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Environmental Impact Mitigation in Diesel Engines Using Emulsified Water-in-Diesel Fuel Blended with Al_2O_3 Nanoparticles

[1]Madusudanprasad M., [2]Abshalomu Y., [3]Dinesh R., [4]Harish B.B., [5]Bala S.S.R.M.

[1]UCEK JNTUK, Kakinada, India
[2]Vignan's Nirula Institute of Technology and Science for Women, Guntur, India
[3]Chaitanya institute of science and technology, Kakinada, Andhra Pradesh, India
[4]VNR Vignana Jyothi institute of Engineering and technology, Hyderabad, India
[5]Lakireddy Bali Reddy College of Engineering, Mylavaram, AP, India

Abstract. The primary objective of this work is to conduct an in-depth investigation into the performance, combustion, and emission characteristics of a diesel engine using Water-in-Diesel Emulsions (WiDE) with alumina oxide (Al_2O_3) nanoparticles to reduce harmful pollutants and enhance efficiency amid increasingly stringent environmental regulations. Emulsified fuels were prepared as containing 5%, 10%, and 15% water by volume. Furthermore, 100 ppm of Al_2O_3 nanoparticles were uniformly dispersed in the blends to enhance atomization and improve combustion characteristics. Engine testing was carried out from no load to full load to assess the performance, combustion behavior, and emission characteristics of the prepared fuel blends. The most important results obtained from this research show that the WiDE blends give higher brake thermal efficiency and significantly lower emissions with respect to diesel. Among all, the best behavior was shown by WiDE10, which showed a 7.14% increase in brake thermal efficiency and reductions in HC by 50.00%, CO by 16.67%, NO_X by 66.67%, and smoke by 46.88%. In combustion analysis, it was observed that diesel shows a peak pressure of 62.74 bar at 366°CA, whereas WiDE blends produce smoother combustion with a lower heat release rate due to water-induced micro-explosions. The importance of the obtained results is to demonstrate that the synergistic effects of water emulsification and Al_2O_3 nanoparticles enhance the processes of atomization and reduce peak temperatures, thus allowing cleaner combustion. Hence, WiDE10 turns out to be a promising and eco-friendly alternative fuel for diesel engines.

Keywords: performance, emission, combustion, emulsified, mitigation.

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Atenuarea impactului asupra mediului în motoarele diesel utilizând apă emulsionată în combustibil diesel amestecată cu nanoparticule de Al_2O_3

[1]Madusudanprasad M., [2]Abșalomu Y., [3]Dineș R., [4]Hariș B. B., [5]Bala S. S. R. M.
[1]UCEK JNTUK, Kakinada, India
[2]Institutul de Tehnologie și Știință pentru Femei Nirula din Vignan, Guntur, India
[3]Institutul de Știință și Tehnologie Chaitanya, Kakinada, Andhra Pradesh, India
[4]Institutul de Inginerie și Tehnologie VNR Vignana Jyothi, Hyderabad, India
[5]Colegiul de Inginerie Lakireddy Bali Reddy, Mylavaram, AP, India

Rezumat. Obiectivul principal al acestei lucrări este de a realiza o investigație aprofundată a performanței, combustiei și caracteristicilor de emisii ale unui motor diesel utilizând emulsii apă-în-motorină (WiDE) cu nanoparticule de oxid de alumină (Al_2O_3) pentru a reduce poluanții nocivi și a spori eficiența în contextul unor reglementări de mediu din ce în ce mai stricte. Combustibilii emulsionați au fost preparați conținând 5%, 10% și 15% apă în volum. În plus, 100 ppm de nanoparticule de Al_2O_3 au fost dispersate uniform în amestecuri pentru a spori atomizarea și a îmbunătăți caracteristicile de ardere. Testarea motorului a fost efectuată de la sarcină zero la sarcină maximă pentru a evalua performanța, comportamentul la ardere și caracteristicile de emisii ale amestecurilor de combustibil preparate. Cele mai importante rezultate obținute din această cercetare arată că amestecurile WiDE oferă o eficiență termică de frânare mai mare și emisii semnificativ mai mici în comparație cu motorina. Dintre toate, cel mai bun comportament a fost demonstrat de WiDE10, care a arătat o creștere de 7.14% a eficienței termice a frânării și reduceri ale HC cu 50.00%, CO cu 16.67%, NOX cu 66.67% și fum cu 46.88%. În analiza combustiei, s-a observat că motorina prezintă o presiune maximă de 62.74 bar la 366°CA, în timp ce amestecurile WiDE produc o combustie mai lină, cu o rată mai mică de eliberare a căldurii datorită microexploziilor induse de apă. Importanța rezultatelor obținute constă în demonstrarea faptului că efectele sinergice ale emulsionării apei și nanoparticulelor de Al_2O_3 îmbunătățesc procesele de atomizare și reduc temperaturile maxime, permițând astfel o combustie mai curată. Prin urmare, WiDE10 se dovedește a fi un combustibil alternativ promițător și ecologic pentru motoarele diesel.

Cuvinte-cheie: performanță, emisii, combustie, emulsionat, atenuare.

Снижение воздействия на окружающую среду дизельных двигателей с использованием эмульгированного водорастворимого дизельного топлива, смешанного с наночастицами Al_2O_3

[1]Мадусуданпрасад М., [2]Абшалому Й., [3]Динеш Р., [4]Хариш Б. Б., [5]Бала С. С. Р. М.
[1]UCEK JNTUK, Какинада, Индия
[2]Институт технологий и науки для женщин им. Вигнана Нирула, Гунтур, Индия
[3]Институт науки и технологий Чайтанья, Какинада, Андхра-Прадеш, Индия
[4]Институт инженерии и технологий им. В. Н. Р. Вигнана Джоти, Хайдарабад, Индия
[5]Инженерный колледж им. Лакиредди Бали Редди, Майлаварам, Андхра-Прадеш, Индия

Аннотация. Основная цель данной работы — провести углубленное исследование характеристик работы, сгорания и выбросов дизельного двигателя с использованием водно-дизельных эмульсий (WiDE) с наночастицами оксида алюминия (Al2O3) для снижения уровня вредных загрязняющих веществ и повышения эффективности в условиях ужесточения экологических норм. Эмульгированные топлива были приготовлены с содержанием воды 5%, 10% и 15% по объему. Кроме того, в смеси были равномерно диспергированы наночастицы Al2O3 в количестве 100 ppm для улучшения распыления и характеристик сгорания. Испытания двигателя проводились от холостого хода до полной нагрузки для оценки характеристик работы, поведения при сгорании и выбросов приготовленных топливных смесей. Наиболее важные результаты, полученные в ходе этого исследования, показывают, что смеси WiDE обеспечивают более высокий тормозной тепловой КПД и значительно меньшие выбросы по сравнению с дизельным топливом. Среди всех вариантов наилучшие результаты показала смесь WiDE10, продемонстрировавшая увеличение термического КПД на 7.14% и снижение выбросов HC на 50.00%, CO на 16.67%, NOX на 66.67% и дымности на 46.88%. Анализ сгорания показал, что дизельное топливо достигает пикового давления 62.74 бар при 366°CA, в то время как смеси WiDE обеспечивают более плавное сгорание с меньшей скоростью выделения тепла за счет микро-взрывов, вызванных водой. Важность полученных результатов заключается в демонстрации того, что синергетический эффект эмульгирования воды и наночастиц Al_2O_3 усиливает процессы распыления и снижает пиковые температуры, обеспечивая тем самым более чистое сгорание. Таким образом, WiDE10 оказывается перспективным и экологически чистым альтернативным топливом для дизельных двигателей.

Ключевые слова: производительность, выбросы, сгорание, эмульгированное, снижение.

INTRODUCTION

The introduction effectively highlights the relevance of alternative fuels and their role in addressing stricter emission norms [1].

The depletion of fossil fuel reserves and growing environmental concerns have led to stringent pollution regulations in India, such as the Bharat Stage (BS) emission standards, aligned with European norms. BS-IV norms were implemented nationwide in 2017, followed by BS-VI in 2020, mandating significant reductions in NOx, CO, HC, and particulate matter emissions from diesel engines [2].

These regulations have driven research into alternative fuels to reduce pollution while maintaining engine performance.

WiDE present a promising solution by lowering combustion temperatures, reducing NOx emissions, and enhancing combustion efficiency through micro-explosions caused by secondary atomization.

This phenomenon improves fuel-air mixing, leading to lower particulate emissions [3]. To maintain stability, surfactants like Span80 and Tween80 help reduce surface tension between water and diesel.

Recent studies indicate that incorporating nanoparticles such as Al_2O_3 further enhances combustion by improving atomization and thermal conductivity. This study investigates the effects of WiDE with 5%, 10%, and 15% water and 100 ppm Al_2O_3 nanoparticles on diesel engine performance at varying loads.

The findings demonstrate a 7.14% improvement in BTE and significant emission reductions, aligning with India's stringent emission norms.

MATERIALS AND METHODS

Emulsified Fuel Preparation

The emulsification process in this study relies primarily on ultrasonication, a high-energy method for the effective dispersion of water droplets within diesel, ensuring a stable water-in-diesel emulsion. Ultrasonication forces the breaking up of larger water droplets into finer sizes with more intense cavitation, ensuring uniform distribution that constitutes long-term stability. Span 80 and Tween 80 were chosen for their efficiency as non-ionic surfactants in the stabilization of water-in-oil emulsions. A combined HLB value of 6.43 was used, in agreement with previous literature that an HLB range of 6-8 exhibits optimum stability for water-in-diesel emulsions [4].

First, 1% volume mixture of Span 80 and Tween 80 was prepared by an ultrasonic agitator running at 20 kHz for 30 minutes to ensure complete and homogeneous dispersion of the surfactants. The water-in-diesel emulsions were prepared by adding water gradually to diesel in proportions of 5%, 10%, and 15%.

Emulsification was done under continuous ultrasonication to prevent droplet coagulation for providing stable dispersion.

Next, 100 ppm of Al_2O_3 nanoparticles were ultrasonically dispersed only into the WiDE blends without adding any such nanoparticles to the pure diesel sample. This was done to ensure that the influence of nanoparticles was evaluated only in the emulsified fuels.

Nanoparticle addition enhances the emulsion through better thermal conductivity, micro-explosion during combustion, and consequently higher completeness of fuel oxidation.

Emulsion Stability Evaluation

Stability is one of the most critical factors that determines whether emulsified fuels are suitable for engine applications.

Literature indicates that emulsions produced through ultrasonic homogenization can remain stable up to 30 days without noticeable phase separation [5].

In this work, both visual inspection and standard stability tests were conducted to assess the durability of these emulsions:

Visual Observation Test:

The resulting emulsions were allowed to settle in transparent glass containers at ambient conditions

$$SI = \left(1 - \frac{H_S}{H_t}\right) \cdot 100\% , \qquad (1)$$

where**,**

Hs is the height of separated layer

$\mathbf{H_t}$ is the total height of the emulsion.

All the samples showed an SI value above 95%, indicating great stability.

Droplet Size Analysis:

The water–diesel emulsion droplet size was precisely assessed using a Dino-Lite digital optical microscope, as shown in Figure 1. The representative micrographs in Figure 2 demonstrate the fine and uniform dispersion of water droplets within the emulsion and monitored daily to observe creaming, sedimentation, or phase separation. Throughout the experimental period, no significant separation was noticed, which confirmed the acceptable stability for engine testing.

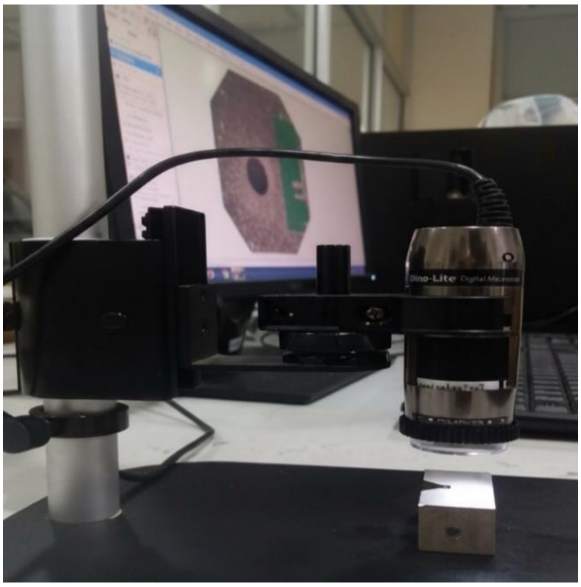

Fig. 1. Digital Microscope Experimental Setup.

Bottle Test (Static Stability Test):

Each of the emulsion samples was left undisturbed for 7, 14, and 30 days and the height of any separated layer was measured with the aid of a calibrated scale. Stability Index was calculated using Equation 1. The measured droplet sizes ranged narrowly between 41.4 μm and 50.6 μm, reflecting the effectiveness of ultrasonication and the suitability of the surfactant with an HLB value of 6.43. Importantly, no droplet coalescence or aggregation was observed, confirming the emulsion's physical stability and consistent droplet size distribution throughout the engine testing period, which validates that the emulsification process was well controlled and effective. This uniformity ensures reliable performance in combustion applications by maintaining consistent fuel properties during engine operation.

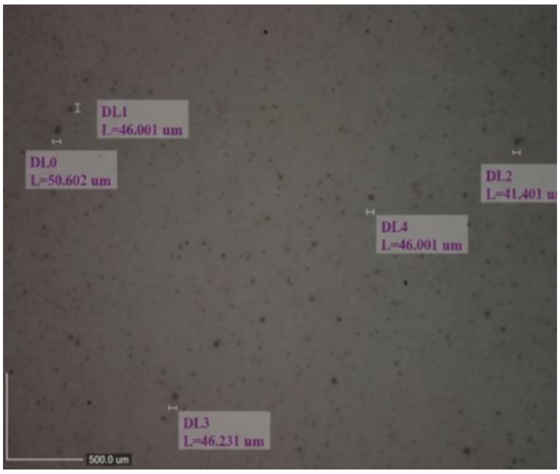

Fig. 2. Micrograph of Emulsion Droplet Size Distribution.

Fuel Property Analysis

The fuel properties of Diesel and WiDE blends containing 100 ppm of Al_2O_3 nanoparticles were tested by following the ASTM test methods. The calorific value was determined by a Bomb Calorimeter, viscosity by a Redwood Viscometer, and density with a hydrometer. Flash and fire points were determined by Pensky–Martens Closed Cup and Cleveland Open Cup testers, respectively. Measured properties are presented in Table 1.

Table 1 Summary of Fuel Properties Evaluated Using Standard Methods

Property	Diesel	WiDE5	WiDE 10	WiDE 15
Calorific value (MJ/kg)	4.3	4.0	3.8	3.6
Kinematic viscosity at 50 °C (mm^2/s)	3.5	4	4.5	5
Density (kg/m^3)	840	860	875	890
Flash point (° C)	55	62	70	75
Fire point (° C)	65	75	80	85

From the table 1, it is observed that both density and viscosity increase upon the addition of water to diesel. This is due to an increase in internal resistance to flow by a dispersed water phase within the fuel, in addition to changes in the intermolecular interactive forces. It is also revealed that the increase in density is not proportionally related to the water content, since the emulsification process and the use of surfactants alter the total structural arrangement of the blend. Physical property changes are of significant concern, as these may affect atomization and combustion behavior, thus impacting engine performance overall.

EXPERIMENTAL SETUP

The experimental setup, as shown in Figure 3, revolves around a Kirloskar single-cylinder, water-cooled diesel engine, chosen for its versatility and reliability in IC engine research [6]. Key technical features include direct injection fuel spray, a two-valve camshaft arrangement (inlet and exhaust), and a water-cooling system for enhanced performance. The engine is integrated with an eddy current dynamometer offering variable load options, ensuring precise testing conditions. To minimize issues like vibration and noise, the engine test rig is optimized for improved testing accuracy and reliability.

Fig. 3. Experimental Setup.

RESULTS & DISCUSSION

Emulsified water-diesel blends (WiDE) with Al_2O_3 nanoparticles. Engine tests were conducted under varying loads to evaluate BTE, emissions (HC, CO, NO_x), and smoke opacity, highlighting combustion improvements and emission reduction potential without engine modifications. The micro-explosion phenomenon and enhanced atomization in WiDE blends contribute to improved combustion efficiency and reduced emissions. However, real-world factors such as fuel injection timing, ambient temperature, and engine load variations may influence performance. While the reduction in NOx and smoke emissions enhances environmental benefits, the increased viscosity and lower calorific value of WiDE blends may impact ignition quality. To ensure stability and efficiency across different engine types, optimizing surfactants and making minor fuel system adjustments are essential.

Brake Thermal Efficiency (BTE) Analysis

Figure 4 illustrates the influence of brake mean effective pressure (BMEP) on brake thermal efficiency (BTE) for diesel and WiDE samples. The BTE improved for emulsified water-diesel blends (WiDE) compared to diesel, with WiDE10 demonstrating a 7.14% higher efficiency than diesel. This improvement is attributed to secondary atomization from the micro-explosion phenomenon and the catalytic effect of Al_2O_3 nanoparticles (100 ppm), which promote better combustion and thermal conductivity.

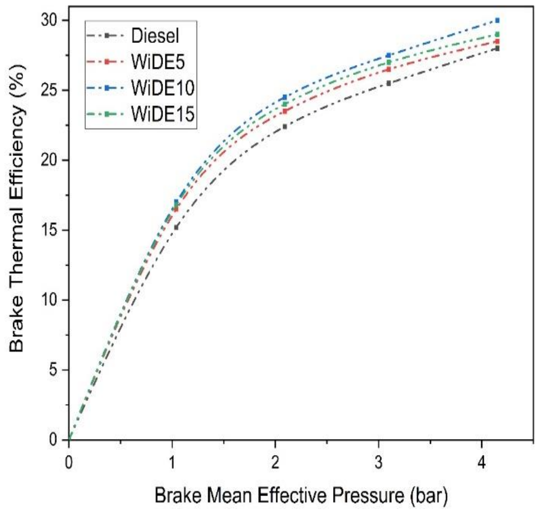

Fig. 4. BMEP Vs BTE.

BTE increased progressively from no load to full load due to improved air-fuel mixing and greater energy demand enhancing combustion efficiency [7-8]. However, at higher water content, the reduced calorific value slightly decreased BTE.

CO Emission Analysis

Figure 5 depicts the variation of CO emissions with brake mean effective pressure (BMEP) for diesel and WiDE samples. CO emissions decreased significantly for WiDE blends compared to diesel, with WiDE10 showing the lowest emissions at 0.05%, a reduction of 66.67% compared to diesel. This decline is attributed to enhanced combustion due to better atomization and improved oxygen availability facilitated by the presence of Al_2O_3 nanoparticles [9].

However, at higher water content (WiDE15), CO emissions slightly increased due to incomplete combustion caused by excess water content, though remaining Figure 6 presents the variation of HC emissions with brake mean effective pressure for diesel and WiDE samples. HC emissions decreased significantly for WiDE blends compared to diesel due to enhanced combustion efficiency and better fuel atomization facilitated by the emulsified fuel's micro-explosion effect [11].

The presence of Al_2O_3 nanoparticles also contributed to improved combustion by increasing thermal conductivity. WiDE10 recorded the lowest HC emissions at 25 ppm, achieving a 50% reduction compared to diesel (50 ppm). WiDE5 also showed a substantial reduction at 30 ppm. However, at higher water content in WiDE15, HC emissions slightly increased to 35 ppm due to incomplete combustion caused by excess water content. lower than diesel [10].

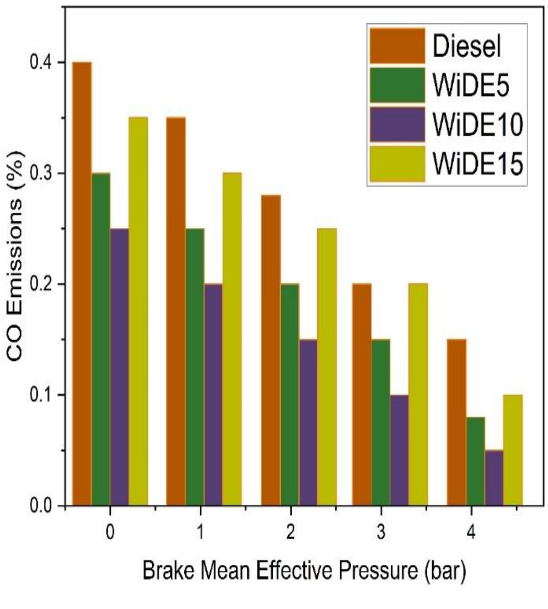

Fig. 5. BMEP Vs CO Emissions.

HC Emissions Analysis.

Despite this, HC emissions for WiDE15 remained lower than diesel, demonstrating the effectiveness of emulsified fuels in reducing unburned hydrocarbons.

The positive trend aligns with literature on the emission-reducing potential of emulsified fuels combined with nanoparticles [12-13].

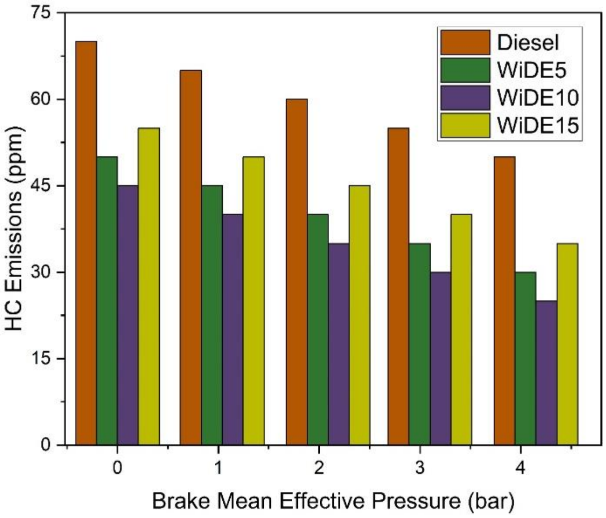

Fig. 6. BMEP Vs HC Emissions.

NOx Emissions Analysis

Figure 7 illustrates the variation of NOx emissions with Brake Mean Effective Pressure (BMEP) for diesel and WiDE samples. NOx emissions decreased consistently for WiDE blends compared to diesel due to lower combustion temperatures resulting from water content in the emulsified fuel [14-15]. The micro-explosion phenomenon and improved heat dissipation from Al_2O_3 nanoparticles further contributed to this reduction. WiDE15 achieved the lowest NOx emissions at 710 ppm, a 21.11% reduction compared to diesel (900 ppm). WiDE10 and WiDE5 also showed reductions at 750 ppm and 800 ppm, respectively [16-17].

In-cylinder Pressure Analysis

Variation of in-cylinder pressure with crank angle for diesel and emulsified fuel blends (WiDE5, WiDE10, and WiDE15) is shown in Figure 9. The peak cylinder pressure was highest for diesel at 62.74 bar at 366° CA. On the other hand, all three emulsified fuels showed a similar trend but with slightly lower peak values. In the case of emulsified fuels, the peak pressure was reduced owing to the latent heat of vaporisation of water that increases the ignition delay and reduces the in-cylinder temperature [21].

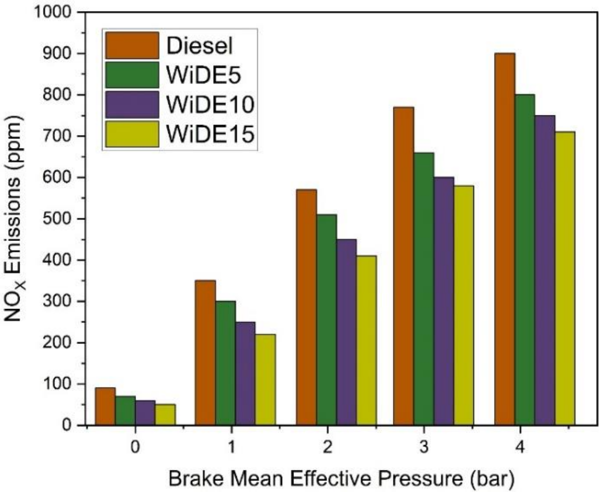

Fig. 7. BMEP Vs NO_X Emissions.*Smoke Opacity*

The trend demonstrates that water content in emulsified fuels effectively reduces peak combustion temperatures, thereby curbing NOx formation while maintaining efficient combustion [18]. *Analysis*Figure 8 illustrates the variation of smoke emissions with Brake Mean Effective Pressure (BMEP) for diesel and WiDE samples. Emulsified water-diesel blends (WiDE) demonstrated a significant reduction in smoke emissions compared to diesel, primarily due to improved fuel atomization and secondary atomization effects facilitated by the micro-explosion phenomenon [19]. The presence of Al_2O_3 nanoparticles further enhanced combustion efficiency by promoting better oxidation of soot particles. WiDE10 and WiDE15 recorded the lowest smoke emissions at 1.7 FSN, achieving a 46.88% reduction compared to diesel (3.2 FSN). WiDE5 also showed a substantial decrease at 2.25 FSN . The reduced smoke emissions highlight the effectiveness of emulsified fuels in improving combustion efficiency and minimizing particulate formation, even at higher water content levels [20].

4.2 Net Heat Release Rate (NHRR)

The variation of net heat release rate with crank angle is shown in Figure 10. The maximum NHRR for neat diesel was 71.24 J/°CA, whereas for emulsified blends, it was slightly lower. Such a reduction could be due to the cooling effect of water and delay in ignition, which have an overall moderating effect on the premixed combustion phase [22].

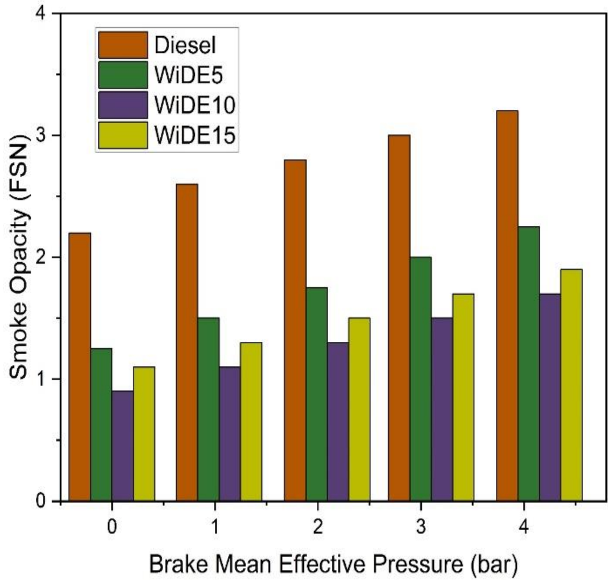

Fig. 8. BMEP Vs Smoke Opacity.

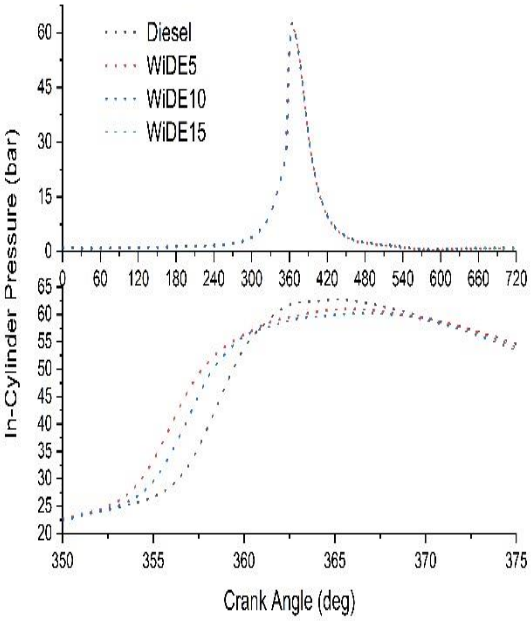

Fig. 9. Crank Angle Vs In-Cylinder Pressure.

Among the emulsified fuels, WiDE10 showed a smoother and sustained heat release pattern. This implies better combustion efficiency. The micro-explosion effect and Al_2O_3 nanoparticles improve the mix and combustion during the diffusion phase of combustion. In contrast, the NHRR for WiDE15 was found to be lower due to excessive water content, as it suppresses flame propagation. In general, the combustion analysis has shown that with WiDE10, balanced combustion characteristics have been achieved with controlled heat release and increased efficiency compared to other emulsified blends [23].

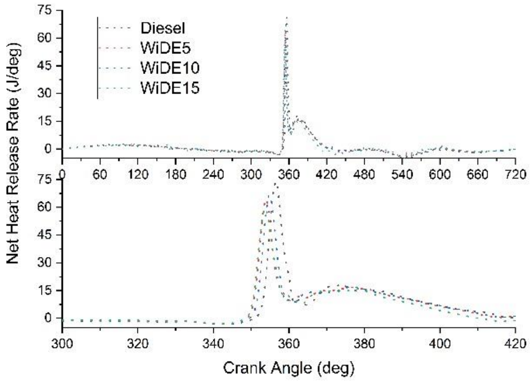

Fig. 10. Crank Angle Vs Net Heat Release Rate.

CONCLUSION.

The present study showed that the emulsified water-diesel blends with Al_2O_3 nanoparticles considerably improved the performance, combustion, and emission characteristics of the engine. WiDE10 resulted in the highest BTE value, which was increased by 7.14% compared to diesel fuel, because of secondary atomization and micro-explosion, and catalytic effect. The combustion characteristic analysis showed that diesel exhibited a maximum in-cylinder pressure and net heat release rate of 62.74 bar and 71.24 J/°CA, respectively. In contrast, the emulsified diesel-water blends showed smoother and more controlled combustion characteristics and reduced peak temperature. The reductions were found as 50% for HC, 16.67% for CO, 66.67% for NOx, and 46.88% for smoke, confirming cleaner and more efficient combustion. These results confirm that water emulsification technique effectively reduces combustion temperature and NOx formation while Al_2O_3 nanoparticles enhance in-cylinder heat transfer and mixing phenomena. Overall, WiDE blends, and particularly WiDE10, can be used as a viable and practical alternative to conventional diesel fuels for diesel engine applications without any modifications.

Future Scope

Further research is needed to assess the long-term stability, injector durability, and compatibility of WiDE blends with different engine types. Studies on economic feasibility, large-scale production, and distribution challenges are essential for commercial implementation. Optimizing surfactant selection and nanoparticle concentration can enhance fuel stability and combustion characteristics. Additionally, real-world testing under diverse operating conditions will help validate the practical benefits of WiDE fuels in transportation and industrial applications.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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About authors.

Madusudanprasad Manchala, M.Tech., Ph.D.
Scientific interests: Thermal, Materials.
Email:
mprasad@jntucek.ac.in
ORCID: 0000-0002-7933-8551

Dinesh Revu, M.Tech.
Scientific Interest: Thermal, Manufacturing,
Email:
dineshkrrish345@gmail.com
ORCID: 0009-0009-3503-5848

Bala Satya Sreekara Reddy Mule, M.Tech., Ph.D. Scientific interest: hermal, manufacturing optimization. **Email:**
mbssreddy2007@gmail.com
ORCID: 0000-0002-8525-969X

Abshalomu Yallamati, M.Tech., Ph.D.
Scientific interests: Thermal, composite materials.
Email:
yallamatiabshalomu@gmail.com
ORCID: 0000-0002-6797-3996

Bachina Harish Babu, M.Tech., Ph.D.
Scientific Interest: Automobile Design & Engineering.
Email:
bachina.harish@gmail.com
ORCID: 0000-0002-8520-842X