Journal of Advanced Engineering Trends
ISSN : 2682 - 2091

Vol. 44, No. 1, January 2025

Experimental Investigation of Biodiesel Spray Combustion Characteristics

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A R T I C L E I N F O

Article history:
Received: 23 August 2024
Accepted: 4 November 2024
Online: 1 January 2025

Keywords:
Biodiesel
Biofuel
Renewable energy sources
Fossil fuel

A B S T R A C T

Non-renewable fossil fuels have met global energy demands, but their dwindling supply raises environmental concerns, urging shifting to sustainable energy sources. Biodiesel with its renewable, biodegradable, and eco-friendly properties has gained attention as a promising alternative. The present study is an investigation of biodiesel combustion characteristics. An experimental test rig has been constructed, comprising an airline, fuel line, burner head, pressure swirl atomizer and combustor tube. The impact of different operating conditions as air/fuel mass ratio of 20, 30, 40 and 50, thermal load of 35, 45, 55 and 60 kW and diesel/biodiesel blend ratio of 0, 5, 10 and 15 are investigated. The temperature patterns, centerline axial temperature, dimensionless visible flame length, exhaust species concentrations and combustion efficiency are investigated. The obtained results indicated that at air to fuel ratio of 30 and thermal load of 45, with increasing biodiesel blend ratio from 0 to 15%, the flame length decreased by about 42 %, CO and NO decreased by about 15% and 24%, respectively while O_2 and CO_2 increased by about 22% and 14%, respectively. Combustion efficiency reduced as the biodiesel blend ratio increased. The small biodiesel blend ratios can replace diesel fuel without any modification in combustion systems.

1. Introduction

Combustion driven by the burning of fossil fuels remains the dominant energy source. Unfortunately, the demand for these fuels is rapidly rising in various applications such as home heating, power generation, boilers, transportation, and industrial furnaces. The increasing of energy needs all over the world have historically been met by nonrenewable fossil fuels, but their rapid depletion and environmental impact require a shift towards sustainable energy sources. Biodiesel, valued for its renewability, biodegradability, and environmental friendliness, stands out as a promising alternative to traditional fossil fuels [1-6]. Biodiesel is divided into four generations depending on the production source. Biodiesel generation firstly uses edible or safe to eat resources such as rapeseed oil, and soybean oil for production, secondly and thirdly generation biodiesel uses nonedible resources such as jatropha curcas, rubber seed, or neem oil. The animal fats in addition to the waste cooking oil are considered the main sources of third-biodiesel generation. Also, algae are used for fourth-generation biodiesel. Waste cooking oil represents almost 11% of the total biodiesel production sources, palm oil was highest source used by 35% [7-9].

Biodiesel produced from different sources and its properties were investigated by Nguyen et al. [9]. Biodiesel is considered a fuel with oxygen rich. The oxygen in biodiesel fuel is approximately 10% weight, the oxygen content in biodiesel leads to a leaner and more complete combustion and will help fuel to burn cleaner [10-11]. Biodiesel blending with blends ratios ranged from 7% to 20% is considered by many countries depending on the waste oils and the environmentally sustainable solution [12-17]. Due to the difficulty of biodiesel atomization, complex combustion mechanism, difficult control of combustion process stability and ensure efficient combustion has always been a difficult problem to solve. Heating is a common way for improving the properties of heavy oils, blending heavy fuels with lower-viscosity hydrocarbons such as diesel and kerosene decreases viscosity with the increasing in volume fraction of the hydrocarbons. Also, raising injection pressure generates finer spray of biodiesel to produce better combustion [18-20]. Modifications could be some additives to biodiesel which improve its combustion such as THERMOL-D [21], bioethanol [22] or CITAF [23]. All previously mentioned additives improved biodiesel combustion by a noticeable amount.

Ghazaly and Salah [24] and Malik et al. [25] investigated the chemical species concentrations of biodiesel fuel. It was found that biodiesel gave reasonable reduction in CO and SO_2 levels; however, it produced higher NOx, CO_2 and O_2 concentrations. Biodiesel exhibited greater ecological efficiency when compared to pure diesel fuel. Furthermore, the ecological efficiency improved as the blend ratio increased [26].

Researchers use combustion efficiency as a more rounded term to measure the combustion quality. Ghazaly et al. [24] compared combustion of biodiesel blends with conventional diesel to study the combustion efficiency for different air flow rates. It was noticed that all biodiesel blends had high combustion efficiency levels than mineral diesel at low energy level while the combustion efficiency decreased with increasing the air flow. Thermal efficiency of biodiesel blends in an industrial boiler was measured by Ghorbani [27]. It was found that with increasing oxygen content in fuel the combustion efficiency decreased. Results showed that the thermal efficiencies of B05 and B10 were comparable to diesel fuel. From B20 up to B100, there was a noticeable decrement between combustion efficiencies compared to diesel thermal efficiency.

Aziz et al. [28] investigated the combustion of biodiesel blends generated from the waste cooking oils and compared the results with diesel fuel. Results showed that B00 gave higher combustion temperatures at lean, stoichiometric and rich mixing conditions. The equivalence ratio contributed to the NOx reduction. Study also showed that the formation of NOx was mainly from high-temperature combustion process.

According to the previous literature review, there has been limited research conducted on combustion of biodiesel blends in a gas turbine combustor model that still do not give a good evaluation of using biodiesel and its blends potential on the combustion characteristics. Also, the biodiesel importance as a renewable fuel is clearly demonstrated. Therefore, the current study is concerned on an experimental investigation of biodiesel combustion characteristics. The biodiesel blends ratio, thermal load and air/fuel mass ratio are studied. The combustion characteristics are the flame temperatures distributions through the combustor, centerline axial temperature, dimensionless flame length, exhaust emissions, and combustion efficiency.

2. Experimental Test Rig

To study and investigate the different operating parameters such as air/fuel ratio (AFR), input thermal load (T.L.), and biodiesel/diesel blend ratio (B number, Bxx) on the combustion characteristics, a test rig is constructed for the previous aims as illustrated in Figure 1. The used rig consists mainly of combustion air line of an air fan i.e., blower, combustion air control valve, calibrated orifice meter thermometer and swirler with a swirl number (S) = 0.87. Secondly, fuel line which consists of fuel tank with level indicator and tank vent, fuel filter, fuel valve, fuel pump coupled to electric motor followed by a non-return valve, delivery fuel filter, pressure gage and the fuel line ended with the pressure swirl atomizer. Finally, the fuel and air are mixed and burned inside a cylindrical thermally insulated water-cooled combustor. The air duct is 100 mm in diameter and 3 m from the blower to the orifice and 2.1 m from the orifice to the burner head. The air mass flow rate is calibrated through the air orifice of 50 mm diameter using the rotating vanes anemometer for air velocity. The fuel flow rate is calibrated using the fuel pressure gauge. The cooling water mass flow rate entering the combustor is kept constant using the water rotameter. The cylindrical water-cooled combustor is 200 mm inner diameter and 1000 mm length. To determine the flame length as well as the temperature measurements, the combustor is provided with nineteen ports located along the combustor. To illustrate and present the temperature patterns, axial and radial temperatures are measured using a water-cooled type-R thermocouple. Dimensionless visible flame length is determined. The infrared A02000 gas analyzer is used to measure the exhaust emissions concentrations. Cooling water inlet and outlet temperature as well as combustor surface temperature are measured using digital thermometer. The ranges and accuracies for the instruments used are presented in Table 1.

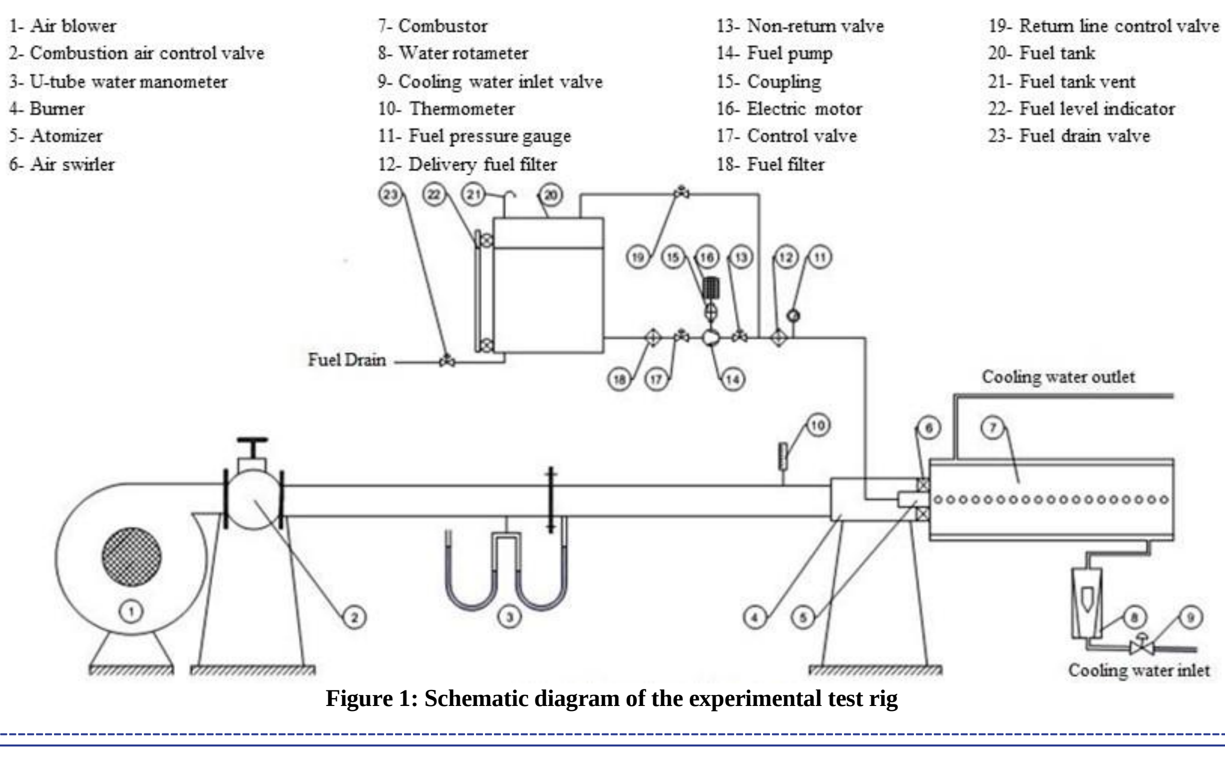

Figure 1: Schematic diagram of the experimental test rig

Table 1: Ranges and accuracies for the used instruments

Device		Range	Accuracy	Standard uncertainty
Type R thermocouple		-50 to 1760°C	±0.5%	0.6°C or 0.1%
Gas analyzer	CO_2	0 -100 vol. %	1 %	-
	CO	0 - 5 vol. %	1 %	-
	NO	0 - 5000 ppm	1 %	-
	O_2	0 – 21 vol. %	0.5 %	-
Thermometer		-40 to 100°C	±0.1%	0.2°C or 0.1%
Rotating vanes anemometer		0-40 m/s	±0.6 m/s	0.2 m/s or 0.5%

3. Experimental Results and Discussion

The experimental results include studying the AFR (20, 30, 40 and 50), T.L. (35, 45, 55 and 60 kW), biodiesel/diesel blend ratio (B00, B05, B10 and B15) on combustion characteristics; temperature patterns, centerline axial temperature distribution, flame length, species concentrations, and combustion efficiency. Table 2 indicates the summary of the changed parameters in the experimental results.

Table 2: Summarization of the used parameters

B number	Air/fuel ratio	Input thermal load, kW	Air swirl number
B00	20, 30, 40 and 50	45	0.87
B00 and B05	30	35, 45, 55 and 60	
B00, B05, B10, and B15	30	45	

3.1. Temperatures patterns

It is important to measure the gas temperatures through the flame in both radial and axial directions along the combustor tube to obtain complete feature about temperatures patterns. Temperatures maps are used to illustrate the temperatures distributions of the flame during the experiment and show the location of the maximum and minimum temperatures. The flame temperature is measured using type R thermocouple through the measuring ports along the combustor. Temperatures maps could be presented for different conditions. The temperatures map is illustrated by different seven regions; there is a different color used to describe each region which has certain temperatures range.

(i) Impact of AFR

Figure 2 shows the effects AFR on the temperatures maps for diesel fuel at thermal load of 45 kW. It is clearly obtained that, for a small AFR of 20, the temperature level is relatively high because of the existence of the reversed hot products a slight decrease in temperature be visible at flame upstream. By increasing AFR the volume of this zone clearly decreases. When AFR increases from 20 to 50, the flame decreases in length while increases in diameter, and the region of the high temperature shifts upstream nearest to burner exit. For AFR of 40 and 50, the high temperatures regions within range of 1300 to 1700 K disappeared from the temperatures map because of the increase in the combustion air mass flow rate, also the temperatures levels in the combustor tube decreased.

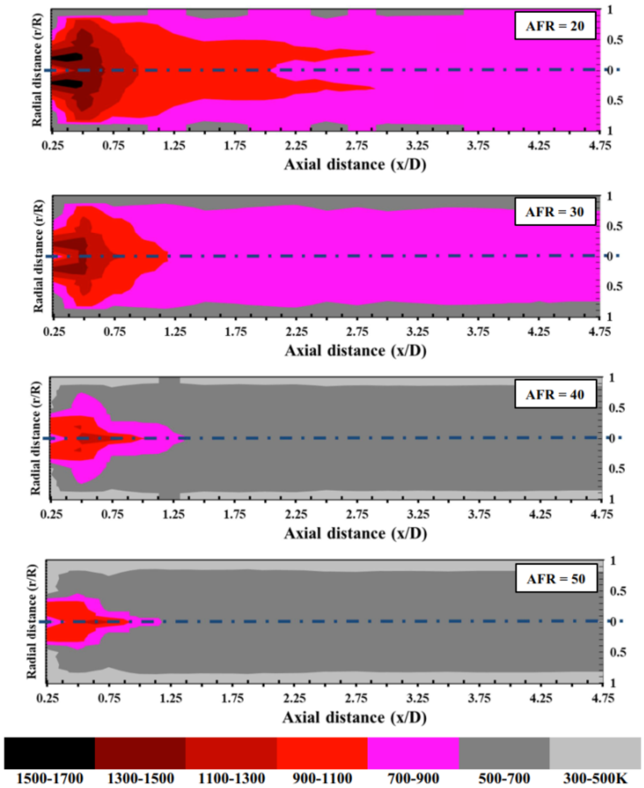

Figure 2: Effect of AFR on temperatures map for diesel [S = 0.87 and T.L. = 45 kW]

(ii) Impact of thermal load

Figure 3 shows the impact of changing the thermal load on flame temperatures for diesel fuel at S of 0.87 and AFR of 30. When the thermal load increases, the size of high temperatures region and the length of the flame increased. The decrease in the temperatures at downstream region is mainly due to the heat absorbed by cooling water through the combustor wall from the combustion products to.

It is clearly obtained that only one main reaction zone is formed around the flame axis because where the fuel and oxidizer flow are most concentrated which allows combustion reaction. This zone increases in size by increasing the input thermal load as with increasing T.L. i.e., the amount of fuel mass flow rate increased, leads to large amount of combustible mixture around the flame axis, thus expanding the size of reaction zone size. Upstream there is a low temperature zone which appears around the centerline because of existence of fuel vapor with high intensity with increasing T.L. the amount of residue fuel vapor increases, thus volume of low temperature zone increases. Also, heat is reduced because of water cooling jacket which helps to absorb excess heat to stabilize combustor temperature and prevent over heating of the combustor.

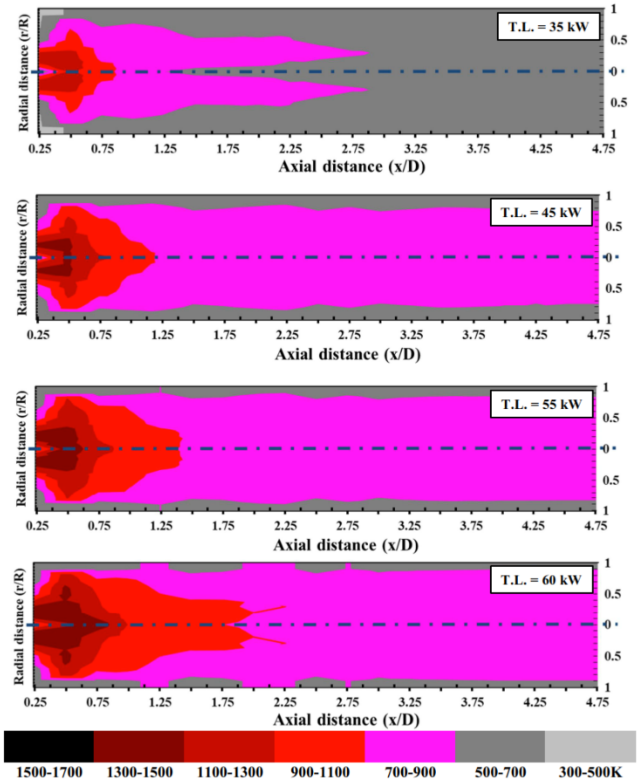

Figure 3: Effect of thermal load on temperatures map for diesel [S = 0.87 and AFR = 30]

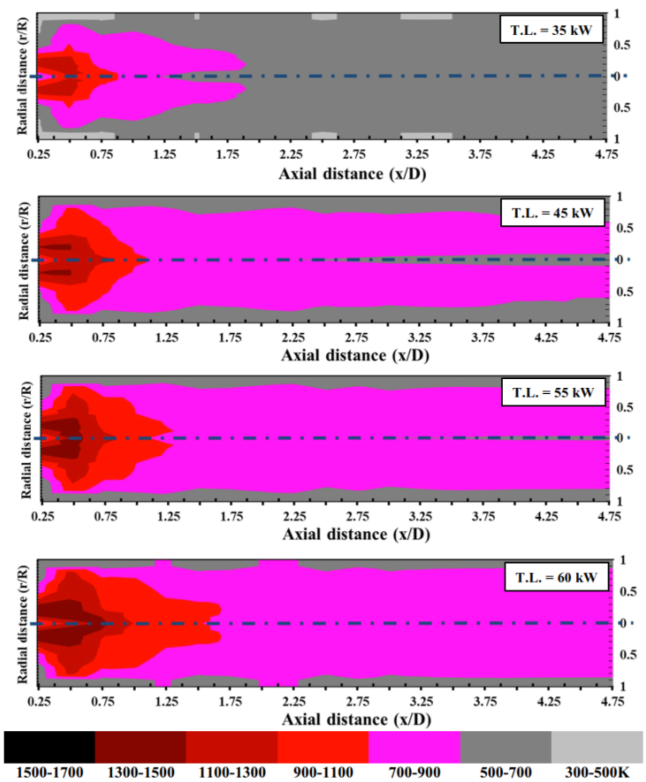

Figure 4: Effect of thermal load on temperatures maps for B05 [S = 0.87 and AFR = 30]

Figure 4 shows the effect T.L. on temperatures distributions for biodiesel fuel blend ratio of B05 at AFR = 30 and S = 0.87. Only one main reaction zone is formed around the flame centerline, this zone increases in size by increasing the thermal load. As previously discussed, there is a low temperature zone in upstream around the centerline because of high intensity of fuel vapor. The volume of this zone and flame length increases by increasing T.L., as with increasing T.L. leads to a large amount of combustible mixture around the flame axis, thus expanding the size of reaction zone size. Comparing Figures 3 and 4, for the same T.L., biodiesel give overall lower combustion temperatures, smaller high temperature region size and shorter flame lengths than diesel due to the high viscosity of biodiesel so it has less chance for complete combustion to produce higher temperatures.

(iii) Impact of biodiesel/diesel blend ratio

Figure 5 shows the effect of biodiesel/diesel fuel blend ratio on the temperatures distributions for biodiesel blends of B00, B05, B10 and B15 at AFR = 30 and T.L. = 45 kW. It is clearly observed that only one main reaction zone is formed around the flame axis. This zone decreases in size by increasing the biodiesel ratio. Increasing the biodiesel ratio, the flame length decreased, due to high viscosity and density of biodiesel. It is noticed that the high temperature region completely vanished at blend ratio of 10 and 15, indicating lower temperature and lower combustion performance. Reduced combustion performance due to fuel properties difference between diesel and biodiesel such as higher viscosity of biodiesel which affects the atomization and mixing of fuel with air.

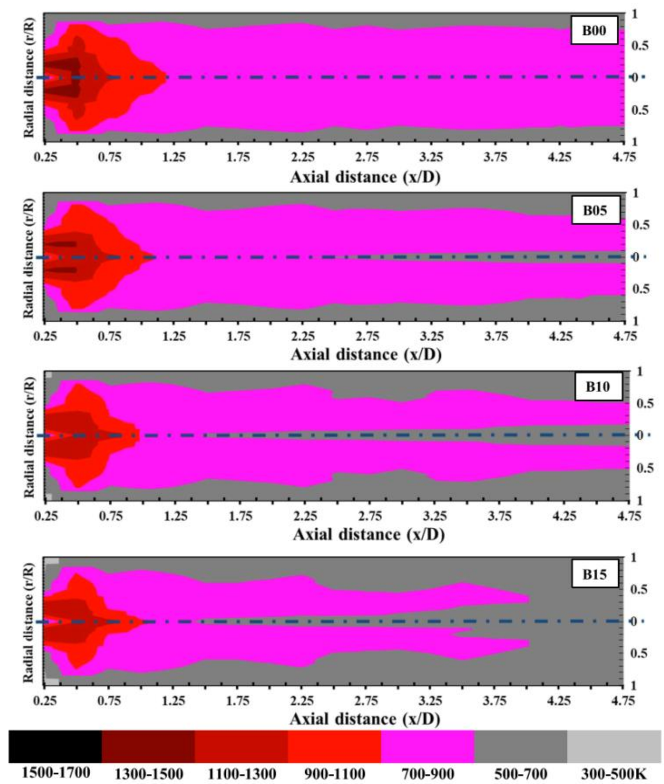

Figure 5: Effect of biodiesel/diesel blend ratio on temperatures map [S = 0.87, AFR = 30 and T.L. = 45 kW]

3.2. Centerline temperature distribution

Measuring axial temperatures along the combustor gives an indication of combustion efficiency, emissions concentrations, and overall system reliability. It shows optimal AFR for efficient combustion, which means higher overall temperatures and larger high temperature zone, detects combustion abnormalities early. For previous reasons the axial temperature distributions along the combustor tube centerline are investigated.

(i) Effect of AFR

Figure 6 presents the centerline axial temperatures for different AFR for diesel fuel at S = 0.87 and T.L. = 45 kW. It is shown that the maximum centerline temperature is observed at AFR = 20. It is also noticed that for AFR = 30 maximum temperatures obtained is approximately 7% less than that obtained at AFR = 20, while for AFR = 40 maximum temperatures dropped by about 15% than that obtained at AFR = 20. The AFR = 20 is closing nearest to the theoretical value of AFR for diesel which is 14.9 and for biodiesel which is 13.5. With increasing AFR from 20 to 50, maximum centerline axial temperature dropped by about 20% for T.L. of 45 kW. The results indicate that when AFR exceeds 30, the peak combustion temperature shifts downward along the combustor centerline toward the combustor exit. This shift can be explained by the air velocity surpassing the atomization, mixing or combustion reaction speeds. Consequently, the peak moves downward because complete combustion occurs further along the burner.

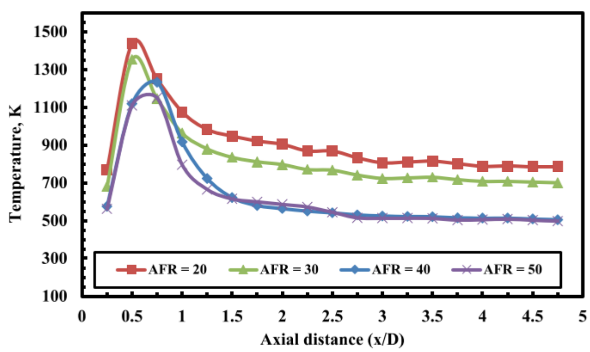

Figure 6: Centerline axial temperatures for different AFR for diesel fuel [S = 0.87 and T.L. = 45 kW]

(ii) Effect of thermal load

Figure 7 indicates the centerline axial temperatures distribution for different thermal loads for diesel fuel. It is observed that increasing thermal load increases the maximum temperature obtained, because of increasing T.L., the fuel supply increases which leads to higher energy input leading to higher heat release. It is noticed that maximum temperature is obtained at T.L. = 60 kW. With increasing T.L. from 35 to 60 kW the highest temperature obtained increased by about 23%. The same trend is obtained from Figure 8 which illustrates the centerline axial temperature for B05 fuel with different thermal loads. It is shown that increasing thermal load will increase the maximum temperature obtained. It is noticed that maximum temperature is obtained at T.L. = 60 kW. With increasing T.L. from 35 to 60 kW the highest temperature obtained increased by about 22%. It is noticed from Figures 7 and 8 that biodiesel has lower centerline axial temperatures than diesel fuel. Increasing thermal load to 60 kW leads to shifting the value of peak temperature downstream because of fuel velocity increase. The location of peak temperature shifts downstream, so the flame becomes longer.

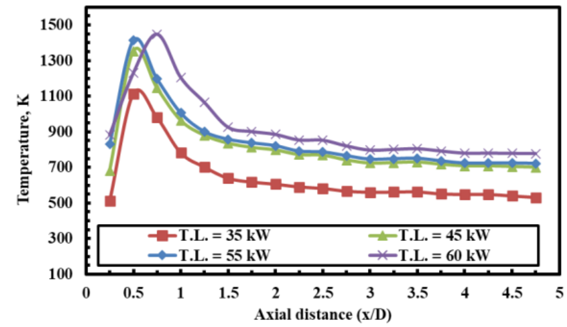

Figure 7: Centerline axial temperatures for different thermal loads for diesel fuel [S = 0.87 and AFR = 30]

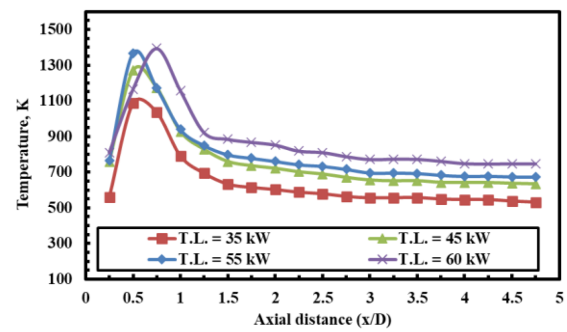

Figure 8: Centerline axial temperatures for different thermal loads of B05 [S=0.87 and AFR=30]

(iii) Effect of biodiesel/diesel blend ratio

Figure 9 shows the centerline axial temperature distribution for different biodiesel blend ratios. It is obtained that the maximum centerline temperature is achieved at diesel (B00). It is noticed that when using higher blend ratios of B15 maximum temperature started to drop by about 13%, compared to diesel. This happens because of fuel properties difference between diesel and biodiesel such as higher viscosity of biodiesel which affects the atomization and mixing of fuel with air. With increasing the B number, the axial temperature clearly decreased. From Figures 6-9, it is noticed that axial temperatures decrease in the downstream region. This decrease is due to heat absorbed by the combustor wall cooling water. The axial temperatures along the flame are affected by many factors, such as the fuel heat release rate, the flow direction, velocity and rate of combustion air and heat lost through radiation, convection or to cooling water. In downstream the flame, the axial centerline temperature is slightly constant which means that the combustion is ended i.e., the reaction is approximately completed and the slight decrease in the flame temperature is because of the heat transferred to the combustor wall and then to the cooling system.

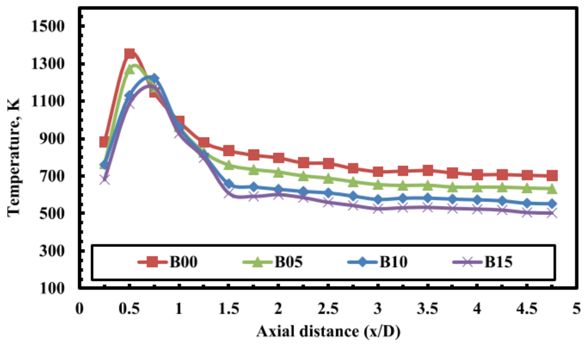

Figure 9: Centerline axial temperatures for different biodiesel/diesel blend ratios [S = 0.87, T.L. = 45 kW and AFR = 30]

3.3. Visible flame length

In the study of combustion systems, understanding flames is a primary objective. Many practical combustion applications require short and stabilized flames under different operating conditions. For example, in gas turbine combustion chambers, it is crucial to minimize heat transfer from the flame to the surrounding surfaces. Conversely, other combustion systems, such as boiler furnaces, aim to maximize heat transfer from the flame to the working medium this results in longer flames with high heat transfer. Flame length is defined as the length of the visible part of the flame, measured from the atomizer or the fuel nozzle to the flame visible endpoint. In the present study, this measurement is typically obtained through observation ports located along the combustor.

(i) Effect of AFR

Figure 10 shows the effect of AFR on visible dimensionless flame length for diesel fuel at different thermal loads; 45 and 55 kW. It is noticed that with increasing AFR the flame length clearly decreases. Higher AFR leads to a shorter flame length because the leaner mixture (more air relative to fuel) ensures more complete and faster combustion. This increases combustion efficiency and results in a higher flame speed and lower flame temperatures, which confines the flame to a shorter length. With increasing AFR from 20 to 50, flame length decreased by about 65% and 70% for T.L. of 45 kW and 55 kW, respectively.

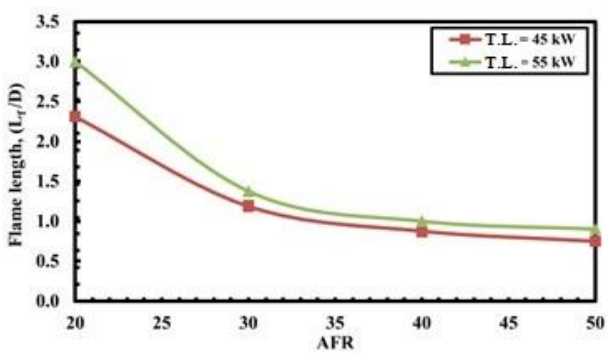

Figure 10: Effect of AFR on flame length for diesel fuel [S = 0.87]

(ii) Effect of thermal load

As observed from Figure 11, certain findings emerged as diesel and B05 subjected to an escalating thermal load while maintaining a constant AFR of 30. It is evident that the flame length for both fuels is experiencing an increase. Interestingly, the flame length exhibited a somewhat more pronounced increase when diesel is considered, in contrast to the use of B05. This observation underscores the influence of the biodiesel component in the blend on flame behavior under higher thermal loads. While both fuels have a growth in flame length, diesel displayed a marginally greater response, potentially indicating altered combustion characteristics when compared to B05. The flame length of diesel fuel increased by about 111% with increasing T.L. from 35 to 60 kW while for biodiesel, flame length increased by about 100% for the same conditions mentioned. Comparing diesel and B05, the flame length for diesel is higher than that for biodiesel by about 17 % at T.L. of 45 kW.

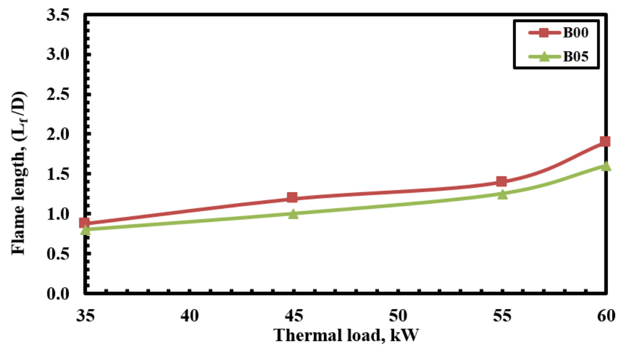

Figure 11: Effect of thermal load on flame length for B00 and B05 fuels [S = 0.87 and AFR = 30]

(iii) Effect of biodiesel/diesel blend ratio

Figure 12 presents the effect of biodiesel/diesel blend ratio on the dimensionless visible flame length. As observed from the results obtained, when maintaining AFR and T.L. constant, a noteworthy trend emerged as the biodiesel/diesel blend ratio increased, the flame length exhibited a gradual reduction. This indicates that as the blend ratio shifted in favor of biodiesel, the flame length experienced a diminishing effect. Flame length decreased by about 42% when the biodiesel/diesel blend ratio increases from B00 to B15. Because biodiesel differs from traditional diesel fuel in its physical properties such as viscosity, density and surface tension which clearly effects on the spray and combustion characteristics such as atomization quality, droplets mean diameter, volatility or evaporation rate, which influences the mixing rate and quality with the combustion air and consequently effects on the chemical reaction rate.

Biodiesel has lower volatility compared with diesel fuel. This lower volatility rate causes the biodiesel to vaporize more slowly leading to less effective mixing with oxidizer, which leads to a shorter combustion duration and a shorter flame length. Additionally, biodiesel can shift the combustion regime from primarily diffusion-controlled combustion to primarily premixed combustion due to lower volatility of biodiesel can change the air fuel mixing characteristics in combustion chamber. Slower evaporation of fuel results in a more homogeneous air fuel mixture before ignition, resembling a premixed combustion process. This homogeneity ensures that the fuel is evenly distributed throughout the air, leading to more efficient and complete combustion. Consequently, this reduces the length of the flame, as the fuel burns more uniformly and quickly. This shorter flame length not only improves combustion efficiency but also reduces emissions, as there is less unburned fuel.

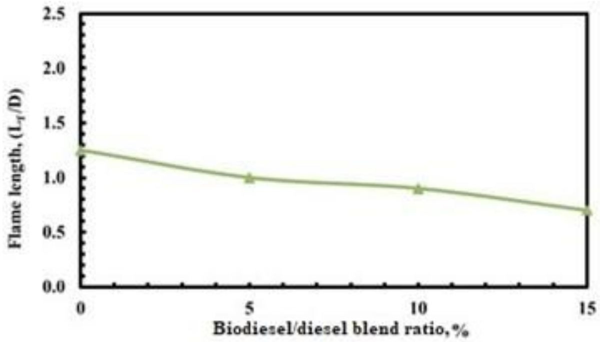

Figure 12: Effect of biodiesel blend ratio on flame length [S = 0.87, T.L. = 45 kW and AFR = 30]

3.4. Emission concentrations

Measuring exhaust concentrations in combustion processes is critically important for several reasons, firstly, it helps assess the efficiency of the combustion process by identifying unburned fuel levels, thereby improving system performance and reducing fuel consumption, secondly, it is essential for environmental protection, as it enables the monitoring and reduction of harmful emissions such as carbon dioxide and nitrogen oxides, helping to mitigate air pollution, lastly, it plays a vital role in complying with local and international environmental standards and regulations, which mandate strict control of emission levels to ensure public health and safety. In the present study the species concentration is measured at the combustor tube end.

(i) Effect of AFR

The impact of AFR on exhaust emissions for diesel fuel at S = 0.87 and T.L. = 45 kW is shown in Figure 13. It is clearly obtained that, with increasing the AFR, O_2 and CO_2concentrations increase, while NO and CO concentrations decrease. O_2 concentrations increase because more excess air is available for combustion; there is an oversupply of oxygen beyond what is needed for complete combustion, resulting in more oxygen at the combustor exit. The concentration of NO is matched with the combustion temperatures, and as previously discussed; higher AFR resulted in lower combustion temperatures, leading to lower NO concentrations. The concentrations of CO and CO_2 are interrelated. With excess air, more oxygen is available, converting more CO into CO_2. Consequently, CO concentrations decrease while CO_2 concentrations increase. By increasing AFR from 20 to 50 at constant T.L. of 45 kW and swirl number of 0.87, O_2 and CO_2 increased by about 22% and 31%, respectively, while NO and CO concentrations decreased by about 37% and 21%, respectively.

(ii) Effect of thermal load

Figure 14 shows the impact of the input thermal load on the exhaust emissions for diesel fuel at S = 0.87 and AFR = 30. It is observed that, increasing of thermal load the flame temperature increased, which consequently leads to increasing in the NO concentration. When T.L. increases from 35 to 60 kW, NO, CO, and CO_2 increased by 42%, 41%, and 38%, respectively while O_2decreased by 29%. It can be noticed that the NO concentrations are raised sharply to reach their peak at maximum tested thermal load of 60 kW. The peak concentration values of NO are close to the high temperature.

The same behavior is obtained for the biodiesel/diesel blend ratio of B05 as illustrated in Figure 15. It is obtained that as T.L. from 35 to 60 kW, NO, CO, and CO_2 increased by 53%, 53% and 52%, respectively while O_2 decreased by 23%.As comparing the results in Figures 14 and 15, differences between concentration of different species are obtained when using B05 instead of diesel fuel, when T.L. values are changed from 35 to 60 kW. The difference of the exhaust species concentration is due to the difference in physical properties between diesel and B05 fuels which influence the characteristics of fuel spray and combustion.

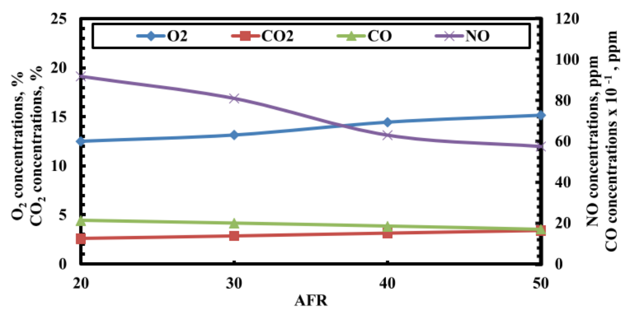

Figure 13: Effect of AFR on exhaust emission for diesel fuel [S=0.87 and T.L. = 45 kW]

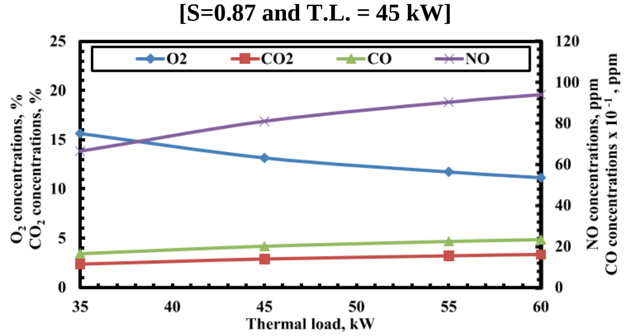

Figure 14: Effect of thermal load on exhaust emissions for diesel fuel [S=0.87 and AFR = 30]

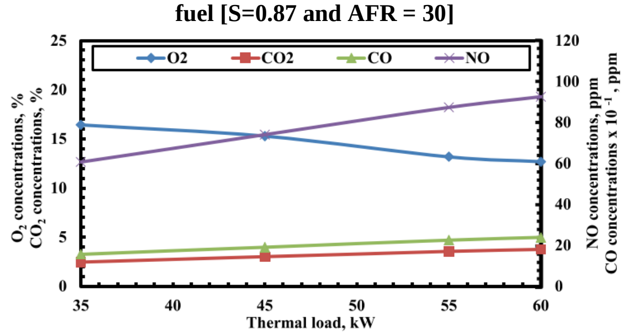

Figure 15: Effect of thermal load on exhaust emissions for B05 [S = 0.87 and AFR = 30]

(iii) Effect of biodiesel/diesel blend ratio

It is observed that biodiesel produces lower NO emissions due to the lower combustion temperatures associated with biodiesel use. Additionally, biodiesel contains about 10% oxygen by mass, which contributes to the higher oxygen content in the emissions. Biodiesel also results in lower CO emissions because it uses a lean mixture, which reduces CO formation. However, as the proportion of biodiesel increases, the oxygen content in the fuel increases as well, leading to the conversion of some carbon monoxide into CO_2. As shown in Figure 16, the increase in biodiesel proportion results in higher CO_2 emissions. According to the previous studies, this increase in CO_2 is not harmful to the environment because biodiesel is derived from plants that absorb CO_2 from the atmosphere during their growth or from waste products such as waste cooking oil. The biodiesel is considered a carbon dioxide neutral in the environment.

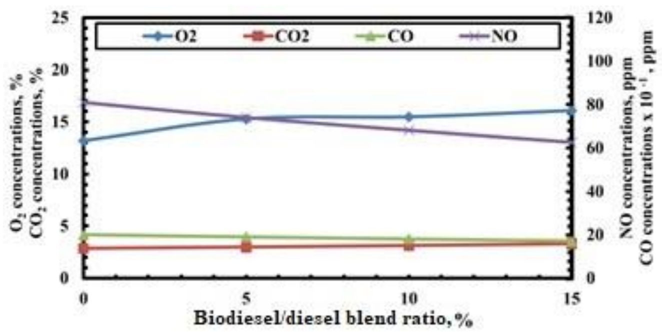

Figure 16: Effect of biodiesel/diesel blend ratio on exhaust emissions [S = 0.87, T.L. = 45 kW and AFR = 30]

The impact of biodiesel/diesel blend ratio on NO concentration and Exhaust Gas Temperature (EGT) is illustrated in Figure 17. It is clearly observed that EGT, and NO emissions are matched with each other. By increasing biodiesel/diesel blend ratio EGT decreased and consequently the NO concentration decreased to reach its minimum value at B15.

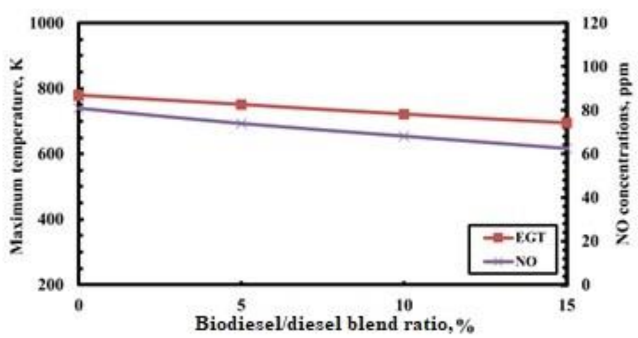

Figure 17: Effect of biodiesel blend ratio on maximum temperature and NO concentration at combustor tube end [S=0.87, T.L. = 45 kW and AFR = 30]

3.5. Combustion efficiency

Combustion efficiency gives a clear indication of combustion performance as all measured results and parameters are included in calculations, such as inflame temperatures patterns and heat lost from combustion, whether it is lost as high temperature exhaust gases, transferred to cooling water, or transferred to the ambient air through convection or radiation. To calculate combustion efficiency certain parameters are measured, such as, cooling water mass flow rate, cooling water inlet and exit temperatures, exhaust gas temperature and combustor external surface temperature. Combustion efficiency ($\eta_{comb.}$) is defined as the ratio between the summation of all the calculated heat to the exhaust, cooling water, radiation and convection to the heat input. Heat input is calculated by multiplication of the fuel mass by the calorific value of the fuel.

$$\eta_{comb.} = \frac{\dot{Q}_{exhaust} + \dot{Q}_{cw} + \dot{Q}_{radiation} + \dot{Q}_{convection}}{Heat\ input} \times 100$$

(i) Effect of AFR

Figure 18 illustrates the impact of AFR on the combustion efficiency for diesel fuel at T.L. of 45 kW. It is shown that with increasing AFR from 20 to 30 combustion efficiency increased by about 4%, due to more complete combustion with optimized air availability. With increasing AFR from 20 to 50, combustion efficiency decreased by about 12%, as excess air absorbs heat and lowers combustion temperatures.

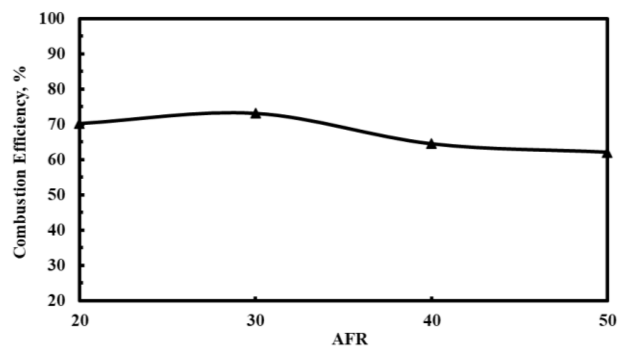

Figure 18: Effect of AFR on combustion efficiency for diesel fuel [S = 0.87 and T.L. = 45 kW]

(ii) Effect of thermal load

Figure 19 presents the impact of T.L. on the combustion efficiency for diesel and B05 fuels at AFR and S of 30 and 0.87, respectively. It is observed that with increasing the T.L. from 35 to 60 kW, combustion efficiency increased by about 28% for diesel while by about 29% for B05. Increasing the T.L. higher combustion efficiencies are obtained, regardless of the fuel type used whether it is diesel or B05. It is noticed that diesel has higher combustion efficiency than that for B05 for all input thermal loads. When comparing efficiency difference between diesel fuel and B05, it is found that combustion efficiency of diesel fuel is higher than that for B05 by about 6%, at input thermal load of 45 kW and AFR of 30. The higher combustion efficiency for diesel fuel than that for biodiesel/diesel blend ratio of B05 is due to lower density and viscosity of diesel fuel which give good atomization of diesel fuel compared with B05 and lower mean droplets size, faster evaporation, good mixing with the combustion air to improve the combustion of diesel fuel compared with B05. The difference in the combustion efficiencies for diesel and B05 is slightly the same through the different thermal loads as indicated in Figure 19.

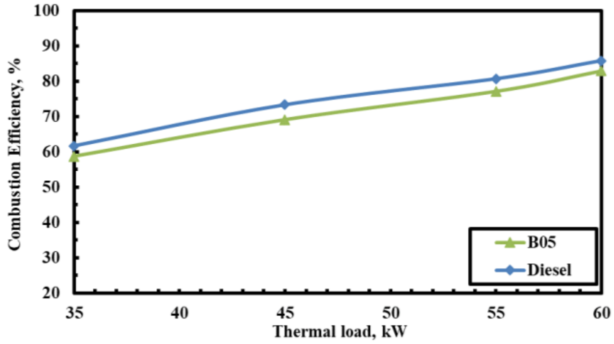

Figure 19: Effect of thermal load on combustion efficiency for diesel and B05 [S = 0.87 and AFR = 30]

(iii) Effect of biodiesel/diesel blend ratio

The effect of biodiesel/diesel blend ratio on the combustion efficiency at AFR = 30, S = 0.87, and T.L. = 45 kW is shown in Figure 20. It is obtained that with increasing biodiesel blend ratio the combustion efficiency clearly decreased especially at biodiesel/diesel blend ratio greater than B05. The reduction in the combustion efficiency with increasing the biodiesel/diesel blend ratio is due to differences in fuel physical properties between diesel and biodiesel such as viscosity and density as previously mentioned. This affects the atomization and mixing with air which leads to less combustion performance and efficiency. When the biodiesel/diesel blend ratio increased from B00 to B15 the combustion efficiency decreased by about 27%.

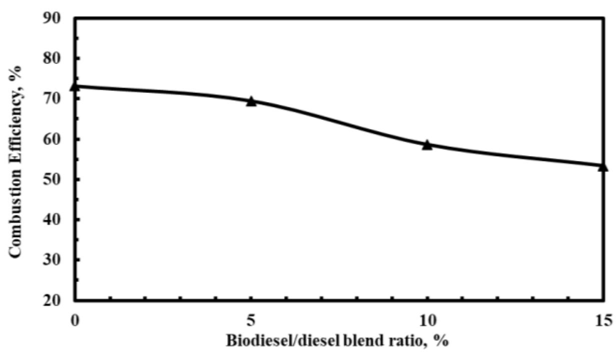

Figure 20: Effect of biodiesel/diesel blend ratio on combustion efficiency [AFR = 30, S = 0.87, and T.L. = 45 kW]

By comparing the present obtained results with the previous works, it is shown that the present work is agreed with the trends of previous works such as obtained by Malik et al. [25] which measured the NO, and CO, Tashtoush et al. [29] which illustrated the NO, CO, and combustion efficiency, and Shaiful et al. [30] which measured the NO. The used biodiesel blends in the present work give slightly increase in NO compared with the previous works while it gives decreases the NO concentration by increasing the biodiesel/diesel blends ratio. The present study gives better combustion efficiency compared with the previous work. Table 3 illustrates a comparison between the preset study and the previous works.

Table 3: A comparison between the preset study and the previous works

Reference	Bxx	Atomizer	AFR	NO,	CO,	η_{comb}, %
Present study	0	Pressure swirl	30	81.0	13.2	73.0
	5			74.1	15.3	69.3
	10			68.2	15.5	58.9
	15			62.6	16.1	53.3
Malik et al. [25]	0:25		20	38.5	41	NA
			14	61	21	NA
			20	37	36	NA
			14	58	3	NA
			20	35	10	NA
			14	51	2	NA
			20	34	4	NA
			14	50	1	NA
Tashtoush et al. [29]	0:100		20	23.5	9	51.5
			10	0	7.5	37.5
			20	0	19	53.5
			10	0	17.5	31.5
Shaiful et al. [30]	0:15		20	65	NA	NA
			14	78	NA	NA
			20	48	NA	NA
			14	61	NA	NA
			20	43	NA	NA
			14	58	NA	NA
			20	37	NA	NA
			14	42	NA	NA

4. Conclusions

In the present study, the effects of air to fuel mass ratio, thermal load and the biodiesel/diesel blend ratio on the combustion characteristics were experimentally investigated. The following conclusions were obtained:

- Increasing AFR at constant T.L. decreases flame temperatures and length, while increasing T.L. at constant AFR increases the flame temperatures and flame length.
- Biodiesel blends have lower temperatures, shorter flame lengths, and reduced high-temperature regions compared to diesel fuel, especially at higher AFRs.
- Increasing biodiesel blend ratio decreases CO and NO levels while increases O_2 and CO_2 levels.
- Combustion efficiency decreases with increasing biodiesel blend ratio while it has a higher value for diesel fuel compared with biodiesel blends.
- Thermal load has a significant impact on emissions, with increasing the T.L. NO, CO, and CO_2 concentrations increased while O_2 concentrations decreased for both diesel and biodiesel blends.
- Biodiesel is considered a good renewable fuel especially a lower blend than B10 to give high combustion efficiency.
- For the future work, it is recommended to preheat the biodiesel using the waste heat in the exhaust gases to enhance the spray performance, test the biodiesel blends in the compression ignition engine, and used the exhaust gas recirculation for NO reduction.

Conflict of Interest

The authors declare no conflict of interest.

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Abbreviation and symbols

AFR	**Air/Fuel Mass Ratio**
Bxx	**Percentage of biodiesel fuel to diesel fuel by volume**
D	**Combustor diameter, 200 mm**
EGT	**Exhaust Gas Temperature, K**
L	**Combustor length, 100 cm**
L_f	**Visible flame length, cm**
L_f/D	**Dimensionless flame length**
$\dot{Q}_{convection}$	**Heat carried out by convection, kW**
$\dot{Q}_{cw}$	**Heat carried out by the cooling water, kW**
$\dot{Q}_{exhaust}$	**Heat carried out by the exhaust, kW**
$\dot{Q}_{radiation}$	**Heat carried out by radiation, kW**
R	**Combustor radius, 10 cm**
r	**Radial distance, cm**
r/R	**Dimensionless radial distance**
S	**Swirl number**
T.L.	**Input thermal load**
x	**Axial distance, cm**
x/D	**Dimensionless axial distance**
$\eta_{comb.}$	**Combustion efficiency, %**