biofuel can be utilized in industrial burners without necessitating any alterations. In addition to being locally available and renewable, biodiesel can serve as a suitable substitute for diesel fuel in these industrial applications.

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