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Enhancing Performance and Emission Characteristics in Industrial Burners Using Waste Cooking Oil Biodiesel and Its Blends

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Abstract: The urgent need to address the global energy crisis and dwindling fossil fuel reserves has intensified efforts to develop sustainable energy solutions. This research examines the combustion performance and emission profiles of biodiesel and its diesel blends using a 35-kW industrial burner within a laboratory furnace setup. Two fuels were analyzed: pure biodiesel (B100) and a 50% biodiesel–50% diesel mixture (D50B50). Temperature distributions across the furnace and emission levels during combustion were systematically measured. Findings revealed that both D50B50 and B100 generated higher flame temperatures and substantially decreased carbon monoxide (CO), unburned hydrocarbon (UHC), and soot emissions relative to pure diesel. Specifically, D50B50 demonstrated emission reductions of ~15% (CO), 19% (UHC), and 9% (soot), whereas B100 showed more pronounced reductions of 28%, 36%, and 30%, respectively. Conversely, nitrogen oxide (NOx) emissions rose by approximately 6% and 12% for D50B50 and B100, attributed to biodiesel's inherent oxygen content and increased combustion temperatures. Higher biodiesel concentrations also correlated with elevated exhaust and peak flame temperatures. The study underscores the viability of waste cooking oil biodiesel blends in enhancing combustion efficiency and curbing detrimental emissions, even with a marginal increase in NOx output.

Keywords: Industrial burner, diesel, biodiesel, emissions, temperature**.**

1. Introduction

Utilizing Waste Cooking Oil (WCO) biodiesel and its blends directly supports several United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). WCO biodiesel offers a renewable, low-emission alternative to fossil fuels, reducing greenhouse gas emissions and improving air quality. It also promotes resource efficiency by recycling waste oil that would otherwise contribute to environmental pollution. Blending WCO biodiesel with diesel enhances fuel sustainability without compromising engine performance, making it a practical and eco-friendly solution for cleaner combustion and reduced dependence on conventional fuels[1-10].

The growing concern for sustainable energy solutions has motivated important study into alternative fuels, with biodiesel emerging as a viable substitute for conventional diesel [11-17]. Derived from renewable sources such as vegetable oils, animal fats, and waste cooking oils, biodiesel offers an environmentally friendly alternative that reduces dependence on fossil fuels [18-25]. The transesterification process is commonly employed to convert these feedstock's into biodiesel, which can be used either as a pure fuel (B100) or blended with petroleum diesel in various proportions [26-32].

It is clear that recently the energy crisis has exacerbated, which necessitates the search for solutions, as the global stocks of traditional fuels have fallen, and the price has risen in addition to the bad environmental impacts. It is necessary to search for alternatives to fossil fuels [33-39]. Biofuels is one of the mainly prominent types

of choice fuels for change common fuels because it is a renewable energy source and sustainable. it is distinguished by its characteristics that make it in the list of alternative and future fuels, especially in the industrial sector [40-45].
Biodiesel's properties closely resemble those of petroleum diesel, allowing its application in diesel engines and industrial burners with minimal modifications. Notably, biodiesel has a upper cetane amount, contains no sulfur or aromatic compounds, and possesses an oxygen content of approximately 10-11% by weight, which enhances combustion efficiency and reduces emissions. Numerous studies have demonstrated that biodiesel blends significantly lower CO, UHC, and PM emissions. However, nitrogen oxides (NOx) emissions tend to increase due to the higher combustion temperatures associated with biodiesel's oxygenated composition.

Using WCO as source for biodiesel manufacture presents an economically and environmentally beneficial approach, as feedstock costs account for 70-95% of biodiesel production expenses. Prioritizing waste oils over edible oils mitigates food security concerns while reducing environmental pollution. In industrial burner applications, biodiesel has demonstrated promising performance characteristics, contributing to improved combustion efficiency and reduced emissions. Studies have shown that while CO, CO2, and PM emissions decrease with biodiesel usage, NOx emissions exhibit an upward trend due to increased flame temperatures [46-50].
Biodiesel is derived from renewable sources, including edible and non-edible vegetable oils, animal fats, and waste cooking oils, through the transesterification process [51]. It can be either used in diesel engines and industrial liquid burners in its pure form or blended with conventional diesel fuel. Due to its properties being similar to petroleum-based fuels, it can be utilized without requiring major modifications to engines or burners [52] Compared to petroleum diesel, biodiesel produces lower emissions, has a higher cetane number, lacks aromatic compounds, is sulphur-free, and contains approximately 10-11% oxygen by weight [53].

Experimental research has explored the combustion characteristics and emissions of biodiesel-diesel blends in industrial burners. Investigations reveal that as biodiesel content increases, CO and SO2 emissions decline significantly, while NOx levels rise due to enhanced oxidation reactions. Additionally, studies using jatropha oil biodiesel blends in swirl burners indicate reductions in CO2, CO, and HC emissions, albeit with an increase in NOx emissions. The presence of biodiesel in the fuel mixture alters combustion dynamics by promoting complete combustion and elevating flame temperatures.
Utilizing waste cooking oil as a feedstock helps lower biodiesel production costs, which constitute approximately 70-95% of the total expenses. Consequently, waste cooking oil and non-edible oils should be prioritized over edible oils for biodiesel production [54]. Additionally, repurposing waste oil for biodiesel contributes to reducing environmental impact [55]. Several studies have examined the combustion characteristics of biodiesel and diesel in industrial burner systems. The results indicate that while emissions of carbon dioxide, carbon monoxide, and particulate matter are reduced, nitrogen oxide emissions tend to increase. Furthermore, the exhaust gas temperature rises significantly, demonstrating biodiesel's strong potential for industrial burner applications [56] .

Ahmad, et al. [57] considers the performance and emissions of a liquid fuel burner. Their findings established that growing the biodiesel content considerably reduced CO and SO2, excluding for NO_x, which showed an increase. Similarly, Norwazan, et al. [58] examined the combustion and emission characteristics of jatropha oil biodiesel blends in a swirl burner. Their results revealed a notable reduction in HC, CO2, and CO emissions, whereas NO_x emissions increased across all biodiesel blends due to the higher oxygen content in biodiesel fuel. Macor and Pavanello [59] analyzed the performance and emissions of a fire tube boiler operating on 100% biodiesel. Amirnordin et al [60] evaluated the combustion performance and emissions of an industrial burner fueled by diesel, biodiesel, and their blends. Their results indicated that biodiesel use led to lower CO, CO2, and particulate matter emissions while increasing NO_x emissions. Additionally, they observed a rise in exhaust gas temperature as the biodiesel percentage increased from B0 to B40. These studies examine the use of biofuels like biodiesel in industry. Experimental studies have examined the effects of biodiesel and a mixture of biodiesel and diesel on the performance and emissions of an industrial burner.
In this study, a 350-kW industrial burner integrated with a furnace was utilized to evaluate the combustion characteristics and emission profiles of pure biodiesel (B100) and a 50:50 biodiesel-diesel blend (D50B50). The experiments were conducted without any modifications to the burner system. Key parameters analyzed included CO, HC, NOx, and soot emissions, as well as exhaust and flame temperatures. Furthermore, flame structure and luminosity variations were examined to assess the impact of biodiesel content on combustion efficiency and thermal distribution.

2. Experimental Setup and Procedure

2.1 Experimental test setup.

The laboratory-scale furnace designed for studying combustion characteristics effectively integrates various components to analyze flame behaviour and emissions, as illustrated in Figures 1 and 2. Utilizing a swirl atomizer-type diesel oil burner with a maximum heat capacity of 350 kW, the setup allows for precise control of airflow and fuel supply, essential for optimizing combustion efficiency and emissions [61-66]. The incorporation of R-type thermocouples facilitates detailed temperature profiling within the flame and exhaust, while the Gasboard-5020 analyzer measures emissions of CO, CO2, HC, O2, and NO_x, providing critical data on pollutant levels [67-72].

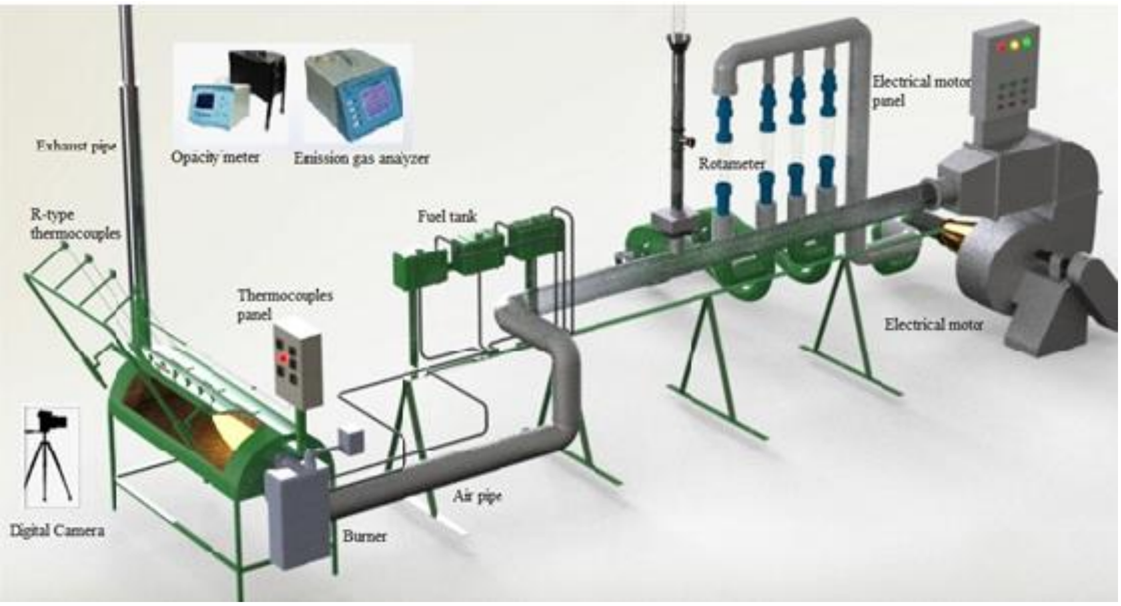

Figure 1. Schematic diagram of the test rig.

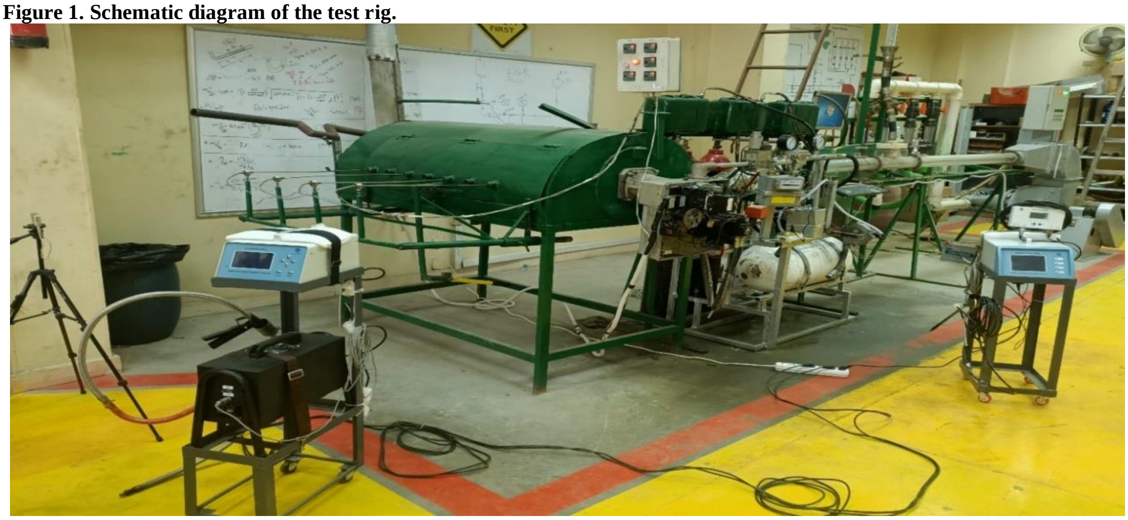

Figure 2. photo of experimental test rig set-up.

2.2. Properties of fuels.

In this experimental study, pure biodiesel (B100) derived from waste cooking oil and a biodiesel-diesel blend (D50B50) were equipped on a volume foundation[73-77]. The fuel data and characteristics of both diesel and biodiesel were analyzed at the National Research Centre (NRC-Dokki), Egypt [78-83]. These measurements were conducted following ASTM standards, as presented in Table 1.

Table 1. The belongings data of fuels used in experimental.

Experiment	**Diesel D100%**	**D50%B50%**	**Biodiesel B100%**	**Method**
Tot. sulf., wt %	0.231	0.129	Nil	ASTM D-4294
Density @ 15.56°C	0.8370	0.8604	0.9064	ASTM D-4052
Tot. aci. Numb. mg KOH/g	0.056	0.522	0.807	ASTM D-664
Kinem. Visc., cSt @ 40º C	*4.38*	*3.73*	*7.17*	ASTM D-445
Cetane index	50	44	46	ASTM 4737
Pou. Poi., °C	*0*	*0*	*3*	ASTM D-97
Ash content, wt.%	---	0.060	Nil	ASTM D-482
Calo. Val. KJ / Kg	44657	43302	37523	ASTM D-240
Copp. Corros.	1a	1a	1a	ASTM D-130

2.3. Uncertainty analysis.

To ensure the reliability and accuracy of the experimental results, an uncertainty analysis was carried out due to the potential errors introduced by the instruments and sensors used in the study. This analysis was essential for validating the measured data and improving confidence in the experimental outcomes[84-87]. The focus was placed on the primary burner operating parameters, such as fuel and air flow rates, along with critical emissions including carbon monoxide (CO), unburned hydrocarbons (UH), smoke opacity, nitrogen oxides (NO_x), and exhaust temperature. Each parameter was carefully analyzed by considering the precision and limitations of the corresponding measurement instruments. Table 3 summarizes the range of experimental values and outlines the accuracy specifications of the devices utilized. This information helped quantify the uncertainty associated with each independent variable, ensuring that the potential sources of error were well-understood and appropriately addressed in the analysis [88-91].

To determine the uncertainty of the independent variables and quantify the errors associated with the measured parameters, the root-sum-squared (RSS) method was applied, as expressed in Equation (1) [92].

$$w_R = \left(\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right)^{\frac{1}{2}} \qquad (1)$$

The uncertainties of the independent variables associated with the experimental operating parameters measured as **X1, X2, ... Xn**.

Table 2. Measurement equipment's data Specification

Instrument	Parameter	Range	Percentage Uncertainty
Fuel meter type "VZO 8"	flow rate of liquid fuel	4:200 l/h	Error value ±1% Repeatability ±0.2%
Gas flow meter	Flow meter of gas	0.025:4 m3/h	±1%
Rotameter	Flow meter of air	18:180 m3/hr	±6%
R-type thermocouple	Temperature of flame	0 °C to +1600 °C	Error value ±1.50 °C Repeatability ±0.25%
Inclined manometer	Air Mass flow rate of air	0 °C to +1600 °C	±0.2%
Gasboard-5020 exhaust analyzer	CO	0-10%	Error value ±3% Repeatability ±0.06%
	HC	0-9999 ppm	Error value ±5% Repeatability ±12 ppm
	NOx	0-5000 ppm	Error value ±5%, Repeatability ±25 ppm
Opacity Meter	Soot emission	0-100%	Error value ±3%
Digital scale	Loading solid ratio	0.002-100 Kg	±1

3. Results and Discussions

Biodiesel and its blends with diesel fuel samples are prepared for laboratory tests as shown in table 3.

Table 3: Types of fuels tested in the experiments

NO	Types of fuels	Description
1	D50B50	50% diesel, 50% biodiesel
2	B100	100% Biodiesel
3	D100	100%Diesel

3. 1 Burner Emission at Equivalence Ratio

3.1.1 Carbone monoxide CO emission.

Figure 3 illustrates the variation of carbon monoxide (CO) emissions as a function of equivalence ratio for different fuel types. Across all tested fuels, a consistent trend emerges: CO emissions increase initially in the lean mixture region, then decrease as the mixture approaches stoichiometric conditions (equivalence ratio ≈ 1), and rise again in the fuel-rich region. This trend highlights the influence of air-fuel mixture on combustion completeness. Compared to conventional diesel, the D50B50 blend (50% biodiesel and 50% diesel) and pure biodiesel (B100) achieve CO emission reductions of approximately 15% and 28%, respectively. These reductions are primarily attributed to the higher oxygen content inherent in biodiesel, which promotes more complete oxidation of carbon species during combustion [10, 93, 94]. Consequently, the presence of additional oxygen supports the conversion of CO to CO_2, resulting in cleaner combustion and improved emissions performance, particularly in the case of higher biodiesel concentrations.

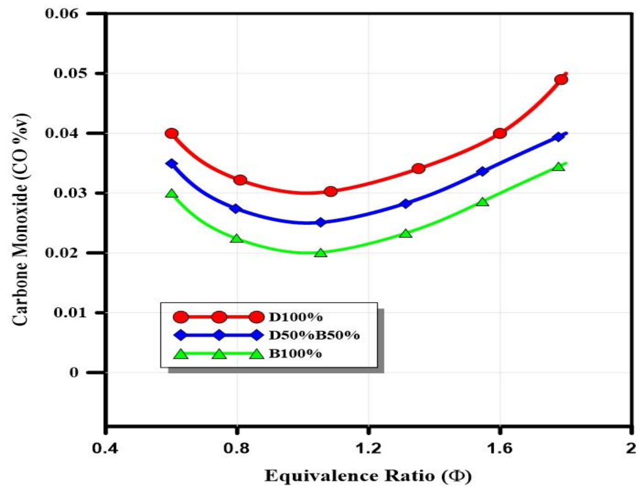

Figure 3. The relationship between CO emission variation and an equivalence ratio.

3.1.2 Unburned hydrocarbons

Figure 4 depicts the unburned hydrocarbon (HC) emissions across different equivalence ratios. Initially, HC emissions increase in the lean fuel region, then decrease, reaching their lowest point at an equivalence ratio of 1.0, before rising again in the rich fuel region. This trend is consistent across all fuel blends.

The results indicate that biodiesel and its blends with diesel produce lower HC emissions compared to pure diesel. Additionally, HC emissions decrease as the proportion of biodiesel in the fuel mixture increases. This reduction is attributed to the higher oxygen content in biodiesel, which enhances combustion efficiency. Compared to diesel, HC emissions decrease by approximately 19% for the D50B50 blend and 36% for B100.

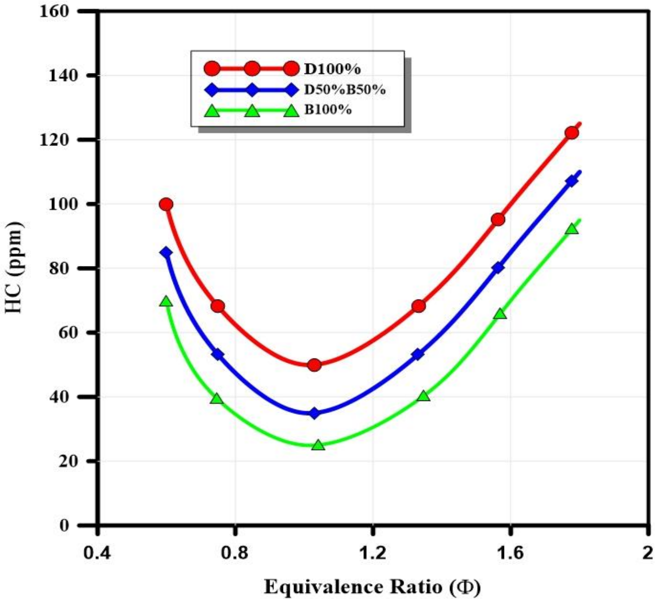

Figure 4. the relationship between HC emission variation and an equivalence ratio.

3.1.3 Nitrogen Oxide NOx

Biodiesel and its blends with diesel generate higher NO_x emissions compared to conventional diesel. This is primarily due to biodiesel's higher oxygen content, which increases flame temperature and accelerates thermal NO_x formation. Figures 5 and 6 highlight the significant impact of biodiesel content on NO_x formation during combustion [95]. As the proportion of biodiesel in the fuel mixture increases, NO_x emissions rise due to more complete combustion and higher flame temperatures. Compared to pure diesel (D100), NO_x emissions increase by approximately 6% for the D50B50 blend and 12% for B100.

Figure 5 illustrates the relationship between NO_x emissions and equivalence ratios for different fuels. The highest NO_x emissions occur at an equivalence ratio of 1 (Φ=1) for all fuel types, which is attributed to complete combustion and elevated flame temperatures. At lower equivalence ratios, NO_x emissions decrease due to reduced flame temperatures, which limit the formation of thermal NO_x.

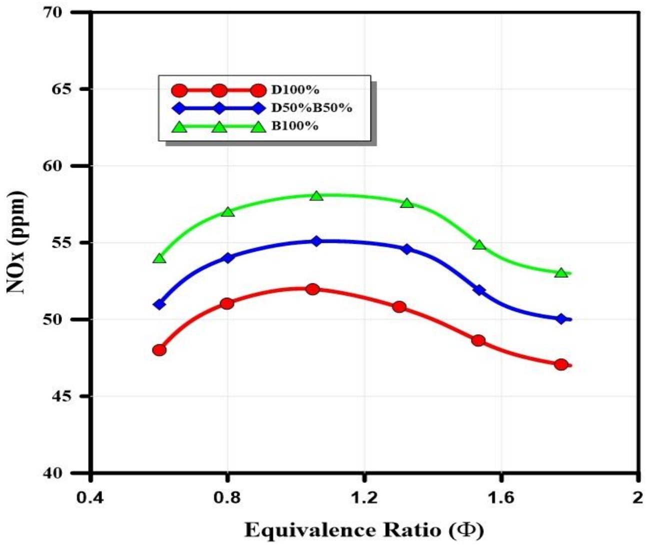

Figure 5. The relationship between NOx emission variation and equivalence ratio.

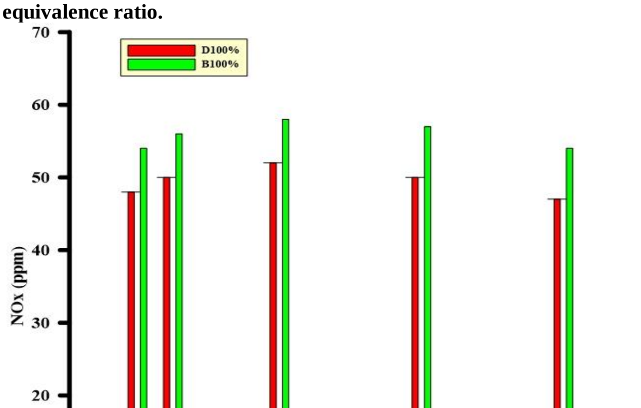

Figure 6. NOx emission of D100% and B100% according to variation of equivalence ratio.

3.1.4 Smoke opacity.

Soot is a carbonaceous nanoparticle generated during the combustion process and is considered a pollutant when released from the burning of hydrocarbon fuels. Figure 7 illustrates the relationship between soot emissions and equivalence ratios for different fuel types. The chemical composition of biodiesel inherently limits its soot formation, and this effect becomes more pronounced as the biodiesel content in a fuel blend increases, leading to reduced soot emissions [96]. For all fuel types, soot emissions are relatively high in the lean mixture region and continue to increase with the equivalence ratio, reaching a peak at an equivalence ratio of 1.0 (stoichiometric conditions). Beyond this point, soot emissions gradually decline in the rich fuel region due to the limited availability of oxygen, which restricts the formation of sulfur dioxide. As a result, sulfide emissions decrease in the fuel-rich mixture, improving combustion efficiency.

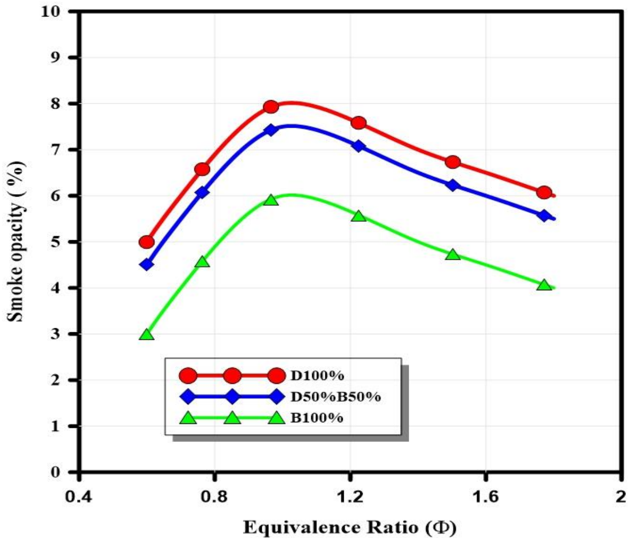

Figure 7. The relationship between the soot emission and equivalence ratio at different type fuels.

Figure 7 demonstrates that increasing the biodiesel content leads to a reduction in soot emissions. Compared to pure diesel, the diesel-biodiesel blend (D50B50) and pure biodiesel (B100) reduce soot emissions by approximately 9% and 30%, respectively. This reduction is attributed to biodiesel’s higher oxygen content, which enhances the air-fuel mixing process and maintains a smaller average fuel spray droplet size, ultimately leading to lower soot formation.

3.2. Effect of Equivalence Ratio on combustion performance.

3.2.1 The effect of different equivalence ratios on the exhaust gas temperature.

In lean combustion conditions, the fuel is in excess of air, leading to lower combustion temperatures. This is because the excess air acts as a heat sink, reducing the maximum temperature of the flame. However, lean combustion is often associated with lower NOx emissions due to the reduced thermal NOx formation at lower temperatures. Also, at stoichiometric conditions, the fuel and air are in the exact proportion required for complete combustion. This typically results in the highest combustion temperature and maximum heat release. However, it also leads to higher NOx emissions due to the high temperatures promoting thermal NOx formation. Rich combustion occurs when there is an excess of fuel relative to air. This leads to incomplete combustion, resulting in lower combustion temperatures and higher emissions of CO and unburned hydrocarbons. The incomplete combustion is due to the limited availability of oxygen, which reduces the overall heat release.

The R-type thermocouple measures the exhaust gas temperature at the furnace exit, positioned 140 cm from the burner nozzle. Figure 8 illustrates that for all fuel types, exhaust temperature increases with a higher equivalence ratio. This rise is attributed to the greater fuel-air mixture, which leads to an overall increase in combustion temperature. In general, as the equivalence ratio increases, more fuel is burned, resulting in higher exhaust temperatures.

However, the exhaust temperature exhibits a decreasing trend with an increasing biodiesel ratio in the fuel blend. This is due to biodiesel's higher oxygen content, which influences flame temperature dynamics. Compared to pure diesel, the combustion of diesel-biodiesel blends (D50B50) and pure biodiesel (B100) leads to an exhaust temperature increase of approximately 14% and 23%, respectively.

3.2.2 The effect of different equivalence ratios on the maximum flame temperature of the furnace.

Figure 9 illustrates the variation in maximum flame temperature for different fuel types, demonstrating a steady increase with rising equivalence ratio. The peak temperature was observed at an equivalence ratio of 1.6 for all tested fuels, attributed to the enhanced combustion process in fuel-rich conditions, where the increased fuel supply leads to greater heat release.

The influence of biodiesel on combustion characteristics is significant, as higher biodiesel content in the fuel mixture results in elevated flame temperatures. This phenomenon is primarily due to the molecular structure of biodiesel, which contains double bonds that facilitate oxidation reactions and enhance heat release. Additionally, biodiesel's higher oxygen content compared to conventional diesel improves combustion efficiency, leading to a more complete burning process and a higher overall temperature profile.

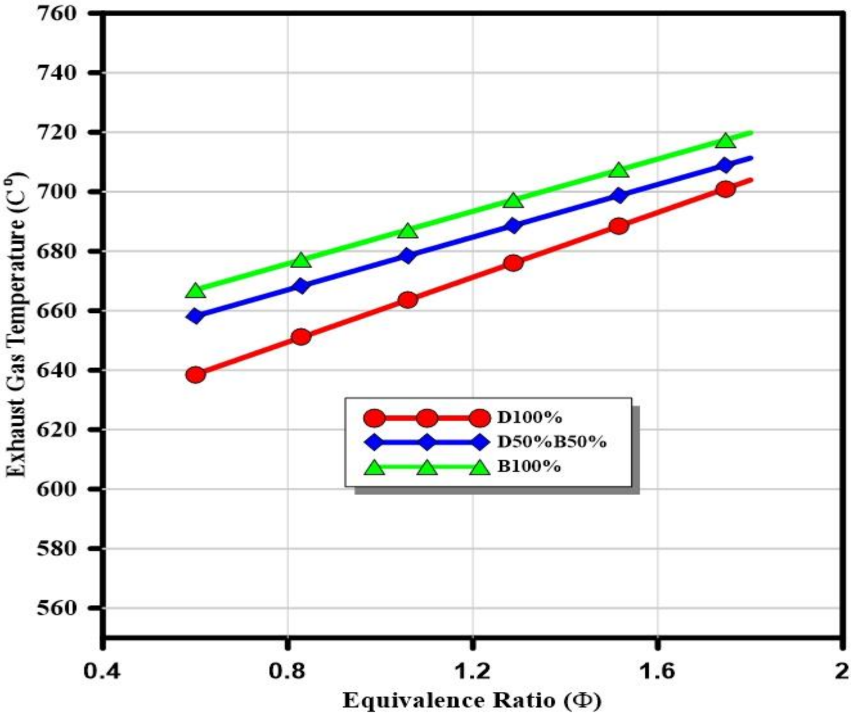

Figure 8. The relationship between change in exhaust gas temperature and equivalence ratio

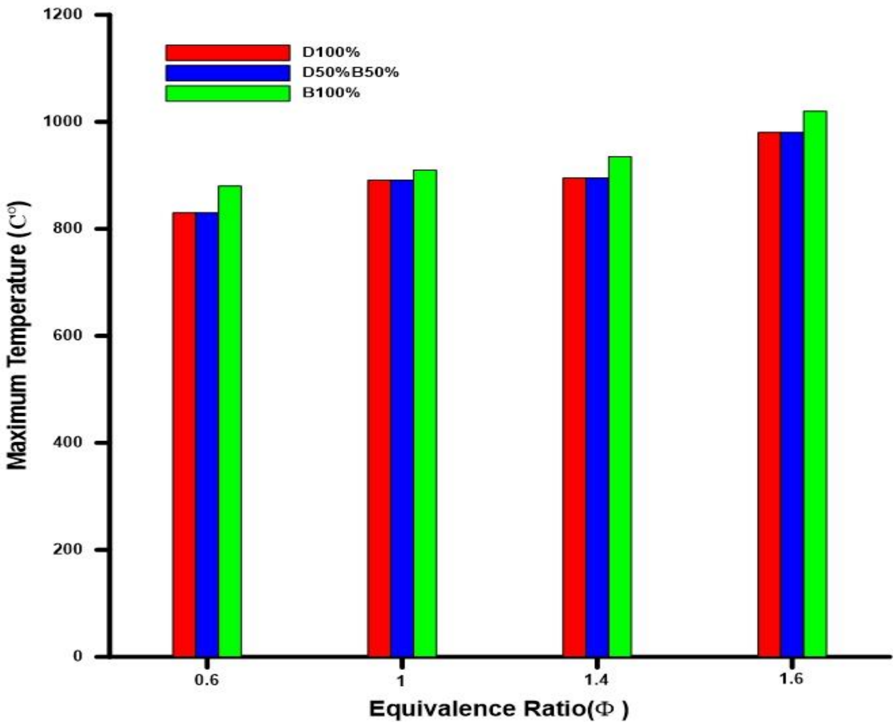

Figure 9. The relationship between change in maximum flame temperature and equivalence ratio

The results indicate that the maximum furnace temperature for the D50B50 blend and pure biodiesel (B100) is approximately 23% and 38% higher, respectively, than that of diesel. This increase is directly linked to biodiesel's intrinsic oxygen availability, which promotes higher flame temperatures and accelerates reaction kinetics. Furthermore, the improved air-fuel mixing due to biodiesel's lower viscosity contributes to better atomization, resulting in more efficient heat generation and combustion stability.

3.2.3. The effect of different equivalence ratios on the flame temperature in the centerline of the furnace.

Four thermocouples were strategically positioned along the laboratory furnace to monitor temperature variations along the centerline of the industrial burner during combustion experiments. Figures 10, 11, and 12 illustrate the flame temperature distribution for different fuel mixtures and equivalence ratios, showing a consistent decline in gas temperature as the distance from the burner increases. This decrease is attributed to convective and radiative heat losses along the furnace length.

The results indicate that the temperature rises from the first thermocouple (0 cm from the burner) and peaks between 30 and 40 cm, where complete combustion occurs, resulting in the highest flame temperature. Beyond 50 cm, the temperature decreases due to heat dissipation and incomplete post-flame reactions.

Figures 10, 11, and 12 compare the temperature trends for three equivalence ratios: 0.5, 1, and 1.6. The data show that the average flame temperature increases with equivalence ratio due to the higher fuel input, leading to greater heat release. Additionally, as the biodiesel content in the fuel mixture increases, both the peak temperature and overall temperature distribution along the furnace rise. This effect is primarily due to biodiesel's higher oxygen content, which enhances combustion efficiency and promotes more complete fuel oxidation, resulting in an overall increase in furnace temperature.

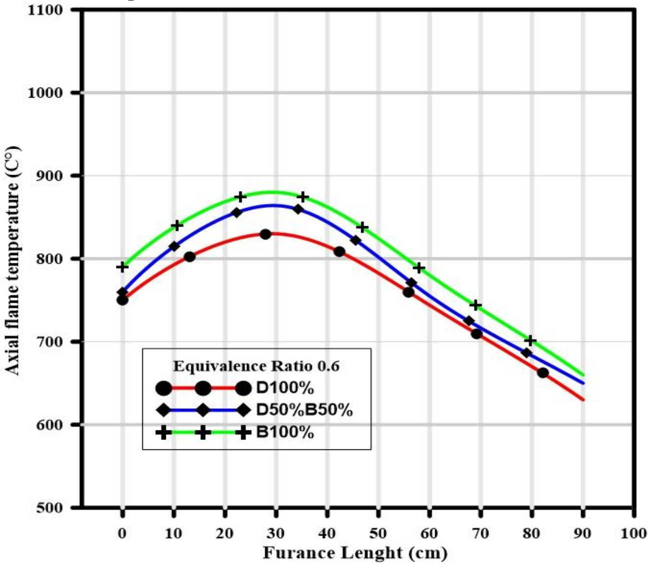

Figure 10. The flame temperature at the centerline of a furnace at an equivalence ratio equal to 0.5.

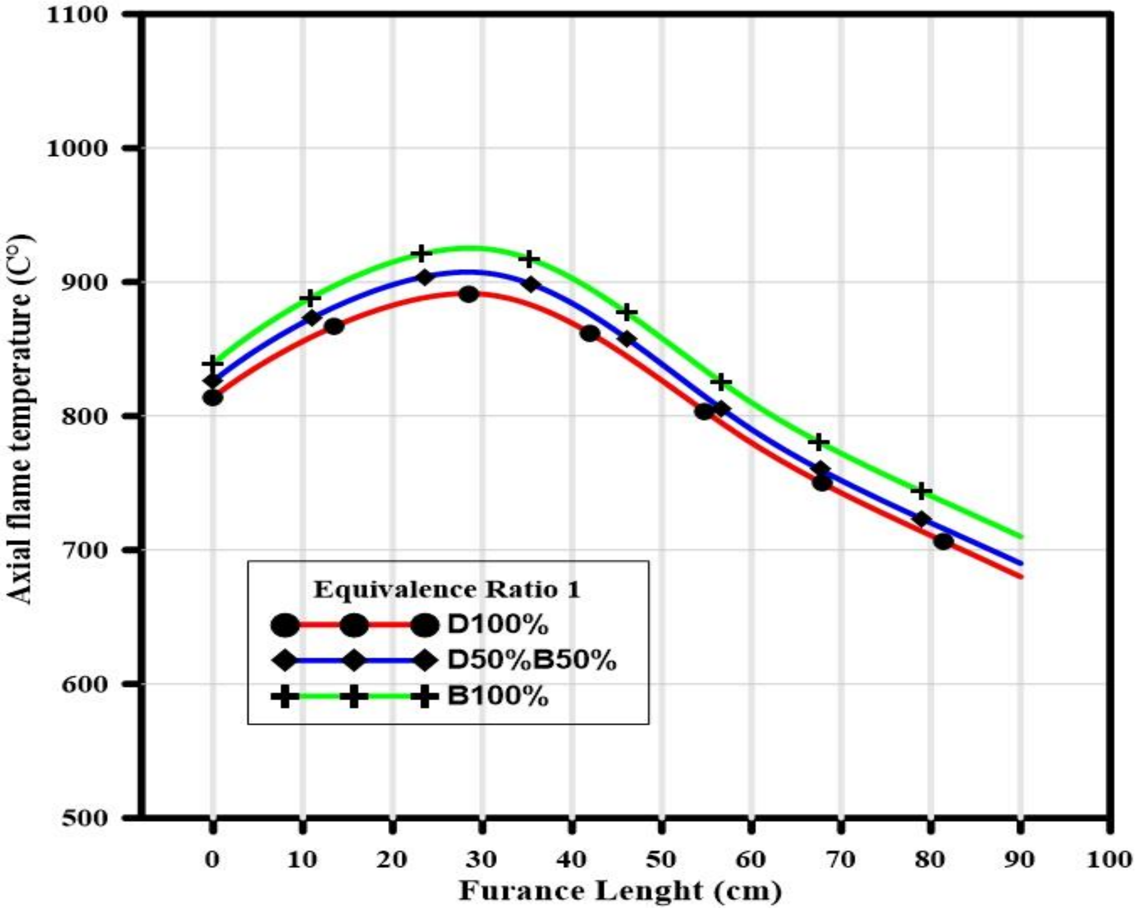

Figure 11. The flame temperature at the centerline of a furnace at an equivalence ratio equal to 0.1.

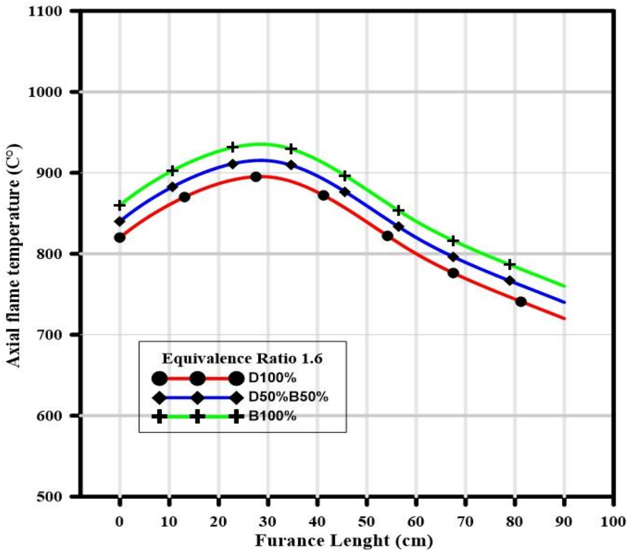

Figure 12. The flame temperature at the centerline of a furnace at an equivalence ratio equal to 1.6.

3.2.4 The effect of different equivalence ratios on the flame pictures.

Figure 13 presents colour photographs of the flame for different equivalence ratios (0.5, 1, and 1.6) and fuel types used in the experiment. These images, captured using a digital camera, highlight the impact of the equivalence ratio and biodiesel content on flame characteristics, including length, volume, and luminosity.

The results demonstrate that the equivalence ratio plays a crucial role in defining the flame structure. As the equivalence ratio increases, both the flame temperature and flame volume expand due to the availability of excess fuel, which promotes heat release. Additionally, increasing the biodiesel content in the fuel mixture significantly affects flame luminosity, indicating improved combustion efficiency. The D50B50 and B100 fuels exhibit a more pronounced reaction zone with higher flame temperatures compared to pure diesel (D100), primarily due to biodiesel's elevated oxygen content, which enhances oxidation reactions.

For all tested fuels, the peak reaction zone is observed at approximately 0.3 to 0.4 meters from the burner, where complete combustion occurs. Visually, the yellow flame luminosity intensifies with an increasing biodiesel ratio, indicating a higher combustion efficiency and a more complete oxidation process. The flame produced by B100 is particularly bright and transparent, suggesting reduced soot formation and enhanced oxidation. Furthermore, as the equivalence ratio increases, the flame brightness intensifies due to the higher fuel supply, reinforcing the role of biodiesel in improving combustion characteristics and flame stability.

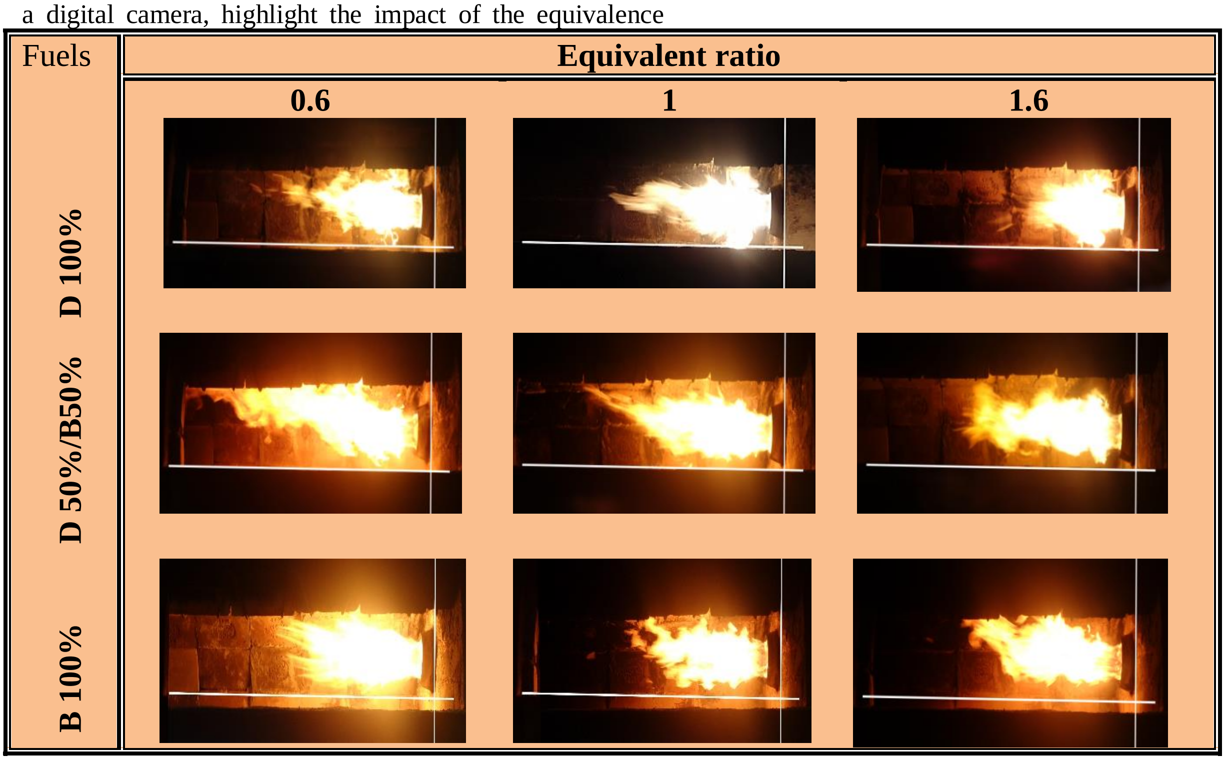

Figure 13. The images of flames of different fuels at various equivalence ratios.

The findings indicate that biodiesel and its blends with diesel significantly influence combustion performance. CO, HC, and soot emissions decreased with increasing biodiesel content, whereas NOx emissions increased due to elevated combustion temperatures. Maximum flame and exhaust temperatures also rose as the biodiesel ratio increased. Additionally, flame luminosity and visibility were enhanced, suggesting improved oxidation reactions facilitated by biodiesel's oxygen-rich composition. These results underscore the potential of biodiesel as a sustainable fuel for industrial burner applications, highlighting both its advantages and challenges in emission control.

4. Conclusion

This study investigated the combustion characteristics and pollutant emissions of a 350-kW industrial burner equipped with a furnace, operating with pure biodiesel (B100) derived from waste cooking oil and its blend with diesel (D50B50). The experimental results demonstrate that biodiesel and its blends enhance combustion performance and emissions characteristics without requiring modifications to the burner system. However, key findings from the experimental analysis include:

1. **Emission Reductions:** The use of B100 and D50B50 significantly reduced emissions of carbon monoxide (CO), unburned hydrocarbons (UH), and soot compared to conventional diesel (D100). This reduction is attributed to the higher oxygen content in biodiesel, which promotes more complete combustion and minimizes incomplete combustion byproducts.
2. **NOx Emissions Increase:** A rise in nitrogen oxide (NOx) emissions was observed with higher biodiesel content in the fuel mixture. This increase is due to the elevated oxygen concentration in biodiesel, which enhances flame temperature and accelerates thermal NOx formation.
3. **Temperature Characteristics:** The maximum flame temperature and exhaust gas temperature increased as the biodiesel ratio in the fuel blend rose. This effect is associated with biodiesel's oxygen-rich composition, which facilitates more efficient oxidation reactions and enhances heat release.
4. **Flame Structure and Luminosity:** The flame produced by biodiesel blends exhibited increased size and brightness compared to diesel flames. The higher luminosity and improved flame visibility indicate more complete combustion and enhanced oxidation processes, which can be linked to the oxygen content in biodiesel.

Overall, the findings confirm that biodiesel from waste cooking oil presents a viable alternative fuel for industrial burners, contributing to improved combustion performance and reduced pollutant emissions while maintaining operational efficiency. Further optimization of burner design and fuel-air mixing strategies could help mitigate NOx emissions while maximizing the environmental and performance benefits of biodiesel.

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