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Original Article

Combustion Characteristics of Biodiesel-Aluminium Oxide Nanoparticle-Powered Marine Diesel Engines

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***Abstract** - Globally, marine diesel engines are the primary source of propulsion for the shipping sector. The maritime industry's growing operations have made a substantial contribution to air pollution emissions. As a result, international environmental standards are becoming increasingly stringent. This study examined the combustion characteristics of B20 palm biodiesel blends that were supplemented with aluminium oxide (Al_2O_3) nanoparticles at 50, 100, and 150 parts per million (namely B20AL50, B20AL100, and B20AL150, respectively). A 14-liter, four-stroke, six-cylinder Cummins NT855 marine diesel engine was used for the experiments. To assess performance in common marine operation scenarios, the tests were carried out with the engine running at a constant speed of 1400 rpm under three distinct engine loading conditions: low, medium, and high loads. Engine parameters such as Cylinder pressure, heat release rate, mass fraction burned, and ignition delay characteristics were measured as part of a combustion analysis using a fibre optic pressure transducer system. Adding Al_2O_3 nanoparticles at all concentrations significantly improved combustion, as indicated by the data. When compared to the B20 baseline fuel, B20AL150 fuel produced a 15.1% rise in cylinder pressure, a 53.9% increase in heat release rate, and a 53.3% decrease in ignition latency under heavy load conditions. Under low load conditions, however, B20AL150 demonstrated a 33.3% decrease in ignition delay and a 5.4% increase in pressure. With increasing nanoparticle concentration, performance benefits become more pronounced, and at high load circumstances, the nanoparticles demonstrated optimal effectiveness in comparison to low load. Al_2O_3 nanoparticle-enhanced palm biodiesel has a great deal of promise to increase marine diesel engines' combustion efficiency. This provides a viable approach to reducing emissions and enhancing fuel efficiency in line with maritime decarbonization objectives.*

***Keywords** - Cylinder Pressure, Heat Release Rate, Biodiesel Combustion, Aluminium Oxide Nanoparticles, Marine Diesel Engines, and Sustainable Marine Fuel.*

1. Introduction

The maritime transport industry forms the foundation of international trade, as over 90 percent of international trade is transported by a fleet of ships that travel across borders [1]. Due to the growing maritime traffic, air pollution has been a major problem, especially around the coastal zone and ports along major shipping lanes. Globally, marine diesel engines produce about twenty million tonnes of nitrogen oxide, ten million tonnes of sulphur oxide, and significant quantities of particulate matter annually [2]. These emissions are highly toxic and may be very dangerous health-wise, like respiratory disease, cardiovascular disease, and other forms of cancer, and lead to global climate change. The growing concerns about environmental pollution have triggered more stringent rules at both the international and national level.

Under the IMO 2020 Regulation, the global shipping industry reduced the maximum amount of sulphur in marine fuel oils to 0.50% (mass by mass), indicating a prevailing movement and effort towards cleaner maritime fuel. The IMO also aims for the global shipping industry to achieve a net-zero emissions goal by approximately 2050. This is an immediate necessity that has led to an increase in researchers working on the development of sustainable marine fuels. Among the options being formulated is the adoption of biofuel in marine diesel engines to form a sustainable source of energy that replaces traditional marine fuels.

Numerous studies have demonstrated that the use of biodiesel in marine engines leads to a significant reduction in harmful exhaust gases. The carbon monoxide and carbon dioxide emissions are reported to be reduced by between 66 and 82 percent based on the engine operating condition [3]. Biodiesel fuel has become a technically feasible and environmentally beneficial substitute for traditional marine diesel fuel. The transesterification process allows the production of biodiesel using several renewable feedstocks, such as oils of plants and animal fats left over. It also possesses physicochemical characteristics that are highly comparable to those of petroleum diesel, enabling it to integrate seamlessly into our current diesel engine systems [4, 5].

Unlike the diesel engines on land, marine diesel engines typically have larger bore and stroke dimensions, operate at lower rotational rates, and have different fuel quality requirements that affect their combustion properties. Essentially, the complexity of the marine engine emissions comes about as a result of the distinct operational parameters of the maritime vessels, which are usually subject to different load conditions over long durations in the marine environment.

2. Literature Review

Previous researchers have indicated that the use of biodiesel results in a visible reduction in the level of particulate matter, hydrocarbons, and carbon monoxide emissions by diesel engines. This reduction can reach up to 50 percent in some combinations of fuel [6, 7]. Biodiesel has an inherent oxygen content (10-11%), which helps raise the efficiency of combustion and minimize incomplete combustion products. Biodiesel is also characterized by better cetane numbers than conventional diesel fuels, with biodiesel sources from vegetable oil registering between 52 and 54 cetane numbers [8, 10]. Blends of B20 have also been shown to provide considerable environmental advantages and be suitable with respect to operating characteristics in the marine industry.

According to recent studies, the use of biodiesel blends with nanoparticles has been widely adopted in automotive diesel engines and may lead to improved performance and reduced emissions [10]. Results indicate that alumina nanoparticles enhance combustion by improving fuel atomization, resulting in a 14% increase in brake thermal efficiency [11]. On the other hand, another finding reported that TiO_2 nanoparticles are able to reduce the concentration of particulate matter by 33 percent [12].

According to a study by Prabhahar et al. (2023), when tamarind oil methyl ester (TME25) is combined with TiO_2 nanoparticles, engine performance is also enhanced by enhancing the cylinder pressure and Rate of Heat Release (HRR) at full load because of enhanced oxidation and in-cylinder temperature. The 100 ppm TiO_2 concentration resulted in a 2.7 percent increase in Brake Thermal Efficiency (BTE) and a 7 percent decrease in Brake Specific Fuel Consumption (BSFC), indicating improved combustion efficiency. Additionally, the authors have found that Hydrocarbon (HC), Carbon Monoxide (CO), and smoke-opacity reductions of 27, 47, and 40 percent, respectively, were notable, but the emissions of NOx increased a little due to the catalytic properties and thermal conductivity of TiO_2. The incorporation of CeO2 nanoparticles in biodiesel has been established to improve engine performance by increasing cylinder pressure and enhancing heat release properties. The B15C20 blend exhibits significant reductions in the emissions of Carbon Monoxide (CO) and Hydrocarbons (HC), but a slight increase in Nitrogen Oxides (NOx) emissions, compared to conventional diesel (B0) [13]. Nonetheless, there is scant data on the characteristics of nanoparticle-enhanced biodiesel fuels in marine diesel engines. The peculiarities of marine engines, including large engine displacement, fluctuating loading rates, and extended service cycles, necessitate more specific research under the conditions of marine operation.

Limited research in the area of marine diesel engine applications is a strategic knowledge gap. Consequently, this paper explores the properties of combustion and performance of B20 palm biodiesel combined with Al2O3 nanoparticles in marine diesel engines under different loads, aiming to promote the development of maritime fuel technology towards sustainability.

3. Materials and Methods

3.1. Fuel Preparation and Characterization

In this research, B20 palm methyl ester biodiesel was taken as the test fuel, and 50, 100, and 150 ppm of Aluminium Oxide (Al_2O_3) were added to the biodiesel as shown in Figure 1. The nanoparticles were purchased from Sigma Aldrich with a diameter range of 12 nm and a purity of 99.8%. The resulting mixture was called B20AL50, B20AL100, and B20AL150, respectively. The source of biodiesel was acquired through a certified local distributor through a transesterification process that was applied to the standard of ASTM and EN 14214 requirements. The 2M diesel was mixed (volume-wise) with the biodiesel to have a B20 composition. As a base fuel for comparative analysis, neat B20 fuel was used.

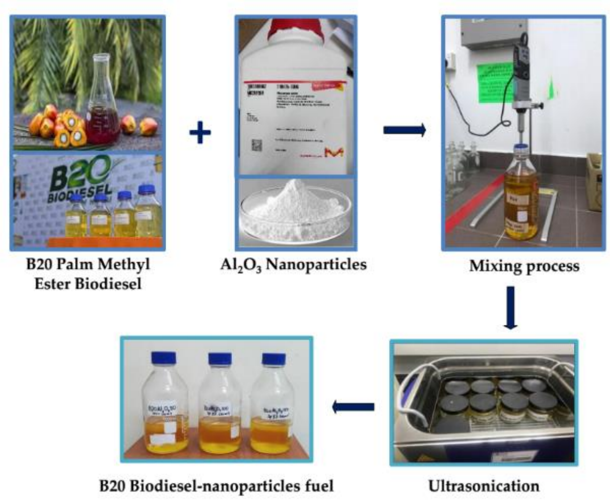

Fig. 1 Fuel preparation process

Two steps of mixing were carried out to ensure that the dispersion of the nanoparticles was successful. Firstly, the dispersal of Al_2O_3 nanoparticles was done with the help of 2% by weight of Span 80 surfactant, then 30 minutes of mechanical stirring at 800 rpm was used. Ultrasonic treatment of the solution to bring homogeneous distribution proposed at 40 kHz is then done, in 60 minutes to prevent agglomeration as suggested by the earlier research [14-16]. Table 1 gives the complete fuel characteristics of each of the blends in terms of kinematic viscosity, density, calorific value, and cetane number, which were ascertained under the ASTM standard procedures.

Table 1. Fuel properties of Al_2O_3 nanoparticle blends B20 biodiesel

Fuel properties	B20 (Baselines)	B20 AL50	B20 AL100	B20 AL150
Density (kg/m^3)	816	818	818	818
Kinematic viscosity (mm^2/s)	3.47	3.62	3.62	3.62
Calorific value (MJ/kg)	44.75	44.96	45.04	45.12
Cetane Number	65	71	71	71

3.2. Engine Testing Setup and Procedures

The experiment was done with a Cummins NT855, four-stroke marine diesel six-cylinder, six-cylinder, 14 litters, in-line engine. The entire experimental setup and engine technical specifications are indicated in Figure 2.

The test engine was carefully warmed up to ensure that the cooling temperature reached 80 to 85 degrees Celsius and the engine lube oil temperature was maintained between 90 and 100 degrees Celsius. Each test was preceded by a 30-minute pre-run period to make sure that the engine and coolant reached a steady thermal condition.

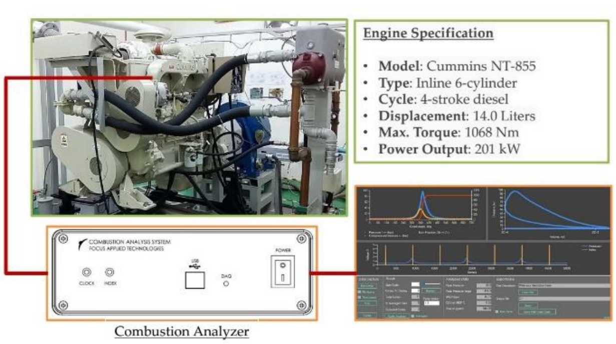

Fig. 2 Engine experimental setup

Engine testing was conducted at a constant speed of 1400 rpm, which represents typical ship cruising conditions for this engine. Engine loads were selected under three different scenarios, namely low load, medium load, and high load. The evaluation covered operating conditions at these different loads to provide a comprehensive assessment of the effects of nanoparticles across different combustion environments. The low load condition simulated the minimum power requirements during slow movements at the port area, while the high load condition represented the maximum power demands during open ocean cruising. This approach ensured a comprehensive characterization of engine performance across a full range of practical marine operating scenarios. Prior to each test run, the engine was operated for a minimum of 15 minutes at steady state to ensure complete stabilization of the fuel system. When switching between test fuel blends, a thorough cleaning protocol was conducted involving the complete draining of the fuel lines to remove fuel residue. Each experiment run was conducted three times to ensure consistency of the results.

Engine tests were done at a steady base operation of 1400 rpm in accordance with the normal ship cruising conditions at this engine. The engine loads under three conditions, that is, low load, medium load, and high load, were selected. The operating conditions were assessed under these various loads to give an overall evaluation of how nanoparticles affect operations under various conditions of combustion. The low-load condition was used to represent the minimum power demands of small movements in the port area, and the high-load condition was used to represent the maximum power demands of open-ocean cruising. Such a method guaranteed a thorough characterization of engine performance at a complete range of realistic marine operating conditions. Before every test run, the engine was run at least 15 minutes in a steady run to enable full stabilization of the fuel system. When changing the test fuel blends, a comprehensive cleaning procedure was carried out, whereby the fuel lines were emptied to clean the fuel residual. Three tests were performed in each test condition, which guaranteed the reliability of the statistics.

3.3. Data Acquisition and Analysis

Combustion analysis was performed using a CAS-5 combustion analyzer, equipped with a fiber optic pressure transducer to capture in-cylinder combustion pressure data continuously. The parameter of heat release was computed using the law of conservation of energy (refer to Equation 1). The mass fraction of fuel burned up to the given *i-th* crank angle was evaluated according to Equation (2) and Equation (3) [17]:

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma-1} p \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dp}{d\theta} \quad (1)$$

$$MFB = \frac{\sum_0^i \Delta p_c}{\sum_0^N \Delta p_c} \quad (2)$$

$$\Delta p_c = p_{i+1} - p_i \left[\frac{V_i}{V_{i+1}}\right]^{\gamma} \quad (3)$$

In this equation, Q_n represents the net heat release rate, θ denotes the crank angle degree, γ is the ratio of specific heats, p refers to the in-cylinder pressure, and V is the cylinder volume. The term Δpc corresponds to the pressure increase due to combustion, while N indicates the total number of crank angle intervals during the combustion phase.

Ignition delay was determined by calculating the difference between the crank angle corresponding to the start of fuel injection and the start of combustion. This period reflects the time required for fuel and intake air mixing and the initial chemical reactions leading to the combustion of fuel. All measurements were taken with a 1° crank angle resolution, and the data were then analysed using combustion analysis software to ensure accuracy.

4. Results and Discussion

4.1. Cylinder Pressure

The combustion pressure in an engine cylinder is influenced by multiple factors, including the physical properties of engine geometry and the chemical properties of the fuel used. The pressure trace is identified based on the instantaneous cylinder pressure and the corresponding crank angle position for each combustion cycle in the engine.

Figure 3 illustrates the cylinder pressure variation for B20 biodiesel and Al_2O_3 nanoparticle blends under low engine load conditions. At low load conditions, it is seen that all test fuels exhibit almost similar pressure and crank angle profiles where cylinder pressure increases after 350°CA and reaches a peak around 370°CA before decreasing during the expansion cycle. The baseline B20 fuel reaches a maximum cylinder pressure of 44.4 bar, representing typical biodiesel combustion behaviour under low load conditions due to the small fuel injection quantity and reduced temperature limiting the combustion intensity. The incorporation of Al_2O_3 nanoparticles shows a moderate pressure increase of around 5.4% compared to neat B20, where B20AL50 reaches 45.1 bar, B20AL100 reaches 45.5 bar, and B20AL150 reaches 46.8 bar. This moderate pressure increase reflects the incomplete combustion at low load, where the reduced fuel quantity limits the catalytic potential of the nanoparticles [18].

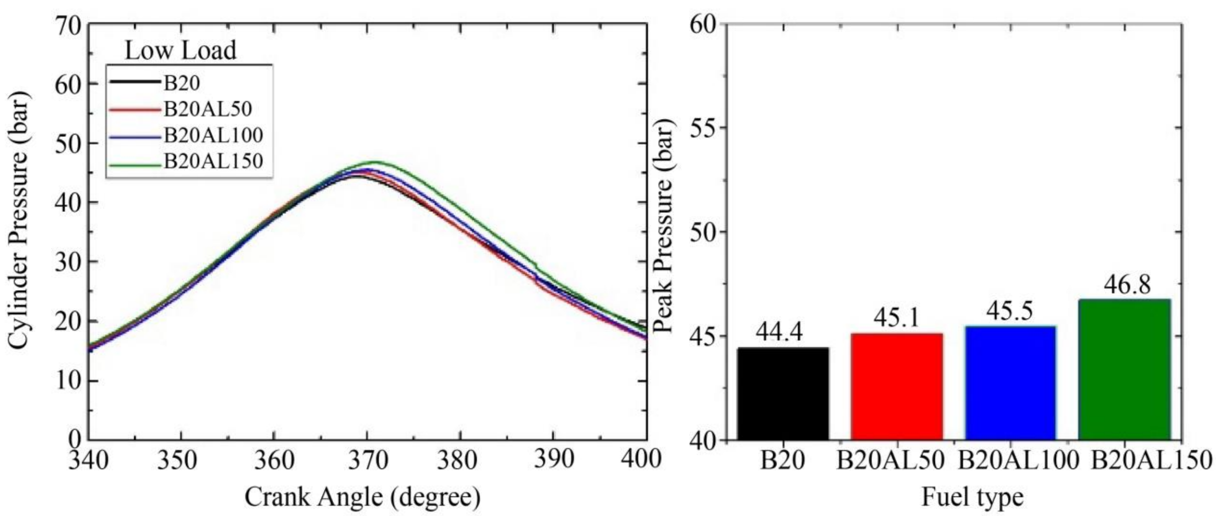

Fig. 3 Cylinder pressure at low load conditions of Al_2O_3 nanoparticles with B20 biodiesel

There is an even stronger pressure difference between the fuel variants at medium load conditions, as shown in Figure 4. Pressure development pattern is similar to the combustion taking place to the tune of 350°CA, and peak pressure is reached to the tune of 370°CA, but the amount of pressure gain is greater than when the load is low. The peak cylinder pressure of the baseline B20 fuel is 46.9 bar, which is about 5.6 percent higher than the low load condition. This means that there will be better combustion efficiency, whereby the rate of fuel injection is better and there is also better mixing of the fuel and air. This enhancement is even more pronounced under such conditions in which the B20AL50 fuel with the nanoparticle addition will achieve a maximum pressure of 49.2 bar, which is a 4.9 percent improvement of B20. The B20AL100 fuel stands at 53.0 bar, which is a 13.0 percent increase. The highest rise is witnessed with B20AL150 that achieves a maximum pressure of 53.7 bar, which is 14.5 percent greater than the base biodiesel. This growing enhancement implies that moderate load conditions have furnished an ideal setting where nanoparticle triggering has been achieved owing to adequate fuel amount and moderate temperature of combustion that enables Al_2O_3 particles to act as good catalysts in the process of oxidation of fuel and enhance the properties of atomizing the fuel.

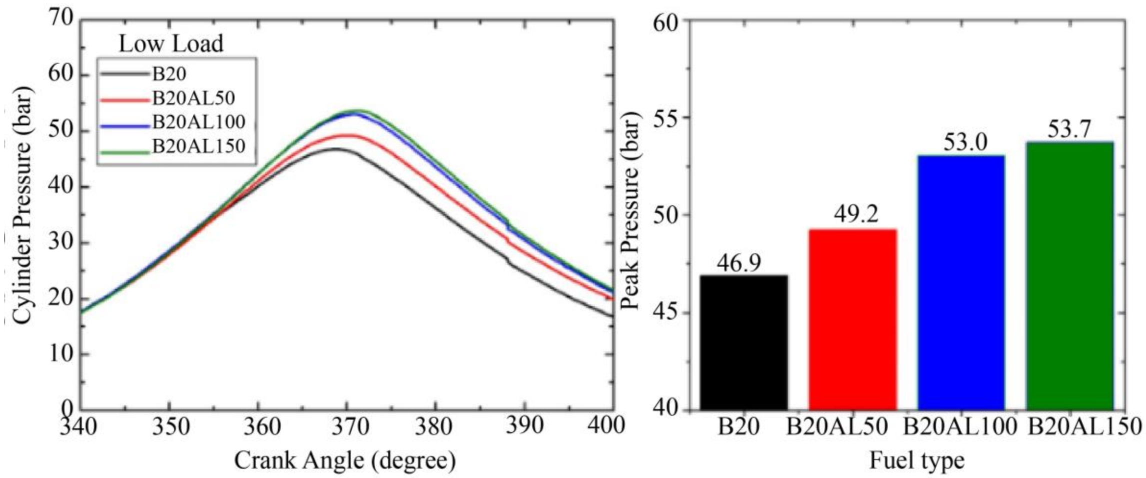

Fig. 4 Cylinder pressure at medium load conditions of Al_2O_3 nanoparticles with B20 biodiesel

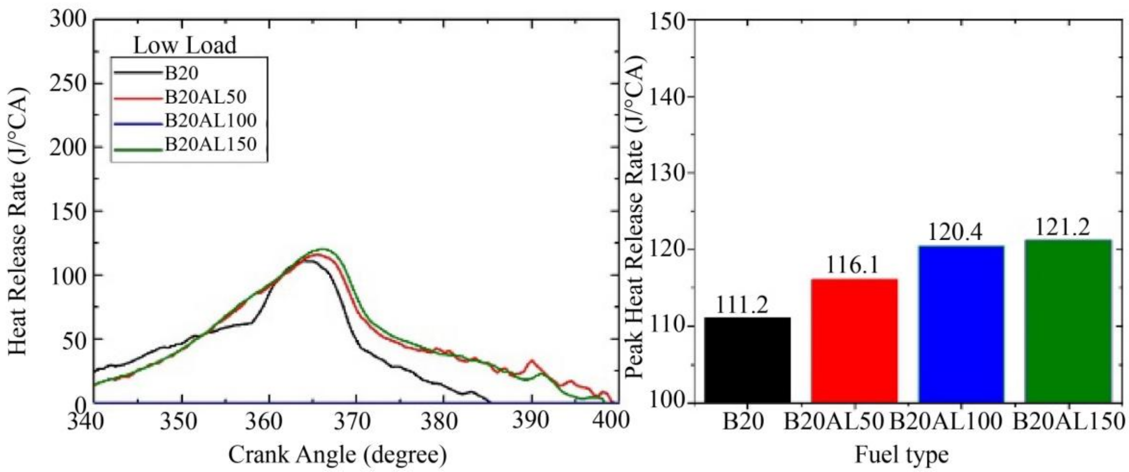

Fig. 5 Cylinder pressure at high load conditions of Al_2O_3 nanoparticles with B20 biodiesel

With high load conditions, the performance is enhanced further, as demonstrated in Figure 5. The peak pressure attained at the base B20 is 56.2 bar, which increases by 26.6 percent of the low load conditions because the optimum combustion environment is achieved by maximum injection of fuel, increased turbulence, and high temperature. The blend of nanoparticles has the greatest improvement with B20AL50 providing 59.7 bar, B20AL100 providing 63.3 bar, and B20AL150 providing 64.7 bar as compared to neat B20, which has an increase of 15.1%. This increased pressure difference shows that the Al_2O_3 nanoparticles are optimized in their efficiency by virtue of the increased atomization of fuels and the expedited oxidation rate [19, 20].

4.2. Heat Release Rate

Heat Release Rate (HRR) is one of the key parameters of combustion that quantifies the rate of the combustion of chemical energy in fuel to thermal energy during the combustion process, which indicates the level of the combustion stage and the performance of an engine. Figures 6-8 depict the nature of combustion under varying load operating conditions of B20 biodiesel fuel blended with Al_2O_3 nanoparticles.

Figure 6 shows the HRR profile under low load conditions, where all test fuels exhibit moderate heat release rates. The trend shows that combustion starts around 350°CA and reaches a peak heat release rate near 365°CA. The baseline B20 fuel reaches a peak heat release rate of 111.2 J/°CA, which reflects the limited combustion intensity due to the reduced fuel injection quantity.

The incorporation of Al_2O_3 nanoparticles causes a progressive increase as B20AL50 reaches 116.1 J/°CA, B20AL100 reaches 120.4 J/°CA, and B20AL150 reaches 121.2 J/°CA. This results in a 9.0% increase compared to neat B20. The moderate peak heat release rate correlated with the earlier cylinder pressure results, proving that the catalytic effect of nanoparticles is constrained under low load conditions [21].

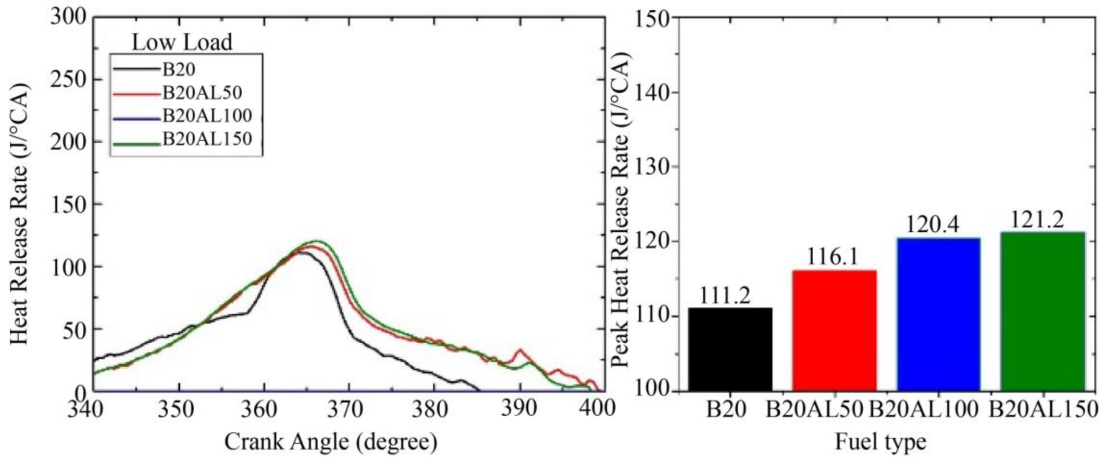

Fig. 6 Heat release rate at low load conditions of Al_2O_3 nanoparticles with B20 biodiesel

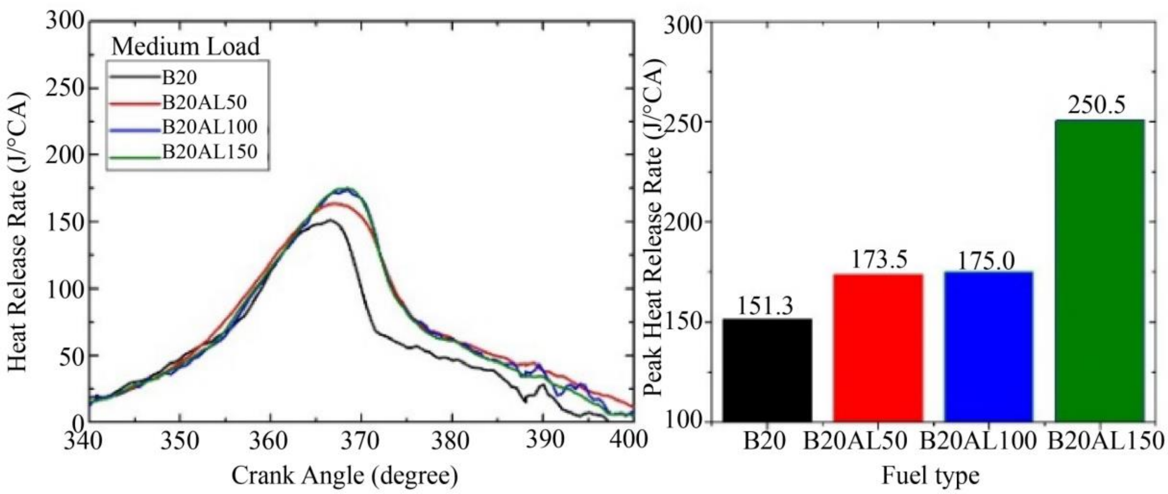

Fig. 7 Heat release rate at medium load conditions of Al_2O_3 nanoparticles with B20 biodiesel

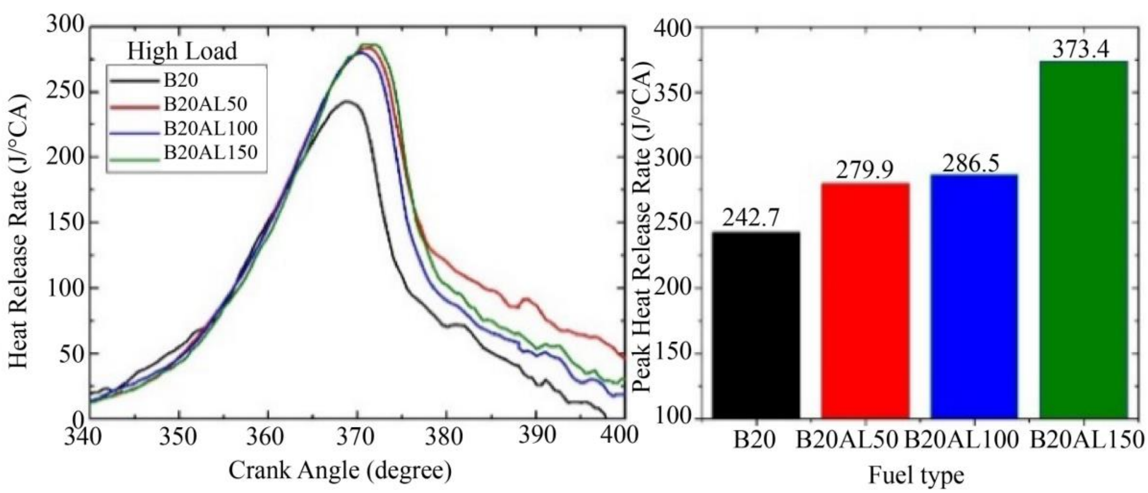

Fig. 8 Heat release rate at high load conditions of Al_2O_3 nanoparticles with B20 biodiesel

Under medium load operating conditions, there is a more significant difference compared to low load operation, as shown in Figure 7. The combustion time remains consistent with ignition occurring around 350°CA, and peak heat release is reached near 365°CA, with the energy release intensity becoming higher. The baseline B20 fuel shows a peak heat release rate of about 165 J/°CA, which represents a 48% increase compared to low load. This indicates better combustion efficiency due to the improved fuel injection rate and better mixing conditions. The nanoparticle-enhanced mixture shows a clear improvement under these conditions. B20AL50 increases by 9.1% compared to B20, which is 180 J/°CA peak heat release rate.

Whereas B20AL100 approaches approximately 195 J/°CA, which is an 18.2 percent increment. HRR is the largest in B20AL150, which peaks at 205 J/°CA, the highest heat release rate increase of 24.2 percent of the base biodiesel increase.

This progressively positive development indicates that moderate load conditions have the potential to offer beneficial conditions of nanoparticles activation under conditions of an adequate amount of fuel and a moderate level of combustion temperature, in which Al_2O_3 particles can be used to improve the process of combustion effectively.

When the load conditions are high, the heat release characteristics are extremely high, as shown in Figure 8. The B20 fuel in the baseline gives a peak rate of heat release of 242.7 J/°CA, which is 118 percent higher than that of the low load scenario. This massive increase is an indicator of the optimum combustion atmosphere generated by maximum fuel injection and high temperatures.

Better increases are even seen in the nanoparticle blends with B20AL50 increasing to 279.9 J/°CA, B20AL100 increasing to 286.5 J/°CA, and B20AL150 increasing to 373.4 J/°CA, which is a maximum increase of 53.9 over neat B20. The high rate of heat release is directly proportional to the high cylinder pressures that had been observed before. The same phenomenon is also in line with earlier research in which Al_2O_3 nanoparticles are the most effective in maximizing the combustion efficiency in cases of high load [22, 23].

4.3. Mass Fraction Burned and Ignition Delay

Mass Fraction Burned (MFB) is the percentage of fuel burned in combustion, and ignition delay is the period between injection and the beginning of combustion in the cylinder. These parameters play a role in assessing the efficiency and timing of a diesel engine combustion. The behaviour of the combustion phase indicates that there is a notable disparity in the rate of fuel burning in operating load conditions of B20 biodiesel and Al_2O_3 nanoparticle blend, as indicated in Figures 9-11.

At low load conditions, referring to Figure 9, all test fuels showed a relatively delayed combustion onset, with B20 fuel having an ignition delay of 15.0°CA. The MFB curve depicts fuel consumption gradually reaching CA10 around 350°CA, CA50 near 365°CA, and CA90 at approximately 385°CA. The increase in the percentage of Al_2O_3 nanoparticles resulted in a 33.3% reduction in ignition delay compared to the base B20 fuel.

The ignition delay values were 14.5°CA, 13.5°CA, and 10.0°CA for B20AL50, B20AL100, and B20AL150 fuels, respectively. This improvement indicates the improved fuel atomization and catalytic oxidation effect provided by the nanoparticles under challenging low-load conditions.

Under medium load conditions, as depicted in Figure 10, the base fuel B20 showed a better ignition delay of 11.5°CA compared to low load operation. The MFB curve shows a trend of a faster fuel consumption rate than in low load conditions. The MFB for CA10, CA50 and CA90 occurred around 345°CA, 360°CA, and 380°CA, respectively. The use of nanoparticles further led to improvements. B20AL50 achieved an ignition delay of 10.0°CA, B20AL100 achieved 9.5°CA, and B20AL150 achieved 8.0°CA. The 30.4% reduction in ignition delay for B20AL150 indicates that the effectiveness of nanoparticles remains significant under medium load conditions.

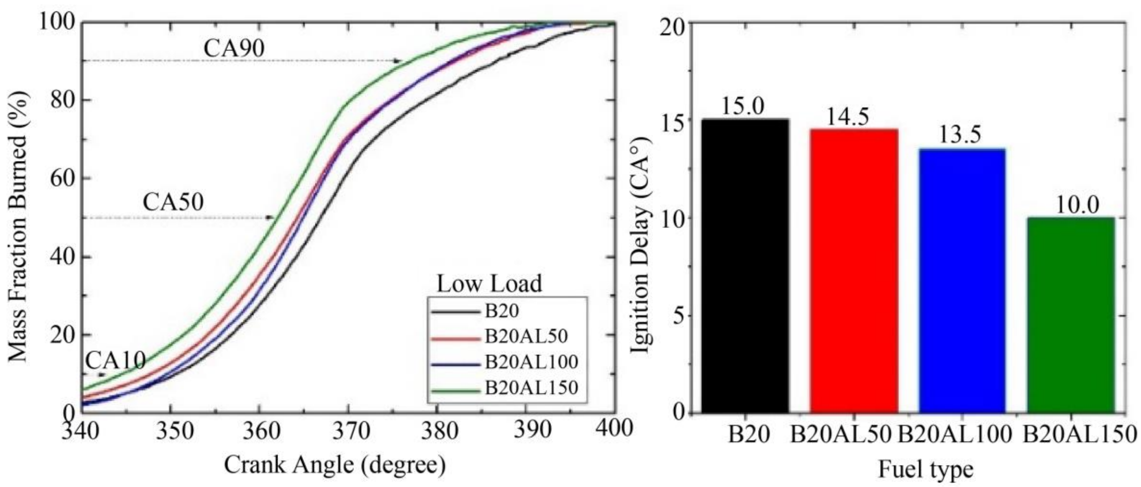

Fig. 9 Mass fraction burned and ignition delay at low load conditions of Al_2O_3 nanoparticles with B20 Biodiesel

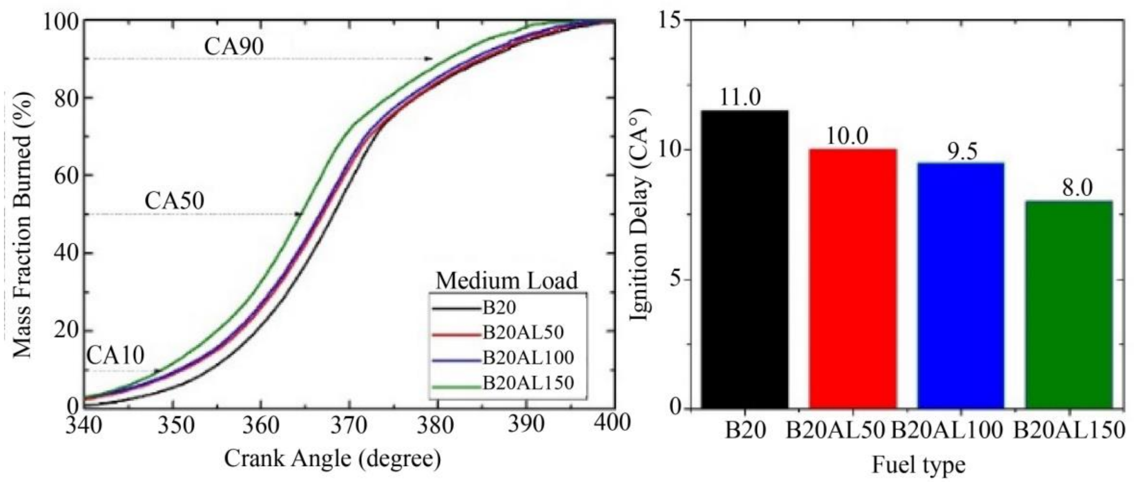

Fig. 10 Mass fraction burned and ignition delay at medium load conditions of Al_2O_3 nanoparticles with B20 Biodiesel

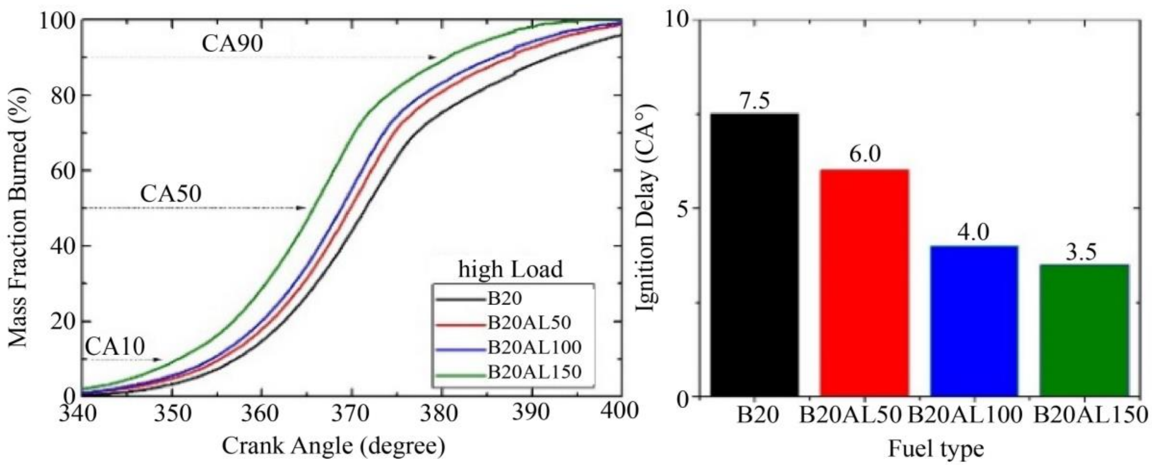

Fig. 11 Mass fraction burned and ignition delay at high load conditions of Al_2O_3 nanoparticles with B20 Biodiesel

Figure 11 shows that the combustion characteristics are significantly improved under high load conditions. The B20 base fuel shows a reduced ignition delay of 7.5°CA due to the high combustion temperature and improved mixing. It can be seen that the MFB curve shifts to the left, reflecting faster fuel consumption by shortening the CA10, CA50, and CA90 times. The nanoparticle mixture has resulted in a reduction in ignition delay where B20AL50 reaches 6.0°CA, B20AL100 reaches 4.0°CA, and B20AL150 reaches 3.5°CA. This has created an improvement of 53.3% compared to pure B20. The combustion phase has been accelerated, which is directly correlated with the enhanced cylinder pressure and heat release rate observed previously. This effect is also used to verify that the Al_2O_3 nanoparticles optimize the fuel combustion properties under high load. This finding is in line with findings from previous studies that reported similar improvements with the use of nanoparticles [24, 25].

5. Conclusion

This study examined the effects of Al_2O_3 nanoparticle additives on the combustion of a marine diesel engine operating using B20 biodiesel under different engine load conditions. Several analyses have been performed, including in-cylinder pressure, heat release characteristics, percentage of fuel mass burned, and time of ignition delay. Based on the experimental results, the key observations from this study are as follows:

- The use of Al_2O_3 nanoparticles has consistently improved the in-cylinder pressure parameter for all load conditions, where B20AL150 fuel achieves a15.1% increment compared to B20 base fuel.
- Nanoparticle additive has also significantly contributed to the accelerated heat release rate, where B20AL150 fuel increased by 53.9% under high load conditions. It results in better combustion efficiency, which can reduce fuel consumption and operating costs in marine transportation systems.
- Ignition delay was shortened with increasing nanoparticle concentration, where under high load conditions, B20AL150 indicates a 53.3% reduction. The accelerated combustion phase has increased fuel reactivity and combustion stability.

- The study indicates that Al_2O_3 nanoparticles provide a strong catalytic effect to marine engine combustion, especially at higher load conditions. Therefore, the nano-fuels are suitable for marine engines that often run at maximum power during ocean voyages.

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