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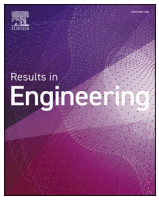

Research paper

Synergistic impact of cerium oxide nano additive along with produced-HHO gas on CI engine behaviors running with pyrolyzed waste plastic oil

A.S. El-Shafay [a], Aisha F. Fareed [b,c], Ümit Ağbulut [d,e], M.A. Mujtaba [f,*], Fahid Riaz [g,*], M.S. Gad [h]

[a] Department of Mechanical Engineering, College of Engineering in Al-Kharj, Prince Sattam bin Abdulaziz University, Al-Kharj, 11942 Saudi Arabia
[b] Department of Electrical Engineering, College of Engineering, Prince Sattam bin Abdulaziz University, Al Kharj, 11942, Saudi Arabia
[c] Department of Basic Engineering Sciences, Benha Faculty of Engineering, Benha University, Benha, Egypt
[d] Department of Mechanical Engineering, Faculty of Mechanical Engineering, Yildiz Technical University, Besiktas, Istanbul, Turkiye
[e] Department of Technical Sciences, Western Caspian University, Baku, Azerbaijan
[f] Department of Mechanical Engineering, University of Engineering and Technology, Lahore (New Campus), Lahore 54890, Pakistan
[g] Mechanical Engineering Department, Abu Dhabi University, Abu Dhabi P.O. Box 59911, United Arab Emirates
[h] Mechanical Engineering Department, Faculty of Engineering, Fayoum University, Egypt

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ABSTRACT

The gain sustainable energy from waste plastic decreases the dependence on fossil fuel. Waste plastics were converted to oil by pyrolysis which combined with pure diesel in 20 % volumetrically. Oil's physical and chemical characteristics were measured. Nano cerium oxide was added to the oil mixture at concentrations of 25, 50, and 100 ppm. Oxyhydrogen gas (HHO) was formed by water electrolysis using an alkaline electrolyser at 0.5 litres per minute. Experiments were run at engine speed of 3000 rpm and load variation. When HHO was added to pyrolysis oil, CeO_2 mixtures (P20C25, P20C50, and P20C100) improved thermal efficiency by 11, 12, and 13 % and reduced specific fuel consumption by 10, 11, and 14 %, respectively. Addition of 25, 50, and 100 ppm nano CeO_2 to pyrolysis oil with HHO resulted in notable decreases of CO concentrations by 15 %, 19 %, and 22 % about P20. There were decreases in smoke concentrations of 25 %, 29 %, and 32 %, along with notable decreases in hydrocarbon emissions of 27 %, 30 %, and 35 % for P20C25 + HHO, P20C50 + HHO, and P20C100 + HHO, respectively. Enrichment with hydroxy to oil blend that contained 25, 50, and 100 ppm of nanoparticles reduced NOx emissions by 19 %, 22 %, and 26 %, respectively. There were improvements in heat release rate and cylinder pressure for oil mixture with nano additives and hydroxy. Pyrolysis oil from waste plastic that has been enhanced with 100 ppm cerium oxide and HHO can be applied to reduce exhaust pollutants, improve combustion, and boost engine performance.

1. Introduction

Scientists have reported substantial variations in the climate in recent years. Many countries struggle to maintain energy security due to growing populations and the massive energy consumption needed to support economic growth. With an average daily production rate of 85 million barrels, the world has produced 3.9 billion tons of oil equivalent annually since 2010. Moreover, coal production reaches 3700 million tons while natural gas output is 2900 million tons [1]. Moreover, the fast industrial growth speeds up the depletion of coal and oil, fuels needed for daily human use. The main elements of petroleum fuels such as hydrocarbons, burn, release dangerous gases like methane, carbon dioxide, and nitrogen oxides. Pollutants released by burning fossil fuels lead to detrimental occurrences such as melting of glaciers, heat waves, and flooding [2]. Internal combustion engines powered by alternative fuels offer a workable answer to these environmental problems. Due to their high availability and tendency to increase in size with global population growth, plastics have emerged as a key component of alternative fuels that share characteristics with fuels derived from petroleum. Waste plastic pyrolyzed oil (WPPO) has a viscosity of 1.98 cSt, lower than diesel oil at 425 °C [3]. Waste plastic pyrolyzed oil and

* Corresponding authors.
E-mail addresses: m.mujtaba@uet.edu.pk (M.A. Mujtaba), fahid.riaz@adu.ac.ae (F. Riaz).

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Nomenclature

BSFC	Brake specific fuel consumption, kg/ kW.hr
BTDC	Before Top Dead Centre
BTE	Brake thermal efficiency, %
CO	Carbon mono oxide emission, ppm
D100	Pure diesel fuel
EGT	Exhaust gas temperature, °C
HC	HC emission, ppm
HRR	Net heat release rate, Joule/Degree
NOx	Nitrogen oxides concentrations, ppm
P20C25	Diesel oil of 80 % + pyrolysis plastic oil of 20 % with 25 ppm of ceria.
P20C50	Diesel oil of 80 % + pyrolysis plastic oil of 20 % with nano ceria of 50 ppm.
P20C100	Diesel oil of 80 % + pyrolysis plastic oil of 20 % with 100 ppm of ceria.
P20C25+HHO	Diesel oil of 80 % + pyrolysis plastic oil of 20 % with 25 ppm of ceria and HHO.
P20C50+HHO	Diesel oil of 80 % + pyrolysis plastic oil of 20 % with 50 ppm of CeO_2 and HHO
P20C100+HHO	Diesel oil of 80 % + pyrolysis plastic oil of 20 % with 100 ppm of ceria and HHO.
P_{cy}	In-cylinder pressure, bar

WPPO50 showed densities of 0.7477 and 0.7943 g/cm^3, respectively, comparable to diesel fuel [3]. The calculated calorific value was 9829.3515 kcal/kg. Experts suggested substituting pyrolyzed WPO for fossil fuel [4,5]. The feasibility of adding cerium oxide nanoparticles to diesel fuel mixtures using waste plastic oil (WPO) was studied. The increasing importance of environmental sustainability and the necessity to develop novel strategies for recovering waste plastic while increasing fuel efficiency were driving forces behind these investigations. As a practical substitute fuel, diesel-WPO mixtures have shown significant potential [6]. Engine performance, emissions, and combustion characteristics were investigated to understand of the real-world impacts of adding cerium oxide to diesel-WPO combinations [7].

Plastic products including plastic oil fuels are transformed from waste into profit via the pyrolysis process. Use of the $AlCl_3$—NaCl catalyst in the pyrolysis WP was investigated. The catalyst's faster reaction rates and lower beginning pyrolysis temperatures contributed to the pyrolysis time's reduction and increased energy efficiency [8]. Additionally, the catalyst provided in the larger oil components breakdown and decreased the initial temperature at which WPE broke, which hindered the synthesis of olefins and promoted the synthesis of simple liquid products. Researchers also assessed numerous natural catalysts and manufactured kaolin, zeolites and fly ash for the pyrolysis process [9]. Tests were carried out to assess catalyst of low-cost for plastic waste catalytic pyrolysis. The pyrolysis method for both HDPE and LDPE polymers made use of inexpensive catalysts like fly ash. Higher yield was obtained by using a catalyst concentration of 5 % than concentrations of 10 % and 15 %. Analysis of the catalyst mass fraction against reaction temperature reveals that the reaction temperature declines with increasing catalyst percentage, therefore reducing the energy input. Concurrently, the reaction time was dropped as the proportion of catalyst was increased and C15 % reacted quicker than C5 % and C10 % [10].

Combining WPO with fuel in an unmodified engine was investigated. The findings of the study revealed that diesel and WPO have thermal efficiencies at maximum load of 25.08 % and 25.91 % respectively [11]. However, when the mixture's WPO percentage decreased, the efficiency was decreased [12]. Blended WPO-diesel fuels produced higher exhaust gas temperature than pure diesel because of the poor heat release brought on by the increased blend fuel viscosity. One might explain the greater cylinder temperature by incomplete combustion. Diesel's brake specific fuel consumption (BSFC) at high loads was determined to be 0.385 kg/kWh, 40 % WPO blend, and 50 % WPO blend accordingly. With the amount of plastic oil used directly related to consumption, WPO-diesel mixtures resulted in larger fuel consumption at higher loads [13]. Efficiency of a diesel engine burning distilled WPO while taking emissions such CO_2, CO and HC were shown [14]. WPO frequently produced more unburned hydrocarbon emissions than diesel fuel owing to incomplete combustion products [15]. TiO_2-boosted biodiesel-diesel combinations were examined [14]. Using B30+100 ppm TiO_2 resulted in lower CO and smoke at both low and high loading levels. Lesser CO_2 emissions were seen at low and high loads, B30+50 and 100 ppm, respectively. At low and high loads, B30 + 25 and B30 + 100 ppm decreased hydrocarbon and NO_x emissions [16,17]. The study found that using TiO_2 nanoparticles increased sheet fluid capacity while reducing emissions due to their greater viscosity and LHV. Additionally, the researchers discovered that the nanoparticles' high activation energy encouraged full combustion. TiO_2 injections elevated combustion temperatures, which enhanced NOx emissions. TiO_2 adds to biodiesel-diesel mixtures enhances the interaction with air and rate of evaporation, therefore reducing the initial ignition delay [18]. In plastic pyrolysis oil (PPO), TiO_2 likewise shortened the length of the igniting delay time [19]. Moreover, because PPO has a LHV than diesel fuel, adding TiO_2 to it reduced the delay time and BSFC. Further research on the impacts of magnesium oxide (MgO) nano additive infusion on diesel and plastic oil blends was carried out [19]. The results show that 100 ppm is the ideal MgO dose for biodiesel mixtures to raise brake thermal efficiency. Adding more nanoparticles, though, might raise NOx emissions Cerium oxide reduced the BSFC and enhanced BTE in comparison to diesel fuel [20]. This was accomplished by increasing the fuel's exposed surface area, decreasing the ignition delay, enhancing fuel-air mixing, and oxidizing carbon deposits [21].

Among possible substitutes for conventional petroleum fuels are hydrogen, methane, and LPG. Zero carbon emissions follow from hydrogen's combustion. For decades, research on the manufacturing and storage of hydrogen gas using several techniques has been continuous. Apart from electrolysis and steam reforming of hydrocarbons, there are other methods to generate hydrogen. Water molecules are broken down into hydrogen and oxygen using direct current water electrolysis [22]. The gas produced by water electrolysis is a stoichiometric mixture of oxygen and hydrogen. Including hydrogen in an engine system causes notable changes in performance criteria and emission profiles. Still, using hydrogen for engine purposes raises questions about safety and storage. While alternative approaches demand significant space for equipment, creating hydrogen on-site by water electrolysis helps to reduce the dangers related to hydrogen storage. Oxygen and hydrogen are produced at the anode and cathode, respectively in water electrolysis. The created mixed gases with no separation produce HHO gas. HHO gas goes by several names, including oxyhydrogen, Brown's gas, hydroxyl, and hydroxy. The HHO gas contains oxygen that aids in combustion and is fit for direct application in engines [22]. Characteristics of hydroxy that could make it a viable fuel replacement in the future were investigated [23]. An injector to deliver the hydrogen at 3 bar pressure into the input manifold of CI engine was added. Before the gas was delivered to the engine, it passed through a wet-type flame arrestor, a flashback arrestor, and a mass flow meter. Solenoid valve control allowed the injection durations 3.3 ms, 6.6 ms, and 9.9 ms to vary. BTE rose nine percent. While a 20 % average decrease in hydrocarbon (HC) emissions was noted, NOx and smoke were lessened by three percent and fourfold, respectively, relative to clean diesel [24].

An investigation was conducted on a diesel engine running in dual-fuel mode with a hydrogen-diesel mixture at varying loads of 25 %, 50 %, 75 %, and 100 %. The supplemental fuel energy contributions were 23 %, 17 %, 13 %, and 10 %, respectively. Hydrogen in dual-fuel mode showed optimal injection time and duration of 5 °CA before

TDC and 30 °CA, respectively [25]. In hydrogen and diesel operations, NOx emission at high torque was identical, while the engine's BTE increased by 17 %. Comparing average smoke emissions to pure diesel, there was 40 % reduction. The effects of adding TiO_2, carbon nanotubes, aluminum oxide, cerium oxide and copper oxide to diesel were evaluated at concentration of 100 mg/litre [33]. The energy contribution from hydrogen was fixed at 20 %. Significant fuel properties did not significantly change during the 25 %, 50 %, 75 %, and 100 % torque levels of the CI engine experiment. Overall running circumstances and fuel composition, cylinder pressure was improved [26]. HHO gas was fed into a spark-ignition (SI) engine under 2 bar pressure. The gases were blended in a mixing chamber, and the gas temperature entering the carburetor was monitored by a temperature controller. BTE grew by 1.2 %, while the indicated mean effective pressure (IMEP) rose by 5.6 % with an air-fuel ratio of 0.92–0.94 [27]. In normal operation, a 3 % increase in BTE and a 17 % rise in IMEP came from raising AFR from 1.18 to 1.20. It is imperative to properly evaluate and reduce the constraints related to the usage of these technologies if one wants to attain both operational safety and environmental advantages [28].

The use of HHO in diesel and diesel-WTPO processes has reduced HC and CO emissions. The fact that H_2 and O_2 in HHO contribute to improved combustion efficiency explains this. Operating diesel fuel in a dual fuel mode with HHO has a greater environmental and economic impact than running diesel, even though using diesel/WTPO blends with HHO helps to lessen those effects [29]. With the exception of NOx, the addition of hydrogen improves combustion parameters, engine performance, and emissions. In particular, cylinder peak pressure and HRR have increased by roughly 6–10 %, BTE has improved by 16–20 %, and BSFC has improved by 5–7 %. Additionally, HC and CO emissions have decreased by 13–16 % and 11–13 %, respectively. On the other hand, NOx emissions have increased by 6–9 %. Adding green hydrogen to waste tire-derived pyrolysed oil and biogas mixes improves engine performance and lowers emissions, suggesting a promising route for environmentally friendly transportation fuel [30]. Additionally, since their fuel characteristics were found to be similar to those of regular diesel fuel, this study investigated the feasibility of using waste tyre pyrolysis oil blends with hydrogen as fuel in compression ignition engines without any changes. The findings showed that adding hydrogen to waste tyre pyrolysis oil enhanced combustion and decreased toxic petrol emissions, which is encouraging. Even though waste tire pyrolysis oil had a lower heating value than diesel, the results showed that hydrogen could be added to the engine's inlet manifold to efficiently increase this heating value [31].

Recent years have seen an increase in global environmental worries and the demand for the sustainability in energy resources, which has oriented the fuel researchers to look at alternative fuels and additives that might increase internal combustion engine efficiency and reduce emissions. Search about appropriate and environmentally safe fuel additives that increase engine performance while reducing harmful emissions are the main challenges in this regard. Waste plastics were converted to pyrolysis oil by the pyrolysis technique. Energy and environmental problems are resolved by recycling waste plastic into pyrolysis oil that can be utilized in engines. P20 offers a reasonable compromise between lowering the need for major engine changes and permitting adequate fuel characteristics. The majority of research employs CeO_2 in conjunction with biodiesel; however, because of its heavier composition and more complicated combustion, this study uses pyrolysis oil, which is innovative. Engine combustion and emissions are affected using nano particles infused with hydroxy gas. Application of nanoparticles can improve the base fuel's evaporation, thermal characteristics and heat transfer. The uniformity problems of fuel-air mixture have been caused by with the atomization and vaporization difficulties of pyrolysis oil. Higher density and viscosity of pyrolysis oil produce the problems in fuel filters and injection system. Addition of nano additives solves these problems in climate condition. The disposal of waste plastic has a great impact on the economy and environment. Ceria improves the oxidation of HC, CO, and smoke inside the combustion chamber by acting as a catalytic oxygen carrier. By lowering local temperature spikes, it lessens the production of NOx. In order to address these issues, oil was recovered from low-cost waste, proving that it might be a useful and lucrative energy source. HHO gas, waste plastic pyrolysis oil, and nano cerium oxide additives are specifically combined and integrated as part of a blended fuel in this work, which is innovative. These three components as HHO gas, nano CeO_2, and 20 % pyrolysis oil-diesel blend were examined for their synergistic impacts on diesel engine performance, combustion characteristics, and emissions under various operating situations. The high diffusivity and flame speed of hydrogen in the HHO gas demonstrate this. Furthermore, by integrating waste-derived fuel with environmentally friendly additives in an effective combustion system, the work supports the continuous global drive towards sustainable energy solutions. HHO gas encourages leaner, more thorough combustion, speeds up flame propagation, and shortens ignition delay. The premixed combustion phase is enhanced by HHO. Engine wear is decreased and combustion is improved when pyrolysis oil, nano additive, and HHO are combined. The combination is unique in managing a clean-burning, fast-igniting alternative sustainable fuel. At different concentrations of 25, 50, and 100 ppm, nano materials were added to mixtures of crude diesel and plastic oil (20 % volume ratio). Vital goal of this study is to improve the ignition, thermal, heat transfer and combustion properties of cerium oxide nanoparticles at various concentrations. Inclusion of nano materials improve catalytic reactivity and surface/ volume ratio about without additives. Hydroxy gas was produced using dry electrolyzer and injected into the air intake manifold at rate of 0.5 liters/minute. The purpose of this work is to show how variations of cerium oxide doses mixed with hydroxy gas affect diesel engine performance, combustion, and exhaust pollutants. Various parameters like BSFC, BTE, Exhaust gas temperature (EGT), cylinder pressure and heat release in addition to NOx, CO, HC, and smoke concentrations were evaluated.

2. Materials and methods

2.1. Pyrolysis oil production

A circular electric heater, condenser, an oil tank that is cylindrical, and thermocouple that is attached to a digital temperature controller make up the plastic oil producing rig. Stainless steel was utilized in the building of the tank to avoid corrosion and any chemical interactions with the produced oil. Moreover, it was designed to withstand 500 °C of temperature. The tank has a circular base and can hold two to five liters by volume. To minimize heat loss, the tank was completely isolated. Pyrolysis was done in a specially rotating reactor at temperatures between 400 and 500 °C using inert gas as nitrogen. The pyrolysis process in the reactor took 120 min. Plastics were heated to a molten state within the reactor. To elevate the waste during the pyrolysis process, an electric heater in the form of circular of 1500 Watt was fastened to the oil tank. Mass of waste plastic was evaluated to determine the reactor's size. Baffles were installed inside this reactor to ensure even heat distribution. Instrumentation was installed in the reactor to regulate the internal temperature as well as the spinning speed. By using an electrical motor to drive reduction speed gearbox, the cylindrical reactor was able to revolve at low speed. The condenser and reactor pipework are connected with Teflon connection to prevent leakage. A digital temperature controller and K-type thermocouple were utilized to monitor and regulate the heating temperature during the pyrolysis process. Fig. 1 shows the plastic oil production process.

The condenser, heat exchanger, condenses the oil and transforms it from a gaseous to liquid phase. Heat exchanger of counter flow shell and tube type was employed to provide greater heat transfer about parallel flow. Thermocouple (k) was used to record the condenser's input and output temperatures. The cooling water has a pressure of 1 bar. Three to six hours are needed for the pyrolysis process to be completed. The

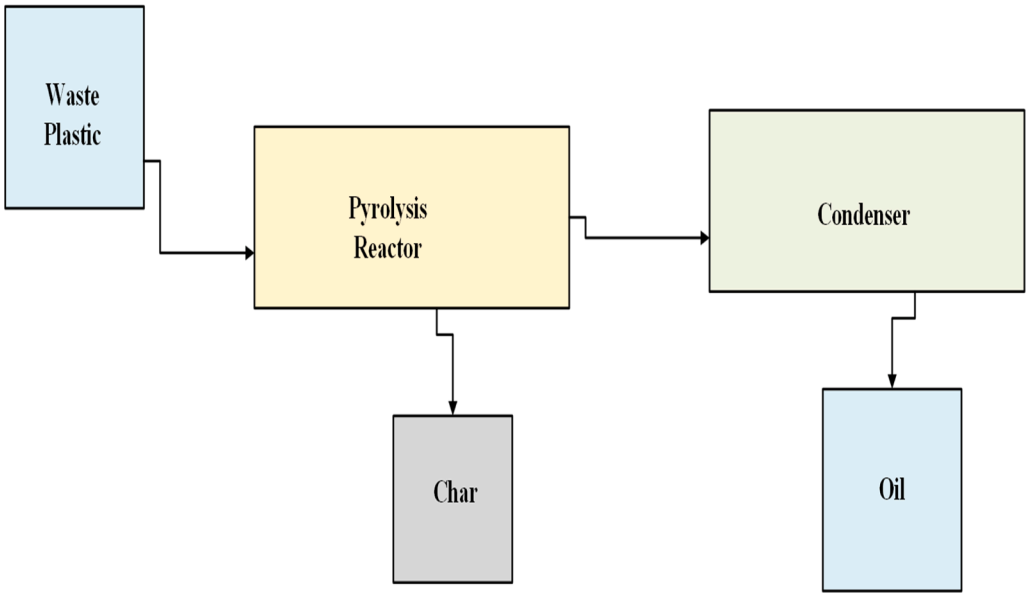

Fig. 1. Pyrolysis oil production process.

reactor's produced vapor was condensed and collected in the receiving flask after the reaction was complete. This condensate is colored yellow and is referred to as pyrolysis oil. The very viscous, black remnants from the pyrolyzed oil precipitate in the reactor's bottom and are commonly referred to black carbon. The resulting vapors can be burnt straight away or condensed into liquid oil. Nitrogen gas was fed into the reactor to purge the air. The generated vapor was driven into the condenser by the use of nitrogen gas.

The feedstock utilized was waste Low-Density Polyethylene (LDPE). Before processing, the plastic trash was cleaned and shred into tiny flakes. The reactor has 2 kg electrical heating capacity and is a continuous fixed bed. Under vacuum, nitrogen was used as a purified inert gas. 10 to 15 °C per minute was the heating rate. At a rate of 12 °C per minute, the pyrolysis was carried out at 470 °C. With 20 % gas and 15 % solid char, the average pyrolysis oil production was 65 % by weight. To eliminate moisture, the generated oil was filtered and dried for two hours at 110 °C. One kg of LDPE plastic shreds was pyrolyzed for 180 min at 470 °C. Char weighed 130 g, non-condensable gases weighed 250 g, and liquid oil weighed 620 g 87 % of the mass was lost overall.

There are some variables affect the yield and quality of pyrolyzed plastic oil. Oil output and quality are influenced by the type of plastic feedstock. More oil is produced by polyethylene and polypropylene. Higher aromatic content is often provided by polystyrene. Lower-quality oil is produced via polyvinyl chloride. Utilizing a catalyst lowers the necessary temperature and affects composition. The type of reactor that is use as batch, fluidized bed, and rotary kiln affects residence duration and offers varying heat transfer efficiencies. Hydrocarbons with a short residence period may be lighter and more volatile. Gas output may rise with time. The pyrolysis temperature influences on the oil yield. The suggested temperature range (400–500 °C) for pyrolysis has a significant impact on oil yield. The pyrolysis temperature has an impact on the oil yield. Light hydrocarbons and highest liquid production are observed at temperatures between 400 °C and 450 °C. Some waxes or heavy hydrocarbons may remain after incomplete cracking. The oil yield somewhat declines beyond that range. Long-chain hydrocarbons, waxes, and paraffins are more prevalent at lower temperatures. The physical characteristics of the generated oil are influenced by the pyrolysis temperature. Although they may lessen stability, high temperatures enhance combustion characteristics.

LDPE waste plastic type was used from commercial packaging. Food contaminants were eliminated. These plastics were washed, dried, removed metals and shredded. To guarantee uniformity in the oil yield and content, each pyrolysis batch was carried out three times under the same conditions. The variance in oil yield and slight variations in calorific value and flash point were caused by variations in the composition of the feedstock. In order to reduce unpredictability, a reliable source of plastic was used.

2.2. Pyrolysis oil mixtures preparation

Table 1 shows the GC–MS analysis of the pyrolysis plastic oil's chemical composition. Mass spectrum displayed peaks between 3.06 and 20.5 min of retention time. Retention time of 5.9 min was shown when the maximum peak (15.1) was seen. The primary component of plastic pyrolysis oil was Benzene, o-Cymene and 1, 2, 3, 4-tetramethyl. Inorganic and organic chemical analysis is presented using Fourier Transform Infrared Spectroscopy (FTIR) analysis. Pyrolysis oil's functional groups exhibit aliphatic and aromatic properties. Table 2 presents the FTIR analysis of the pyrolysis oil. The amines, alkenes, alkanes, phenyl rings, and aldehydes are all shown through FTIR analysis. Because pyrolysis oil's properties are near pure diesel, it was mixed with

Table 1
GC-Mass analysis of plastic oil.

RT (min)	Compound name	Area %	Molecular formula
3.00	1- Ethyl Metycylcohexane	0.9	C_9H_{18}
3.1	p- Xylene Benzene, 1, 3- dimethyl	4.6	C_9H_{10}
3.3	Propyl cylcohexane	1.02	$C_6H_{11}CH_2$–CH_2CH_3
3.6	M-Ethyl methyl benzene	1.04	C_9H_{12}
4.1	Decane	3.5	$C_{10}H_{22}$
4.7	Benzene	6.27	C_9H_{12}
5.1	Benzonitrile	2.1	C_6H_5CN
5.7	Benzene, 1, 2, 3, 4-tetramethyl, o-Cymene	15.2	$C_{20}H_{26}O$, $CH_3C_6H_4CH(CH_3)_2$
6.00	D- Limonene	5.25	$C_{10}H_{16}$
7.2	Dodecane	2.1	$CH_3(CH_2)_{10}CH$
10.3	1 H- Indene, 2, 3- dihydro-1. 1, 5-trimetyl	2.4	C_9H_8
12.1	Naphthalene, 2, 7- dimethyl	3.6	$C_{10}H_8$, $C_{10}H_6(CH_3)_2$
12.3	Quinoline. 4, 8- dimethyl	4.3	C_9H_7N, $C_{11}H_{18}$
13.2	Naphthalene, 2, 3, 6-trimethyl	4.6	$C_{10}H_8$, $C_9H_{12}O$
15.7	n-Hexadecane	3.5	$CH_3(CH_2)_{14}$ CH_3
17.6	Octadecane	2.5	$C_{28}H_{58}$
20.3	Tetracosane	1.3	$H(CH_2)_{24}H$

Table 2
Pyrolysis oil FTIR analysis.

Wave length frequency (cm^{-1})	Functional groups
650–750	C-H bend (Alkenes)
810–1050	*C = C* stretch (Alkenes)
1200–1320	*C = S* stretch (Amines)
1360–1570	C—H bend (Alkanes)
1620–1830	*C = C* stretch (Aromatics)
1910–2130	*C = H* (Phenyl ring)
2240–2570	C-H stretch (Aldehydes)
2700–2950	C—H stretch
2970–3000	*C = H* bend
3030–3150	*C = C* stretch (Alkenes)

diesel oil at 20 % volumetrically ratio as P20. Plastic oil has greater density and viscosity than diesel oil. Mixtures of pyrolysis oil and pure diesel have greater flash point and viscosity about diesel fuel. Compared to pure diesel, the oil's cetane number and LHV are lower. As indicated in Table 3, measurements of kinematic viscosity, density, LHV, and flash point were made and compared to crude diesel.

Due to increased internal resistance to breakup, bigger droplets occur after injection when the pyrolysis oil–diesel mixtures have higher kinematic viscosity than pure diesel fuel. The fuel-air mixture is less homogeneous when there is poor atomization, particularly when there is little load. Reduced spray tip penetration and slower spray velocity are the results of higher viscosity. This has an impact on fuel droplet evaporation and mixing time, particularly during the initial phases of injection. The reduced cylinder pressure and delayed combustion seen with a higher pyrolysis oil level were indicative of these atomization challenges. However, these effects were enhanced by the inclusion of CeO_2 nanoparticles and HHO gas, which improved local ignition and oxidation behavior and enhanced premixed combustion.

2.3. Preparation of pyrolysis oil with nano blends

The examination of the morphological structure and surface of the nano additives utilizing Transmission Electron Microscope (TEM) of JOEL JEM-2100 model was done. Figs. 2 (a and b) clearly display the nanoparticles images that were obtained using TEM and Spectroscopic Electron Microscope (SEM). The distribution of the nano additives in plastic oil-diesel mixture was uniform. To produce the tested fuels, nanoparticles were dispersed into the oil and crude diesel blend at mass fractions of 25, 50 and 100 ppm as 0.0025, 0.05 and 0.01 % by volume. The labels P20C25, P20C50, and P20C100 were applied to the blended oil mixtures that contained nanoparticles. These doses were specifically chosen to increase stability and show fuel imbalance, which confirming the nano additives aggregate into smaller molecules and preventing agglomeration. Using pulse rates combined with ultrasonication and magnetic stirring, the nanomaterials were dispersed throughout the base fuel while being continuously stirred for 45 min to ensure uniform dispersion. To ensure stability and uniform dispersion, surfactants as Tween-80 (1 %) and Span-80 (1 %), were added to the oil blend containing cerium oxide. TEM images unequivocally confirmed the stable homogeneity and uniform spreading of nanoparticles in the base fuel. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) were used to verify the efficacy of these stabilization techniques. The images (Fig. 2a and 2b) clearly demonstrate uniform dispersion and no discernible agglomeration of the nanoparticles in the fuel blend. Therefore, for the course of the experiment, the nano cerium oxide stayed stable, non-agglomerated, and uniformly suspended in the fuel blend thanks to the combination of physical dispersion and chemical stabilization.

Table 3
characteristics of pyrolysis oil mixtures compared to diesel oil.

Properties	Method	Diesel oil	Pyrolysis oil	P20	P20C100
Density at 15 °C, kg/m^3	ASTM D4052 [3]	835	990	850	855
Kinematic viscosity, cSt, at 40° C	ASTM D445 [10]	2.5	36	12	14
Flash point, °C	ASTM D93 [12]	72	90	80	82
LHV, kJ/kg	ASTM D224 [3]	42,000	39,500	40,750	41,100
Cetane number	ASTM D613 [10]	49	45	46	47

Cerium oxide improves combustion and encourages carbon monoxide and unburned hydrocarbons to oxidize. At lower temperatures, it improves combustion efficiency by lowering the activation energy of oxidation reactions. It serves as an oxygen buffer, holding excess oxygen and supplying it when needed. Depending on the surrounding gas environment, cerium can absorb and release oxygen, demonstrating its high oxygen storage capacity. Consistent catalytic activity is guaranteed by this capacity. In rich combustion, redox enables the release of oxygen from micro cerium oxide. During oxidizing lean conditions, it restores oxygen. This keeps the flow of active oxygen species constant, which is essential for long-term, full oxidation.

Optimal performance and emissions reduction have been shown in the literature at nano ceria concentrations between 25 ppm and 100 ppm. Catalytic improvement and long-term, safe use are observed at 25 ppm. The best balance between cost/safety and performance improvement is demonstrated at 50 ppm. The greatest NOx reduction and thermal efficiency gains were observed at 50 ppm, but 100 ppm offered no more benefit at the expense of injector clogging risk. Nanoparticles stay stable in suspension at concentrations below 100 ppm. This causes aggregation and obstruction of the filter at concentrations higher than 100 ppm. Stable suspension, safe atomisation through injectors, and little chance of ash formation or deposit building are all confirmed by the recommended concentration range. This also results in adaptation to safety regulations and emission standards related to nanotoxicology.

In order to assess the catalyst's impact at various doses and determine the recommended concentration for improved combustion and emissions performance, it was added to the fuel blend at three different concentrations: 25 ppm, 50 ppm, and 100 ppm. These levels were chosen because previous research showed that nano-additives exhibited better oxidation and thermal behavior within this range, avoiding the dangers of agglomeration or injector fouling. It should be confirmed that nanoparticles don't disrupt after-treatment systems or leave behind hazardous exhaust nanoparticle residues. It was recommended the used concentration for striking a balance between stability and performance.

2.4. HHO production

The electrolyzer configuration included the water reservoir, bubbler, electrical wiring, solenoid relay, fittings, and parallel dry cell with pulse width modulation. The cell is a rectangular of 250 × 200 mm. A flame arrestor was included to stop engine backfire. The dry cell received electricity from 12 V and 20 Ampere DC battery. Water was permitted to percolate between the spaces between the rectangular stainless steel plates of 316 L composition and clamped gaskets that made up this specific dry cell. The hydroxy gas produced by the cell, which had 9 plates, was directed towards the bubbler. The gas was fed into the air intake manifold of engine at a steady rate of 0.5 litres per minute. The used catalyst is potassium hydroxide (KOH) with 20 % concentration. HHO flow rate was determined by measuring the volume of water collected in the graded reservoir over a predetermined period of time. A schematic representation of the dry HHO electrolyser is shown in Fig. 3.

The hydrogen in HHO has a rapid flame speed and low ignition energy (~0.02 MJ/m^3). This shortens the ignition delay time by encouraging a faster ignition of the diesel-air mixture. By accelerating the premixed combustion phase, HHO raises the rate at which peak pressure

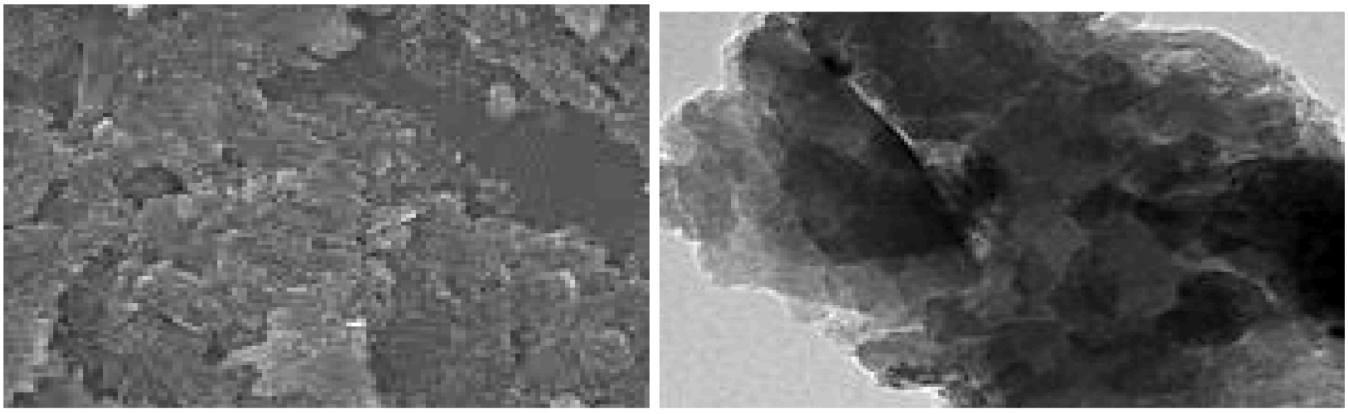

Fig. 2. SEM and TEM photos of nano cerium oxide.

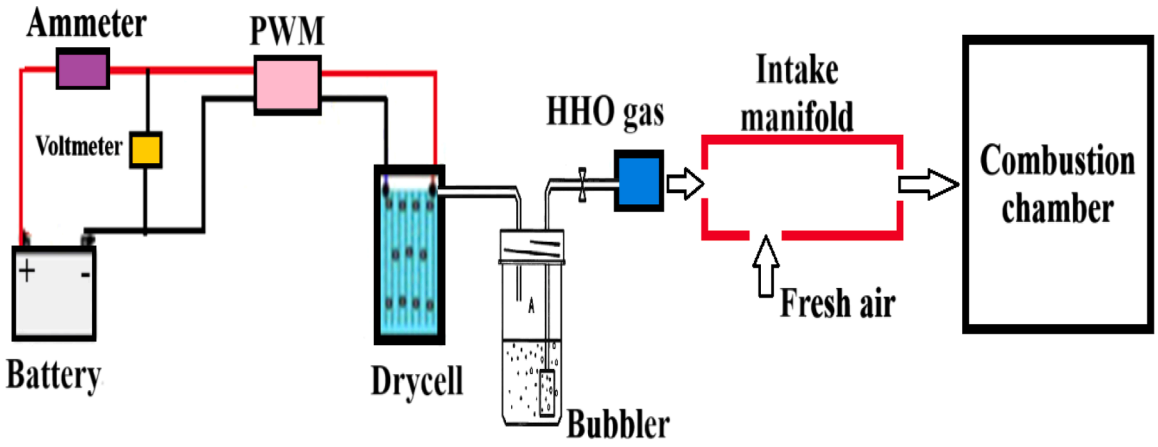

Fig. 3. Dry electrolyzer schematic diagram.

rises and enhances thermal efficiency. More thorough fuel oxidation is supported by the oxygen in HHO. Diesel oil is significantly slower than hydrogen, which has a flame speed of 1.9 to 3.5 m/s. HHO improves combustion propagation in the lean region by increasing the laminar flame speed at 0.5 L/min. Enhanced combustion resulted in lower emissions of CO and HC.

Usually, an HHO of 0.5 LPM is sufficient to maintain appropriate stoichiometry, prevent pre-ignition or knocking, and encourage more thorough combustion without throwing off engine balance. Engine size and HHO dosage should be matched. Low supply power is needed for HHO petrol at 0.5 LPM, which reduces the influence on alternator and battery life. Hydrogen is highly flammable, and excessive flow of HHO can increase backfire risk. In order to guarantee safe operation and efficient combustion enhancement without introducing excessive thermal loading or instability, HHO gas was created using dry cell electrolyzer and fed at a predetermined flow rate of 0.5 L/min. This was established through preliminary testing. For increased clarity and reproducibility, these precise values which were selected to balance catalytic activity, hydrogen enrichment, and engine compatibility are now mentioned directly in the methods section.

2.5. Experimental set up

During the testing, which involved several fuel disparities under different out power, from zero to full output power at 25 % as step size, the engine ran continuously at 3000 rpm. For the experiments, Lombardini-LDW (502-M3) diesel engine was utilized. The engine has stroke of 62 mm, bore of 72 mm, compression ratio of 22.8:1, and it is inline, 2 cylinders, 4 strokes, direct injection with water cooling. Figs. 4 and 5 display the schematic description and photographic view of test rig, respectively. A standard edge orifice on the side of the air box was utilized to evaluate the air flow rate to decrease pulsations in the air flow, and U-tube manometer was used to measure the pressure drop in the orifice. Type K thermocouples were used to evaluate the temperatures of the intake air and exhaust gases. Smoke opacity meter of OM-100 model measures between 0 and 100 % with a precision of 0.1 %, was used to evaluate the emitted smoke. Additionally, the KOEN KEG-500 model exhaust gas analyzer was used to analyze exhaust pollutants in the following ranges: HC (0 to 9999 ppm), O_2 (0 to 25 %), CO (0 to 10 %), CO_2 (0 to 20 %), NOx (0 to 5000 ppm), lambda (0 to 2) and AFR (0 to 99). Engine loads were controlled during the testing, going from zero to the maximum at a constant 3000 rpm rated speed.

To get statistically significant average values with low standard deviation, all engine performance and emission tests were conducted three times. To stabilize the engine under constant conditions, it was initially operated without load for 20 min using diesel oil before the measurements were taken. The engine was then exposed to the nanoparticle-containing oil blend P20, followed by the addition of HHO. Throughout the experiment, the rated speed was maintained at 1500 rpm while the load was varied from no load to full load. Initially, the engine was warmed up using only pure diesel fuel without any additional load until the exhaust temperature was steady. After switching to

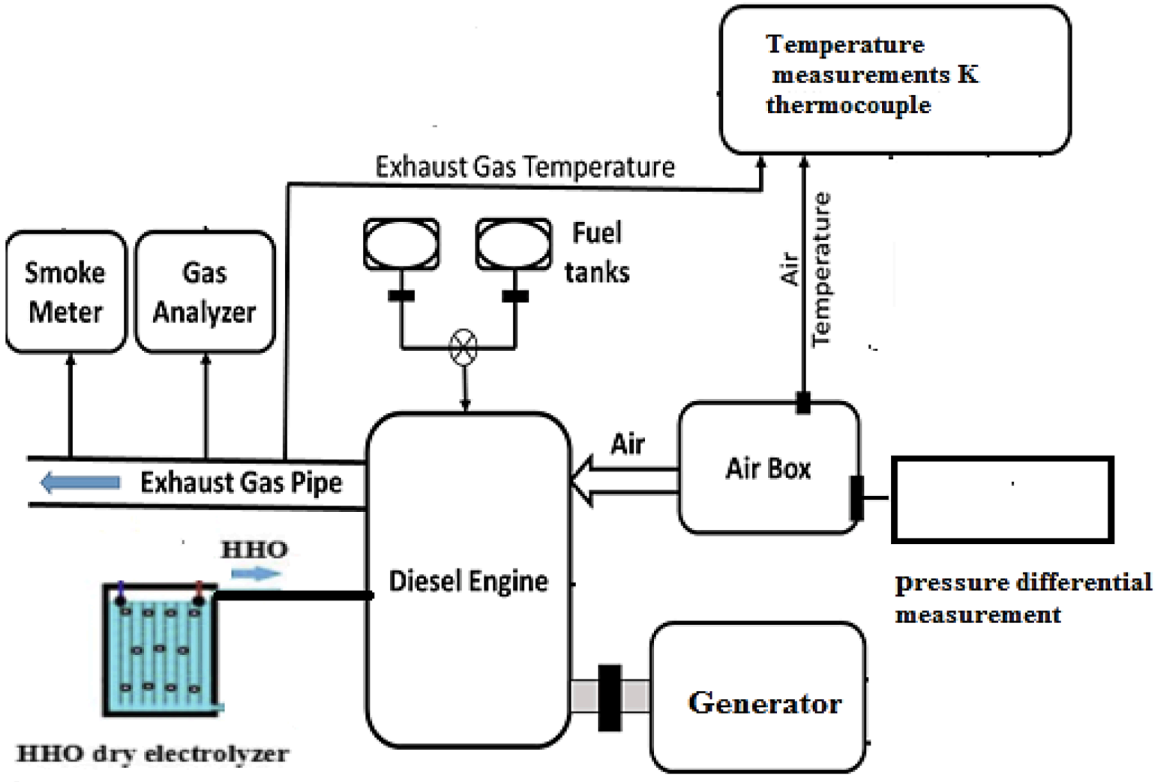

Fig. 4. Experimental setup schematic design.

Fig. 5. Test rig photographic view.

the tested fuel line, the engine load was controlled. Readings were gathered once the situation had stabilized. To make sure there were no repeatability problems, each test was conducted three times. Variable environmental variables and measurement errors frequently contribute to measurement uncertainties. Establishing the accuracy limits determined from error analysis for the measured and anticipated engine parameters is crucial, and assessing uncertainty helps assess the trustworthiness of observed values. Thermocouples have a temperature range of 0–1300 K, precision of ±1 °C, and uncertainty of ±0.15. The load indicator's range is 250–5000 W, its accuracy is ±10 W, and its uncertainty is ±0.2. Exhaust gas ranges include HC (0–20,000 ppm), CO (0–10 %), and NO (0–5000 ppm). Accuracy is 12, 12, and 0.06, while uncertainty is 0.2, 0.2, and 0.2. Pressure transducers have a range of 0–250 bar, precision of 1, and uncertainty of 2. Overall uncertainty percentage of the tests is calculated as follows:

$$\sqrt{(uTexh)^2 + (ubp)^{2.} + (usfc.)^{2.} + (uN.)^{2.} + (uthers)^{2.} + (u.CO)^{2.} + (uHC)^2 + (uNOx)^{2.} + (usmoke)^2}$$

$$= \sqrt{(0.2)^2 + (0.85)^2 + (2.2)^2 + (0.15)^2 + (1.5)^2 + (0.01)^2 + (1)^2 + (1)^2}$$
$$= \pm 3.3\ \%$$

3. Results and discussions

3.1. Brake specific fuel consumption (BSFC)

Effect of pyrolysis oil mixtures with 25 ppm, 50 ppm, and 100 ppm concentrations of cerium oxide and HHO are shown in Fig. 6. Both fuel types showed decreases in BSFC as engine load increased owing to the drop in injected volume of fuel at greater output power, which led to poor combustion efficiency. Due to its LHV regarding diesel oil, the BSFC of pyrolysis oil exceeded that of pure diesel. Oil's higher density and viscosity made it more difficult to atomize fuel, which raised the fuel's BSFC in comparison to diesel oil. Pyrolysis oil's decreased LHV, higher aromatic content and poor combustion as compared to gas oil leads to the reduced output brake power. Fuel viscosity determines the spray cone angle, which can impact combustion and fuel-air mixing. The more energy that needed to be broken, the more aromatics there were in the pyrolysis oil. By improving atomization, vaporization, and combustion properties, addition of nanomaterials to oil mitigated these issues and decreased specific fuel consumption. Presence of nano materials significantly enhanced combustion, improved evaporation and surface catalytic activity, primarily attributed to nano material's superior thermal conductivity, heat transfer and higher surface area to volume ratio. Furthermore, compared to its absence, the influence assessment of adding cerium oxide showed that the induction of the hydroxy gas within an identical load range resulted in a decrease in specific fuel consumption. Because of its improved fuel-air combination, HHO's oxygen composition promotes improved ignition and combustion [32]. Because of the improved fuel-air mixing and increased Brown gas diffusivity, BSFC decreased as a result. Because hydroxy gas is more flammable and requires less fuel due to its rapid flame speed, low ignition energy and short quenching distance, the BSFC of the tested fuels was lowered. Comparing P20C25 + HHO, P20C50 + HHO, and P20C100 + HHO to oil combination P20, the most notable drops in BSFC values were 11 %, 12 %, and 13 %, respectively. These results are

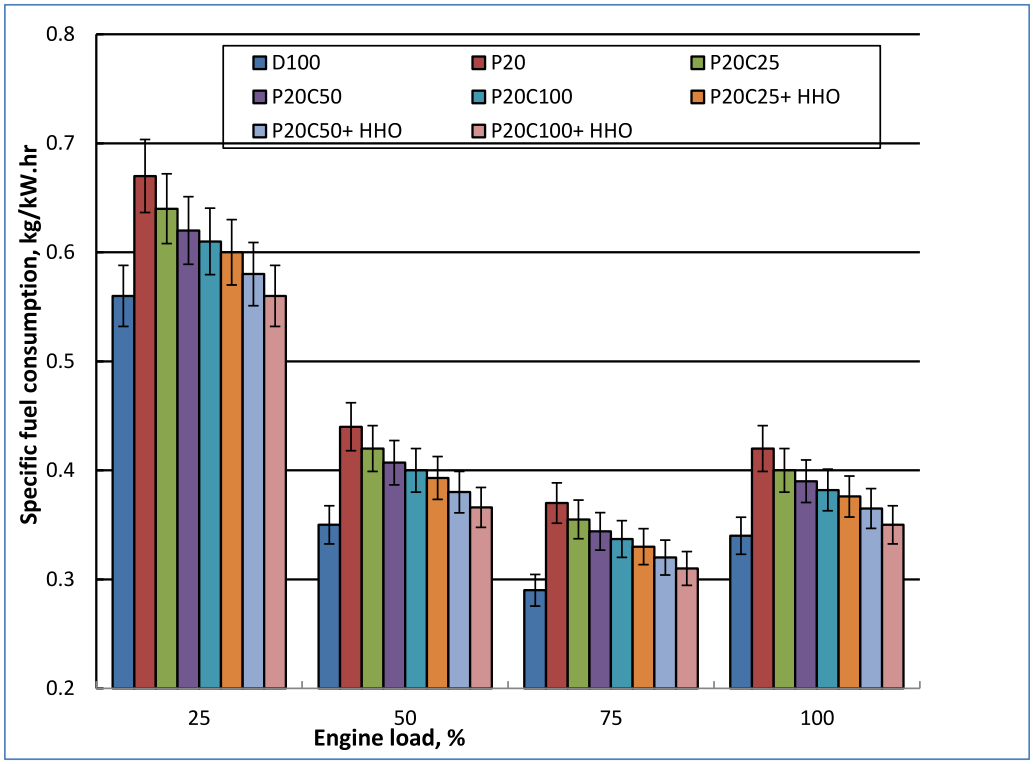

Fig. 6. BSFC of tested mixtures under at different engine loads.

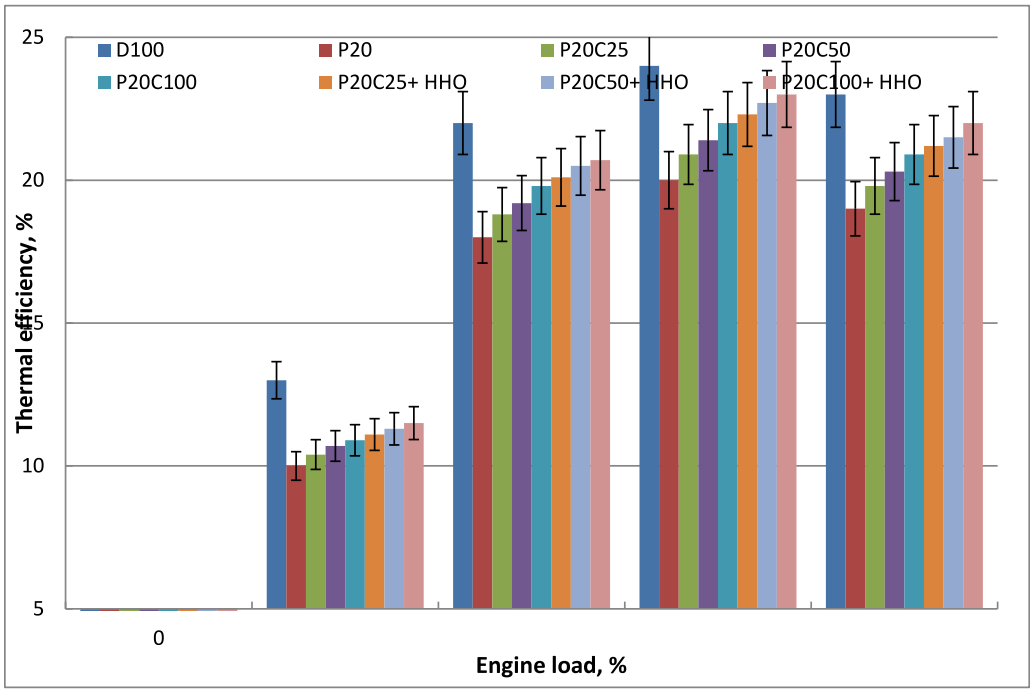

Fig. 7. Influence of nano materials and HHO on BTE and change of engine load.

consistent with previous research [33,33].

3.2. Brake thermal efficiency (BTE)

Thermal efficiency of blend of pyrolysis oil and nanoadditives enriched by hydroxy gas was shown in Fig. 7. Higher BSFC and greater fuel consumption were noted as engine load increased. Because the oil blend had higher viscosity and LHV than diesel oil, its BTE was significantly lower than crude diesel. The thermal efficiency decline is shown because of the lower volatility, reduced LHV, and increased viscosity. The thermal efficiency was decreased by improper fuel air mixing and burning characteristics. High aromatic content, high viscosity and low volatility lead to incomplete combustion and poor atomization. The thermal efficiency was declined by worse combustion and decline in the rate of evaporation. Addition of nanoparticles to the oil mixture showed significant increases in the catalytic activity, heat

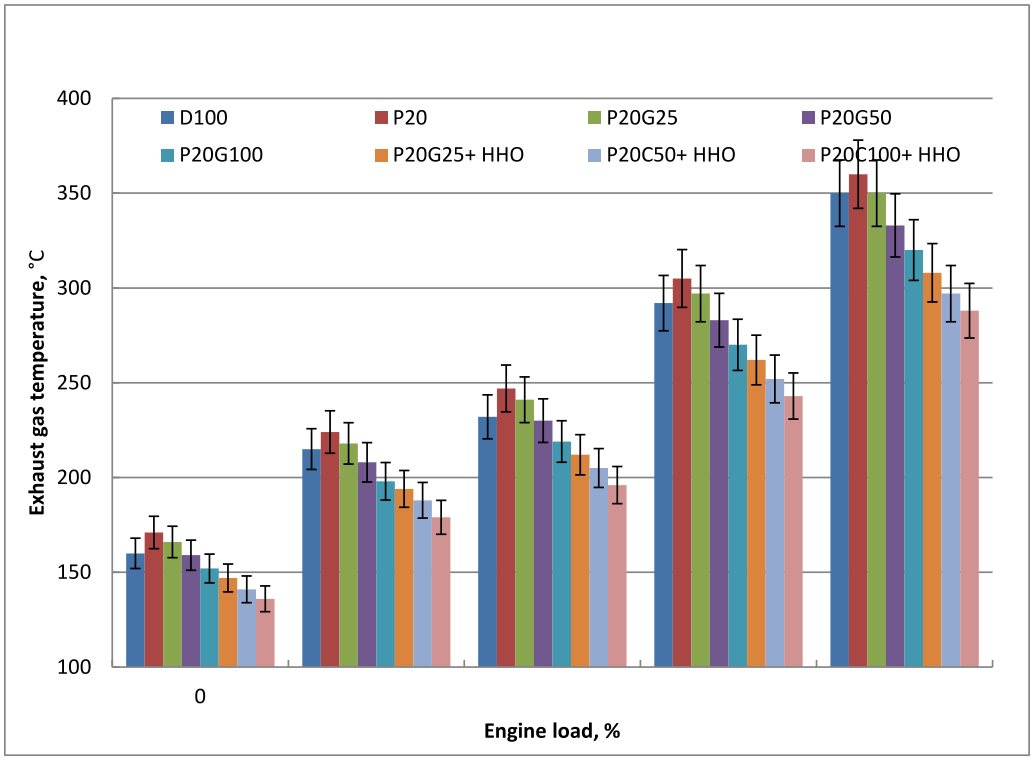

Fig. 8. EGT of the used mixtures at different output power.

transfer coefficient, heat of evaporation and fuel-air mixing. Adding nano cerium oxide reduced the vaporization time of the base fuel, improved heat transfer, and increased thermal conductivity. Ceria provides oxygen which enhances combustion, improve catalytic reactivity. Fuel droplets' enhanced characteristics made it possible for them to function as heat sinks inside the combustion chamber. Micro-explosion and secondary atomization resulted from this effect, which raised BTE and combustion efficiency. Nanomaterial's oxygen content promotes more thorough combustion by enhancing the oxidation. During the combustion process, their increased surface area and catalytic activity enable faster reaction kinetics. The fuel blend's thermal conductivity is enhanced by nanoparticles. CeO_2 improves fuel-air mixing and combustion phasing by lowering the ignition delay. The improvement in BTE was observed as the mixture's richness in the diffusion decreased. Air mixing and fuel injection are aided by HHO gas's quicker flame velocity and diffusive properties, which improve fuel combustion. The high energy content and flame speed of hydrogen in hydroxy. Because of the interaction between H_2 and O_2 atoms in the subatomic form of hydroxy gas constitute the chemical composition of brown gas greatly outperformed that of oil, improving combustion efficiency without delaying the propagation of fire. Interestingly, HHO gas had a faster flame velocity than any of the fuels that were tested. Hydrogen in HHO gas enhances flame propagation and promotes burning. HHO enhances the first stage of combustion and increases the amount of energy that may be obtained from the same quantity of fuel. Additionally, the HHO gas promotes micro-explosions and improves fuel droplet atomization, particularly in blends that contain pyrolysis oil, which helps offset its low volatility. With gains of 10 %, 11 %, and 14 %, respectively, the largest increases in thermal efficiency regarding P20 were noted at 25, 50, and 100 ppm doses of CeO_2 with HHO. CeO_2 nanoparticles and HHO gas work together to improve the engine's thermal efficiency by promoting faster and more complete combustion, reducing heat losses, and increasing pressure rise at the ideal crank angle. These effects add up to a claimed 10–14 % increase in BTE. The literature sources are incorporated with these results [34,35].

3.3. Exhaust gas temperature (EGT)

Fig. 8 explains the effect of pyrolysis oil mixture containing varying proportions of nano cerium oxide and hydroxy gas concerning EGT at different loads. The main cause of the increase in EGT was the higher engine load associated with higher fuel consumption. Because of increased heat loss and decreased thermal efficiency, the oil mixture's EGT exceeded about pure diesel. The oil combined's higher viscosity and molecular weight caused problems with improper fuel-air mixture, vaporization and atomization, which raised the EGT about diesel oil. As the mixing ratio of pyrolysis oil grew, so did the exhaust gas temperature. Slow flame propagation and high aromatic content lead to improper combustion. Delayed combustion and LHV of the pyrolysis oil results in less heat transfer, more losses in higher transfer and higher EGT compared to diesel oil. However, the drop in EGT was caused by the introduction of nanoparticles to the oil blend. Because of the substantial drop in energy density and reduced post combustion losses, the use of nanomaterials greatly improved the catalytic activity and combustion characteristics which assisted in lowering exhaust gas temperature and heat loss. The surface area to volume ratio was increased as a result of catalytic oxidation and the inclusion of nano additives. Lower EGT was the outcome of increased thermal efficiency and decreased fuel consumption. Because nano cerium oxide has better heat transfer and thermal characteristics, it allowed for lower EGT. The lean mixture phenomena brought on by the presence of HHO and the diffusion mechanism's diminished capacity to produce rich mixing zone also had a role in the exhaust temperature drop. HHO addition enhances combustion initiation and flame propagation. Hydroxy's rapid flame and high oxygen concentration improved combustion, increasing diffusivity and reducing heat loss from exhaust gases. Residual heat is decreased as more energy is used for mechanical work. With regard to oil blend, the most significant EGT decreases were 12 %, 15 %, and 18 % for P20C25, P20C50, and P20C100 with HHO, respectively. These results are consistent with the inferences made from earlier literature sources [36, 37].

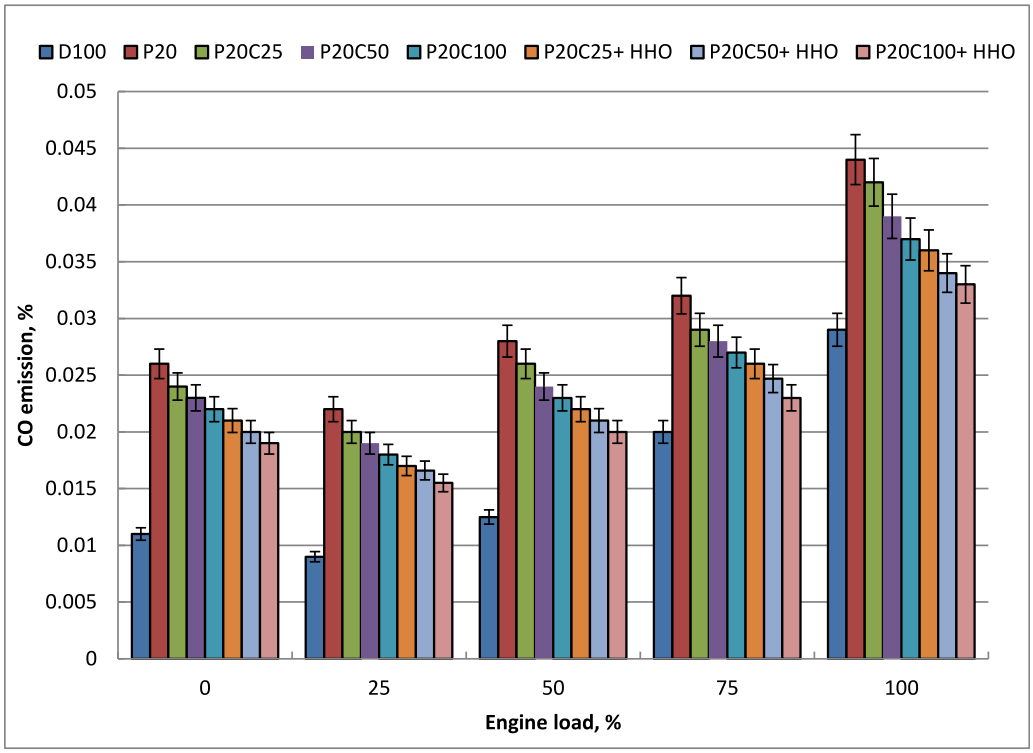

Fig. 9. Influence of nano additives with hydroxy on CO concentrations.

3.4. CO emissions

Fig. 9 shows the carbon monoxide concentrations results of the plastic oil containing cerium oxide nano additives with hydroxy at engine output power variation. Owing to the fuel consumption increase and air-fuel richer combination, CO concentrations were increased with higher output power while decreasing at lower loads. Because of its incomplete combustion, poor atomization and high viscosity, pyrolysis oil usually emits more CO than diesel oil. Carbon monoxide was increased as the result of pyrolytic oil's volumetric blending ratio increasing. Because pyrolysis oil has higher viscosity and density than diesel oil, it has low volatility and improper fuel-air mixture, which contribute to the increased of CO emissions. The reasons for increased CO emissions include increasing aromatic content and degradation of combustion. Pyrolytic oil has greater carbon: hydrogen about diesel oil [3,12]. For the same energy output, more carbon must be converted from carbon to CO_2. Improved ignition properties, improved combustion, improved fuel-air mixing, and increased catalytic reactivity were all brought about by the addition of nanoparticles. This development led to shorter burnout periods and fewer CO emissions because of the nanoparticles' improved heat transfer capabilities. CO's residence duration in the combustion zone is decreased with ceria. Larger surface area to volume ratio and improved chemical reactivity of nanomaterials greatly aided in the CO emission reductions that were seen. Additionally, cerium oxide demonstrated improved heat transfer to base fuels, increased evaporation rate, and enhanced thermal conductivity. Furthermore, the conversion of CO into CO_2 was aided by the strong redox-activity of nano additives. Because HHO petrol has higher oxygen, hydrogen contents and better combustion properties than P20, it resulted in lower CO emission concentrations. By adding hydroxy gas, carbon emissions were reduced and combustion efficiency was improved. Shortage of carbon in hydroxy gas was the cause of decreased CO emissions related to pure diesel. Injection of Brown gas enhanced fuel-air mixing, burning, flame propagation acceleration and combustion efficiency. Regarding the oil mixture, there were significant decreases in CO emissions of 15 %, 19 %, and 22 % for P20C25 + HHO, P20C50 + HHO, and P20C100 + HHO, respectively. These results are consistent with similar patterns found in other studies [33,38].

3.5. NO_x emissions

Fig. 10 shows the impact of mixing 20 % oil blend with hydroxy and nanomaterials on the levels of nitrogen oxides. Larger NOx emissions are caused by higher cetane numbers, higher adiabatic flames, and higher cylinder temperatures. Because of the increased fuel-air blend ratio, NOx concentrations increased as engine output power increased. Nitrogen oxide concentrations were higher in oil with higher oxygen content than in diesel oil. Percentage of pyrolysis oil increased, which in turn caused the increase in nitrogen oxides percentages in relation to diesel oil. Because pyrolysis oil has lower cetane number, it has worse ignition and combustion characteristics. The increased NOx emissions are caused by the pyrolysis oil's greater aromatic content. The increased adiabatic flame temperature was caused by the tire oil's ring structure. Increased fuel injection time, premixed combustion, and NOx emissions were all encouraged by the ignition delay increase. The increases in NOx emissions were because of the pyrolysis oil's increased nitrogen content related to diesel oil. Nevertheless, NOx concentrations dropped when P20 was exposed to nanoparticle concentrations of 25 ppm, 50 ppm, and 100 ppm cerium oxide. Nanoparticles significantly improved heat transfer, fuel droplet atomization, and combustion, speeding up combustion to yield less hydrocarbons and active radicals, which in turn reduced NOx emissions. Compared to base fuel, the nano additive's capacity to enhance evaporation rate, heat transmission, and combustion helped to lower NOx concentrations. The largest decreases in NOx emissions were associated with higher percentages of nano cerium oxide [13]. The reduction in NOx production was caused by improved air-fuel rate mixing and air entrainment in the nano oil mixture. Hydroxy gas's improved combustion because of the presence of O_2 and H_2 decreased NOx emissions. Reduced NOx emissions were caused by cooler cylinders and faster hydrogen burn rates. The decrease in NOx emissions was facilitated by the HHO gas's enhanced premixed flame burning and quicker flame. It was demonstrated that using HHO gas reduced NOx

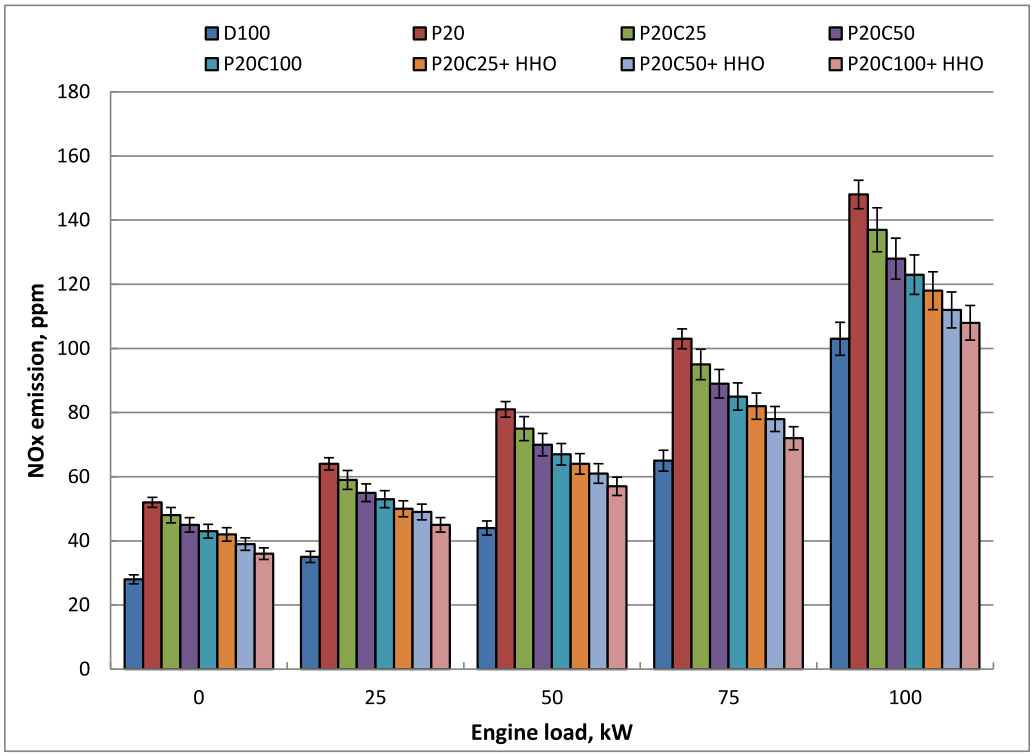

Fig. 10. Various loading analyses of NOx values for HHO and nanoadditives.

emissions. Adiabatic flame temperature was decreased when brown gas was added to the fuel, there was more air than needed, which caused significant NOx concentrations. As an oxygen buffer, CeO_2 stores oxygen in lean zones and releases it in rich zones. This reduces local hot patches where NOx is most likely to accumulate and promotes more uniform combustion. CeO_2 functions as a micro heat sink by absorbing some of the heat. As a result, NOx production and peak flame temperature are decreased. Hydrogen has a faster flame speed in HHO. It reduced igniting latency and enhanced responsiveness. It causes combustion to occur earlier. Faster combustion, lower cylinder and flame temperatures, and reduced NOx are the results of combining CeO_2 with HHO. HHO gas has low ignition energy and high flame speed. This result in rapid burning and a shorter ignition delay. Instead of the diffusion phase, more energy was released in the premixed phase [33]. HHO enhances the pyrolysis oil's turbulence and atomization. Reduced NOx and residual oxygen at high temperatures are the results of improved mixing and more thorough combustion [34,35]. By minimizing the ignition delay, HHO and CeO_2 help to spread combustion more evenly and lessen temperature spikes. Combustion occurs early and more quickly with HHO and CeO_2. NOx has less time to build because the in-cylinder gases don't remain hot for as long. Faster and more thorough combustion is encouraged by HHO and nanoceria. This lessens local fuel-rich areas, which frequently result in hot spots where NOx is produced. Peak NOx production zones are reduced as a result of more consistent and controlled combustion [33,35]. Fuel consumption was reduced as a result of the addition of HHO. In comparison to P20, NOx concentrations were decreased by 19 %, 22 %, and 26 %, respectively, when nanomaterial at 25, 50, and 100 ppm blended with HHO was added to pyrolysis oil. These results support the continuous pattern of NOx emissions and are consistent with previous research [37,39].

3.6. HC emission

Fig. 11 illustrates the effect of oil combination containing nano materials and HHO on hydrocarbons. Because of the reduced oxygen percentages and greater consumption of fuel brought about by elevated loads, there were more HC emissions. Because of the larger droplet size and less airborne fuel injection penetration, HC emissions rose with the pyrolysis oil ratio increase. Higher HC emissions were the outcome of the fuel vaporization and atomization issues. Hydrocarbon production was increased by the pyrolysis oil blends' greater aromatic content due to the greater density, poor atomization, declined LHV, and higher viscosity. Higher HC emissions and flame quenching at the combustion chamber walls were caused by inadequate fuel volatility, low volatility and incorrect atomization. By acting as a catalyst, nanoparticles increased the oxidation of hydrocarbons and, consequently, the efficiency of combustion. This also is due to the active oxygen during combustion. Use of nano additives dramatically improved ignition and fuel-air mixing in comparison to base fuel, exhibiting a micro-explosion event. Cerium oxide's higher thermal conductivity caused fuel molecules to heat up more quickly, which increased the pace at which they evaporated. The nanoparticles improved the blend's surface-to-volume ratio, vaporization, and catalytic activity of oil. Due to the impact of the nano particles, this led to shorter burnout time and less late combustion, which in turn reduced hydrocarbon emissions. HC concentrations can be decreased by improved fuel oxidation, high flame speed, increased O_2 content brought in by hydroxy from the air intake. Hydrogen shorter quenching distance and increased flammability extension produced lower hydrocarbon concentrations. Compared to without hydroxy, higher hydrogen diffusivity and flame speed are the causes of reduced HC emissions. Hydrocarbon concentrations were decreased when the hydroxy gas's carbon content was decreased. In comparison to pyrolysis oil, P20C25 + HHO, P20C50 + HHO, and P20C100 + HHO showed notable decreases in HC emissions of 27 %, 30 %, and 35 %, respectively. These findings are consistent with the patterns observed in the literature [33,40].

3.7. Smoke opacity

Smoke emissions from crude diesel, oil mixtures containing nano cerium oxide, and HHO are depicted in Fig. 12. A richer air-fuel mixture and higher fuel consumption that accompanied higher engine loads were the causes of the higher smoke percentage. The oil mixture's longer ignition delay, poor volatility and lower cetane number resulted in

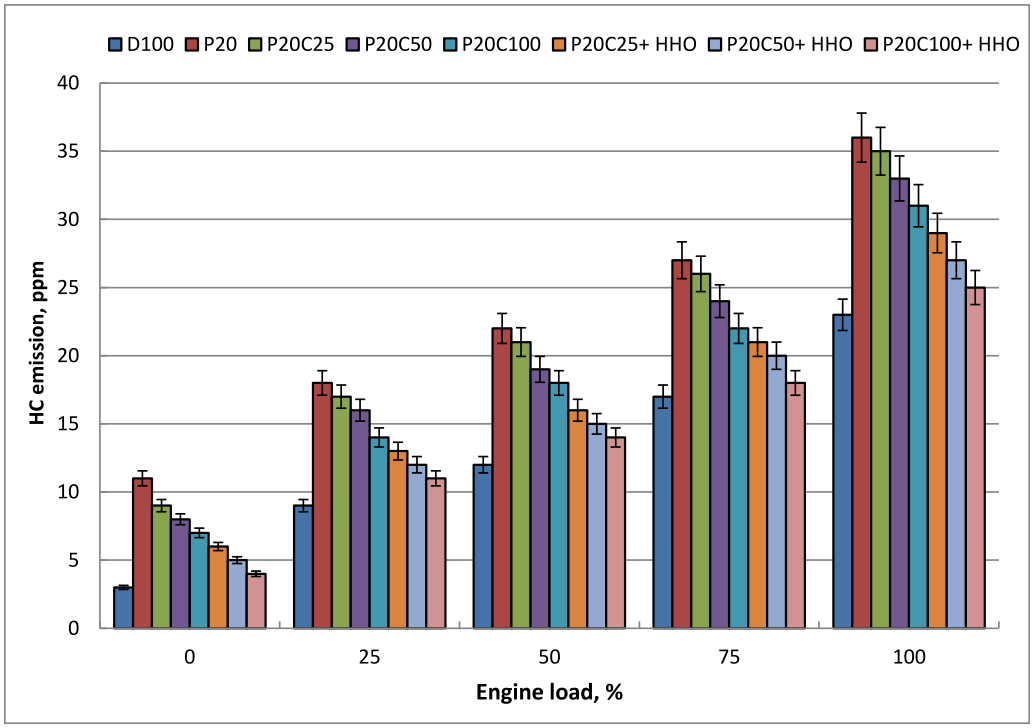

Fig. 11. Hydrocarbon concentrations of oil blend with nano additives and hydroxy at different loads.

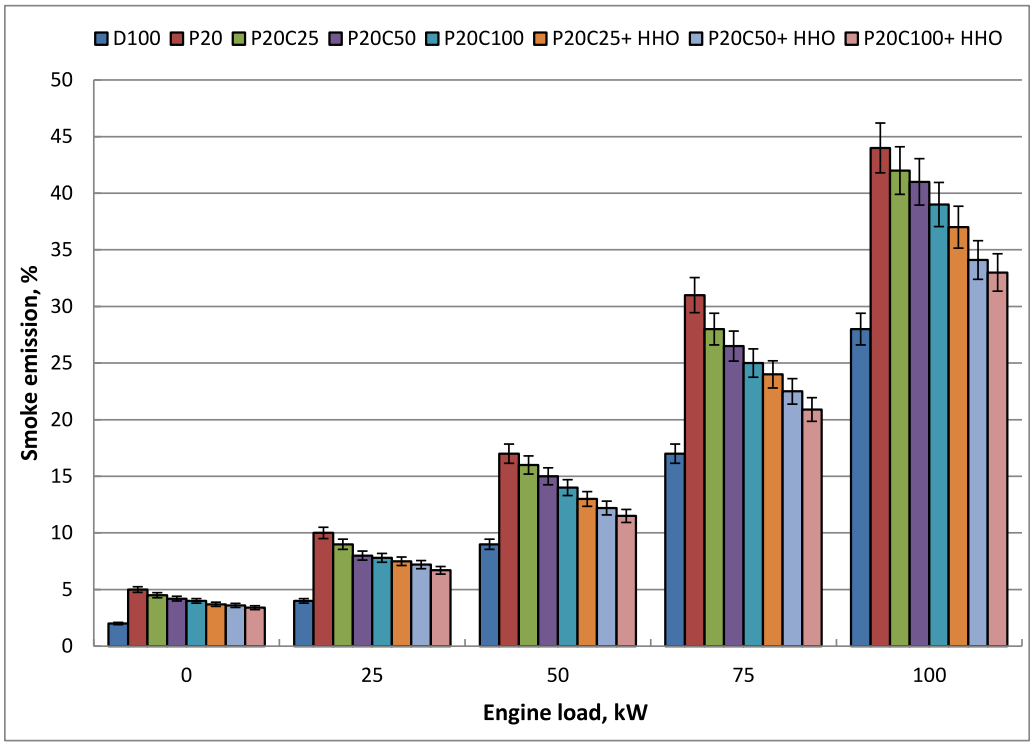

Fig. 12. Values smoke emissions of tested fuels according to the load engine.

higher smoke concentrations than pure diesel. The increased smoke was caused by the greater density, high aromatic content and viscosity of the pyrolysis oil. The smoke released from oil blends was increased with the increasing pyrolytic to diesel oil mixing ratio. Addition of ceria minimizes the buildup of carbon on injector nozzles and cylinder walls. By increasing fuel-air mixing, oxidation enhancement and fuel droplet evaporation, which in turn improved thermal conductivity, the integration of nanoparticles decreased smoke emissions. By improving the surface to volume ratio and catalytic activity reactivity, nano additive helped to increase combustion. The introduction of nanoparticles

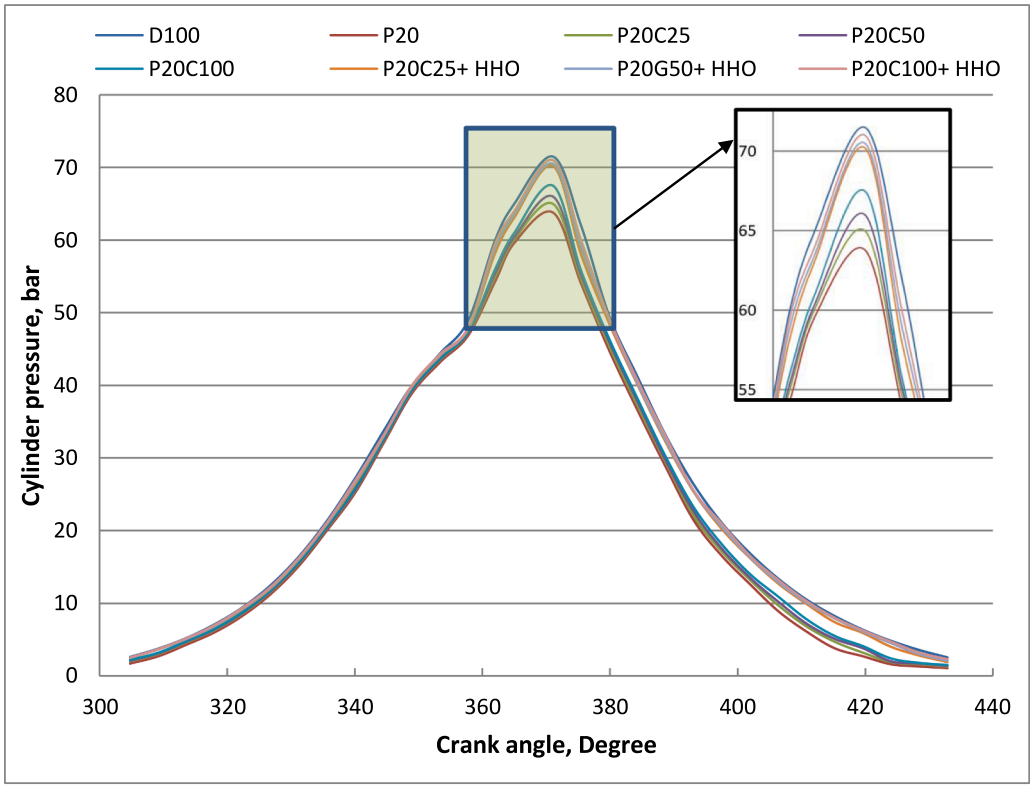

Fig. 13. Cylinder pressure of all tested fuels for oil mixture with hydroxy at full load.

increased the rate of heat transmission and evaporation, which decreased smoke emissions. Nanoparticles' increased reaction rate and catalytic activity sped up the start of combustion, which decreased smoke emissions. When combined with oil blend, HHO gas's low carbon percentage reduced smoke production and accelerated burning, while its high oxygen level encouraged quicker and more thorough combustion. The addition of HHO was linked to improved combustion, higher oxygen concentration, reduction of local rich zones and better fuel oxidation. The inclusion of oil with 25, 50, and 100 ppm cerium oxide coupled with HHO demonstrated the greatest significant decreases in smoke when compared to oil mixture. In particular, smoke concentrations for plastic oil mixtures containing 25, 50, and 100 ppm cerium oxide with HHO were reduced by 25 %, 29 %, and 32 %, respectively. The results are consistent with other published research [34,41].

3.8. Cylinder pressure

Fig. 13 displays the cylinder pressure fluctuation with crank angle for all fuels under peak load. Higher fuel burn rate in premixed combustion is due to the increased highest rate of pressure increase and peak cylinder pressure. Due to the decreased fuel usage in premixed stage, the P_{cy} of oil mixture is lower than pure diesel. Decreased peak cylinder pressure and lower rate of pressure rise were caused by the higher fuel consumed during the premixed combustion stage of pyrolysis oil. Improper air-fuel blending and worse combustion resulted in the decrease in cylinder pressure for pyrolysis oil blends about diesel oil. Greater density, viscosity and declined LHV of the oil about crude diesel lead to the cylinder pressure decrease. Poor atomization and high viscosity lead to **slow combustion**. Compared to lengthy paraffin chains, the pyrolysis oil's increased aromatic concentration requires more energy to break. Cylinder pressure of oil blends was decreased with the pyrolysis oil ratio increase. Use of nanoparticles resulted in shorter ignition delay, higher cetane number, and faster rate of burning. Improved surface area and catalytic action of the nano materials enhance the combustion properties. Addition of ceria leads to the reduction of ignition delay and burning rate acceleration. The nanoparticles enhanced the heat release rate, evaporation rate and thermal conductivity, which increased the maximum cylinder pressure. Primary cause for the greater peak cylinder pressure is the increased fuel burning during premixed combustion phase about diffusion. Because P_{max} and combustion advance earlier, the ignition delay has decreased. The hydrogen component in oxyhydrogen gas speeds up ignition. Pressure during combustion is increased by the hydroxy gas included in the oil blend. High flame speed and faster flame propagation was shown by HHO enriching. A greater cylinder pressure is a result of the enhanced diffusivity, fast flame, and low ignition energy of brown gas. Oxygen component in hydroxy is what causes the rise in flame propagation speed. Pressure inside the cylinder increased and energy release increased as the result of hydrogen's improved combustion properties and evaporation. Enhancement of cylinder pressure is due to the introduction of CeO_2 nanoparticles and HHO about P20 blends due to improved premixed combustion phase, improved oxidation under nano additive, and quicker flame propagation. Additionally, it shortens the ignition delay, which causes more fuel to burn earlier near TDC. A favorable shift in combustion phasing is shown by the peak pressure occurring earlier. In contrast to P20, which had a delayed peak pressure because of poor atomization and slower burning, P20C100 + HHO exhibited more sophisticated combustion phasing. Within the load range, no knocking tendency was noticed in the P20C100 + HHO blend, despite the increase in peak pressure. Pressure oscillations were avoided and combustion smoothness was preserved by the controlled and progressive rise in pressure, which was made possible by catalytic oxidation and homogenous combustion. Additionally, a crucial component of knocking, hot-spot development, was probably inhibited by the regulated release of active oxygen from cerium oxide nanoparticles. Increment in the peak pressures for P20C25 + HHO, P20C50 + HHO, and P20C100 + HHO were 4, 7 and 10 %, respectively at 100 % load. The findings are within good agreement to the published previous works [33].

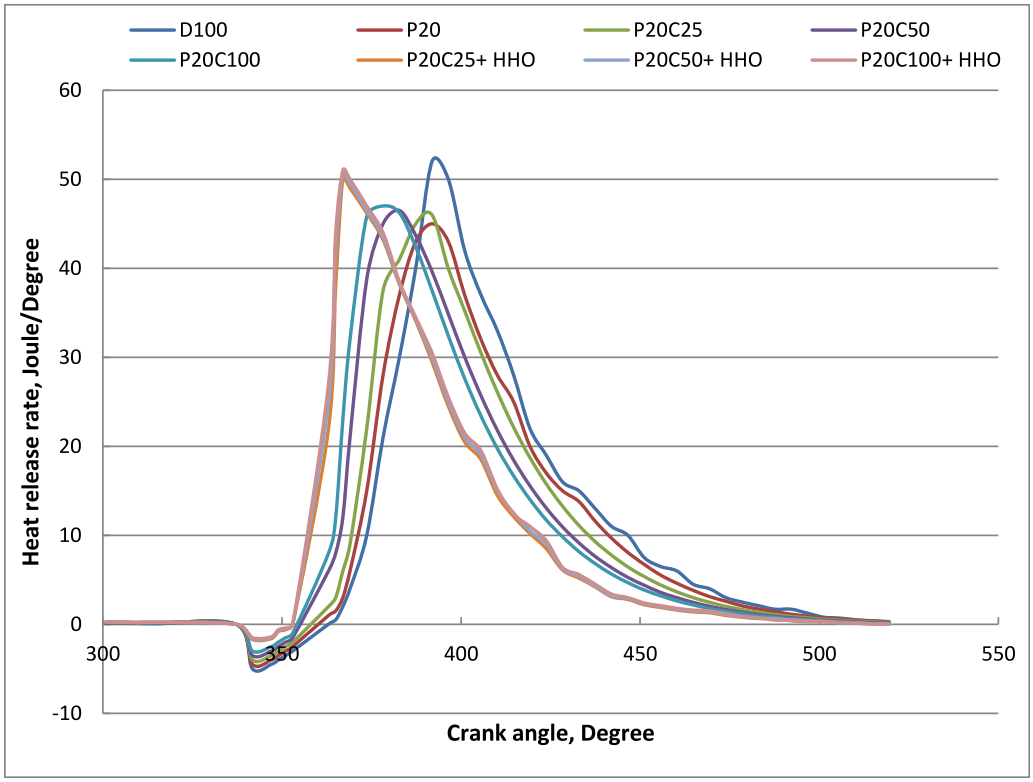

Fig. 14. HRR of oil blend with nano cerium doses and HHO at full brake power.

3.9. Heat release rate (HRR)

Fig. 14 investigates the HRR distributions of oil blend with nano additions and HHO at full load and crank angle variation. The oil mixture has a lower in-cylinder pressure and heat release rate owing to premixed combustion, which burns less fuel and ignites more slowly than diesel oil. Pyrolysis oil showed improper fuel atomization and fuel-air blending than diesel oil. Rate at which heat is released from diesel oil was decreased as the amount of pyrolysis oil increased. Catalytic reactivity and HRR both improved with the introduction of nano materials. This facilitates fuel penetration and ignition characteristics. The blended oil's reaction rate is triggered by its high surface area to volume ratio, improved heat transfer, catalytic reactivity and enhanced thermal characteristics. The more fuel in the premixed combustion, the more it contributes to the combustion process; the higher the heat release rate. As a result, adding more nanoparticles to oil mixtures tends to increase the pace at which heat is released. Improved catalytic oxidation and surface/ volume ratio was shown due to the introduction of nano additives. Brown gas ignites and burns faster than diesel oil because it has a higher flame velocity. There is a larger rate of heat release when HHO oxidation occurs more quickly. It has been shown that higher flame speeds improve combustion and evaporation. Brown gas produces higher cylinder pressure and burning velocity due to its lower ignition energy and higher hydrogen diffusivity. Premixed combustion is accelerated by the induction of hydroxy gas, leading to faster burning and combustion acceleration. Because pyrolysis oil burns more in the diffusion phase than the premixed phase, its application reduced and postponed the HRR peak compared to diesel. Higher viscosity and more aromatics cause the combustion to go slowly. Poor atomization and increased fuel buildup before to ignition are the results of a longer ignition delay. Higher HRR, better oxidation, faster flame speed, and improved fuel-air mixing at P20 are the results of combining pyrolysis oil with ceria and HHO. Because of the nanomaterial's catalytic reactivity and the lower ignition energy of HHO, the ignition delay was decreased. The enhancements in peak HRR values for P20C25 + HHO, P20C50 + HHO, and P20C100 + HHO are 5, 8 and 12 %, respectively about P20 at peak output power, which confirms with the references [33,42].

3.10. Mass fraction burned

Using the Wiebe function, the combustion process is characterized by the mass fraction burned as a function of engine crank angle. The Wiebe function is a distinctive S-shaped curve that rises from zero at the beginning of combustion to unity at the end and it was calculated from Eqs. (1) and (2). The mass of injected fuel consumed during combustion is correlated with the mass fraction burned. A flame front passes through the injected fuel at the beginning of combustion until it burns. The mass fraction burnt with crank angle at full load for HHO and nano additives with pyrolysis oil was displayed in Fig. 15. As can be seen from the figure, oil blends begin to burn earlier than diesel. Due to delayed ignition, mass fraction burned curve of P20 typically starts out slower before rapidly increasing once combustion begins. Diesel fuel begins to burn after the blends, surpassing and finishing the burning that occurred before the blends. This is because diesel has superior flammability. Burning of oil mixtures diminishes as combustion proceeds, which could be related to the oil blends' increased viscosity. Blends with higher oil content have longer combustion times. By increasing the rate of evaporation and improving fuel-air mixing, adding nanoparticles to pyrolysis oil shortened the duration of combustion and hastened the onset of combustion [43]. HHO gas reduces ignition latency, promotes leaner, more complete combustion, and accelerates flame propagation. For D100, P20, P20C25, P20C50, P20C100, P20C25+HHO, P20C50+ HHO and P20C100+HHO, the mass fraction burned at TDC is 25.5 %, 26.2 %, 27.2 %, 28 %, 28.5 %, 29 %, 29.3 % and 29.7 %, respectively.

$$X_b(\theta) = 1 - \exp\left(- a \times \left(\frac{\theta - \theta_0}{\theta_d} \right)^{m+1} \right) \quad (1)$$

$$\tau_{\max} = \frac{\theta_{\max}}{\theta_d} = \left[\left(\frac{1}{6.908} \right) \times \left(\frac{m}{m+1} \right) \right]^{\frac{1}{m+1}} \quad (2)$$

Where:

θ: Crank angle, Degree.

X_b (θ) is the burned fuel fraction at the instantaneous crank angle, a is a constant for combustion duration corresponding from 0 to 99.9 % mass fuel burned, and it is equal to 6.908,

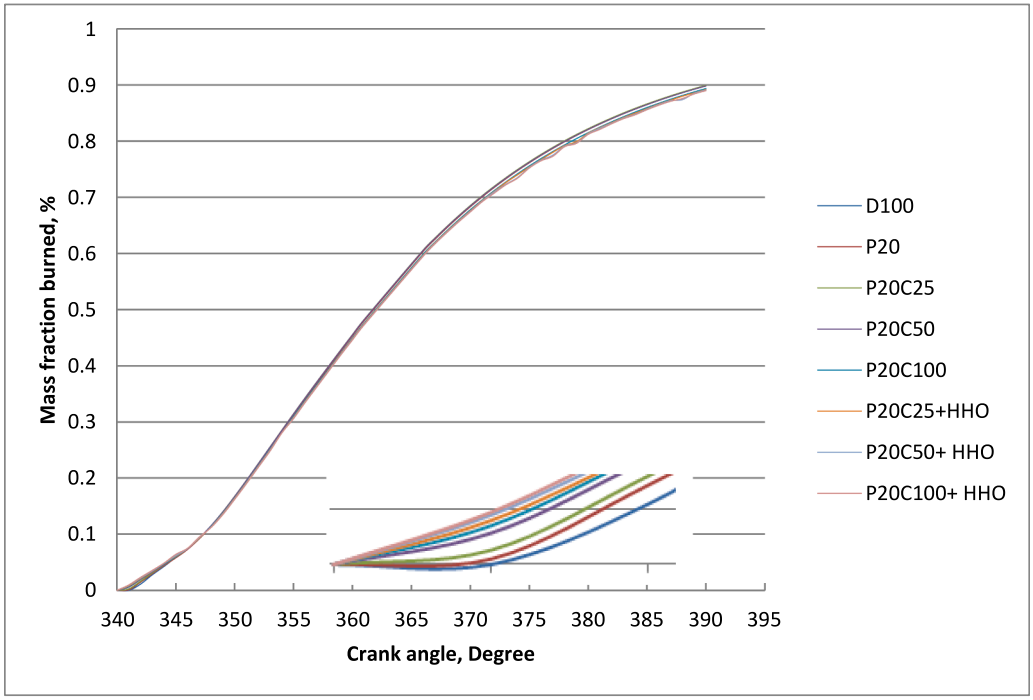

Fig. 15. Mass fraction burned of oil blend with nano additives and HHO at full load.

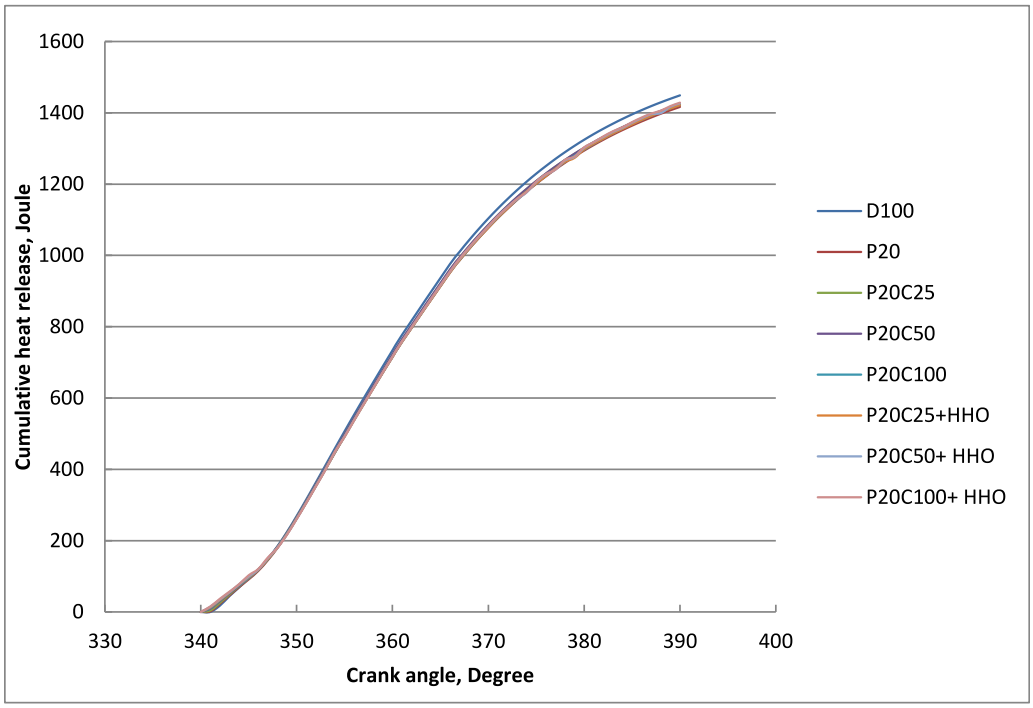

Fig. 16. Cumulative heat release of pyrolysis oil with nano ceria and HHO at full load.

θ_0 is the position of the crank at start of combustion, θ_d is the duration of combustion, and

θ_{max} is the duration from the start of combustion to the position of maximum heat release. m is a parameter that determines the speed of combustion which was calculated for different fuel blends at rated engine speed of 1500 rpm and various loading.

3.11. Cumulative heat release

Cumulative heat release offers more insight into the combustion process. The entire heat released from the fuel's chemical energy is known as cumulative heat release. Fig. 16 shows the cumulative heat emission of several blends at 100 % load as the crank angle changes. It is lower for diesel in the early stages of combustion, which could be explained by the fact that diesel burns more slowly than mixtures. Cumulative heat release for blends follows a similar pattern to diesel as combustion progresses [43]. The cumulative heat output of diesel fuel surpasses that of oil blends as combustion progresses, despite the fact that the start of combustion is delayed. For P20, the heat release curve is delayed due to poor combustion. A higher total heat release and a faster cumulative heat release are the results of adding ceria. It shows a very early and sudden increase for HHO addition, especially during the premixed period. Values of cumulative heat release were 1450, 1420, 1425, 1428, 1432, 1435, 1441, and 1445 Joule were for D100, P20, P20C25, P20C50, P20C100, P20C25+HHO, P20C50+ HHO and P20C100+HHO, respectively.

4. Comparative analysis

Pyrolysis oil's high viscosity causes issues with atomization and vaporization, which leads to the use of additives like HHO and nano materials. The viability of pyrolysis oil as an alternative fuel for diesel engines is greatly increased by the addition of nano ceria (CeO_2) nanoparticles and HHO gas to blends of pyrolysis oil and diesel. The direct use of pyrolysis oil in compression ignition engines is restricted due to its shortcomings, which include low cetane number, high viscosity, weak volatility, and incomplete combustion. However, these restrictions are successfully lessened when HHO and nano ceria are added. When combined, these additives result in a significant improvement in engine performance, combustion, decreases in CO, HC, and smoke, and noticeable rise in brake thermal efficiency. Pyrolysis oil, nanoceria, and HHO together provide a viable, cleaner-burning, and more effective substitute for traditional diesel fuel, advancing the transition to waste-to-energy and low-carbon transportation options. In comparison to oil mixture P20, Table 4 describes the emissions and engine performance of diesel engines running on P20C25, P20C50, P20C100, P20C25 + HHO, P20C50 + HHO, and P20C100 + HHO.

Table 4
Comparative differences of engine performance and emissions based on oil blend (Increases indicated by (+) and reductions by (-)).

Relative change, %	P20C25	P20C50	P20C100	P20C25+ HHO	P20C50+ HHO	P20C100+ HHO
BSFC	−3.5 %	−6.5 %	−9 %	−11 %	−12 %	−13 %
BTE	+3 %	+6 %	+8 %	+10 %	+11 %	+14 %
EGT	−2 %	−6 %	−10 %	−12 %	−15 %	−18 %
CO emission	−6 %	−10 %	−13 %	−15 %	−19 %	−22 %
HC emission	−9 %	−16 %	−22 %	−27 %	−30 %	−35 %
NO_x emission	−6 %	−11 %	−16 %	−19 %	−22 %	−26 %
Smoke emission	−8 %	−14 %	−19 %	−25 %	−29 %	−32 %
Cylinder pressure	+1.5 %	+2.5 %	+3 %	+4 %	+7 %	+10 %
Heat release rate	+2 %	+3 %	+4 %	+5 %	+8 %	+12 %
Mass fraction burned at TDC	+3.8 %	+6.8 %	+8.7 %	+10.7 %	+11.8 %	+13.3 %

5. Conclusions

In conclusion, this study aimed to produce pyrolysed oil by combining waste plastic with crude diesel and turning it into pyrolysis oil. Diesel oil and pyrolysis oil were combined at 20 % volume ratio. Using a dry alkaline electrolyser to inject hydroxy gas and integrating nano cerium oxide at ratios of 25, 50, and 100 mg/l, experiments were conducted on a diesel engine operating at 3000 rpm under different loads. The key conclusions are summed up as follows:

- Significant increases in thermal efficiency of 10 %, 11 %, and 14 % were demonstrated by blends of pyrolysis oil including 25, 50, and 100 ppm cerium oxide in addition to hydroxy addition. At the same time, they showed an 11 %, 12 %, and 13 % drop in BSFC values. Additionally, when related to the base crude oil blend, EGT for P20C25+ HHO, P20C50+ HHO, and P20C50+ HHO decreased by up to 12 %, 15 %, and 18 %, respectively.
- When 25, 50, and 100 ppm of nano cerium oxide were added to the pyrolysis oil blend, the CO was significantly was decreased by 15 %, 19 %, and 22 % but the decreases in smoke were 25, 29 and 32 %, respectively, in contrast to the P20 oil combination. After adding HHO, the oil mixture with the nano addition saw a considerable reduction in NOx emissions of 19 %, 22 %, and 26 %, respectively. With HHO addition, P20C25, P20C50, and P20C100 showed the biggest drops in HC concentrations compared to the oil combination, with decreases of 27 %, 30 %, and 35 %, respectively.
- For P20C25 + HHO, P20C50 + HHO, and P20C100 + HHO, the increases in peak HRR values were 5, 8, and 12 %, respectively, while the peak cylinder pressure increases at full load were 4, 7, and 10 %.
- For D100, P20, P20C25, P20C50, P20C100, P20C25+HHO, P20C50+ HHO and P20C100+HHO, the mass fraction burned at TDC is 25.5 %, 26.2 %, 27.2 %, 28 %, 28.5 %, 29 %, 29.3 % and 29.7 %, respectively but values of cumulative heat release were 1450, 1420, 1425, 1428, 1432, 1435, 1441, and 1445 Joule.

The use of nano cerium oxide of 100 ppm addition led to a significant enhancement in performance along with a decrease in emissions in blends of biodiesel. Furthermore, these advancements in engine performance, combustion and pollution reductions were further strengthened by the advent of HHO.

5.1. Long-term effects of using fuel blends on engine

Because of its high acidity, pyrolysis oil can contain heavy metals, sulfur, and chlorine, among other pollutants. It causes more cylinder wall deterioration and acidic blow-by gases. The greater viscosity of pyrolysis oil results in less effective lubrication. By functioning as a solid lubricant and preventing lubricating liquid from oxidizing, nano ceria lessens wear. HHO lowers blow-by and fuel dilution while increasing combustion efficiency. Ceria and HHO together decreased piston ring and cylinder liner wear related to pyrolysis oil. When pyrolysis oil is applied, deposits and residues of polymers accumulate at the tips of the injectors. Carbon fouling is the result of incomplete combustion. As a catalyst, CeO_2 lessens the accumulation of carbon residue. HHO addition decreases spray impingement, enhances fuel-air mixing, and lessens wall wetting and coking. Because of heavy molecules and incomplete combustion, using P20 produces the development of soot and hard carbon deposits. As a result, deposits on valves, injector tips, and piston crowns rise. CeO_2 increases oxidation and decreases deposit formation. By ensuring faster and more thorough combustion, HHO reduces the amount of time and temperature that carbon can accumulate.

5.2. Effect of ceria on human health

In the engine cylinder, metal oxides such as CeO_2 do not burn or combust. Even at high temperatures during combustion, they maintain their oxidised form and function as catalysts rather than reactants. Up to 2400 °C, cerium oxide remains thermally stable. Due to turbulent mixing and high surface temperatures, majority of CeO_2 nanoparticles adheres to combustion chamber surfaces, piston crowns, or valves, or remain suspended in exhaust gas as solid or agglomerated particles. If inhaled, ultrafine cerium oxide particles can cause oxidative stress and respiratory problems. Filters that can capture nanoparticles, including cerium, should be installed in engines. The fuel system's incorporation of CeO_2 nanoparticles is consistent with current after-treatment technologies that are made to absorb and use these kinds of materials. The mobility of CeO_2 nanoparticles is decreased by their propensity to aggregate into bigger clusters at high doses. In order to reduce the hazards to the environment and human health, very low dosages of CeO_2 (20–100 ppm) should be advised.

5.3. Limitations and strengths of this research

High viscosity and low volatility are characteristics of pyrolysis oil. Its use may cause tar-like deposits to build in the combustion chamber and injection system, as well as corrosion of engine parts. Over time, CeO_2 nanoparticles in the fuel blend have a tendency to aggregate, which lowers their surface area and catalytic performance. Over time, this might reduce combustion improvement by clogging injectors or filters. Long-term consequences of employing nanoparticles include engine oil pollution over time and the possibility of abrasive wear if the particles are not completely combusted or filtered. Because HHO gas is unstable in storage, it should be produced on board. Nanoparticles need to be dosed precisely and are costly. The need for a specialized HHO generator raises the engine's electrical demand, weight, and system complexity. Because hydrogen is extremely combustible, leaks could result in explosions if not controlled.

Problems in atomization and vaporization of pyrolysis oil are minimized by the applications of ceria and HHO. As a catalyst that donates oxygen, CeO_2 enhances the oxidation of CO and hydrocarbons. Because of its rapid flame speed and low ignition energy, HHO gas encourages quicker, more thorough burning. Better oxidation resulted in a considerable reduction in CO, smoke, and HC. CeO_2 promotes soot oxidation and inhibits carbon deposits. Because of their increased surface area and superior thermal conductivity, nanoparticles enhance fuel atomization. Finer droplets, a more uniform air-fuel mixture, and more effective combustion are the results of improved atomization. CeO_2 prolongs the life of fuel injectors, pistons, and valves by lowering carbon accumulation and engine deposits. Reduced maintenance needs are another benefit of cleaner combustion. The mixture is more engine-compatible since CeO_2 and HHO make up for the blend's low cetane number, poor volatility, and high viscosity. In order to improve clean and sustainable combustion technologies, the study provides a thorough experimental assessment of engine performance, combustion behavior, and emission characteristics. It also offers valuable information about improving low-quality alternative fuels through catalysis and hydrogen assistance.

CRediT authorship contribution statement

A.S. El-Shafay: Writing – review & editing, Supervision, Data curation, Conceptualization. **Aisha F. Fareed:** Writing – original draft, Investigation, Data curation. **Ümit Ağbulut:** Writing – review & editing, Methodology, Investigation, Formal analysis. **M.A. Mujtaba:** Writing – review & editing, Software, Formal analysis. **Fahid Riaz:** Writing – review & editing, Resources, Funding acquisition. **M.S. Gad:** Writing – review & editing, Validation, Data curation.

Declaration of competing interest

I on the behalf of the all authors, declare that there is no conflict of interest and all the elements of the submission are also in compliance with the journal publishing ethics. By submitting this manuscript, the

authors agreed that the copyright for their article should be transferred to this journal if the article is accepted for publication. The work contained within the research paper is our original contribution and has not been published anywhere.

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Data availability

Data will be made available on request.

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